Australasian Universities Power Engineering Conference, AUPEC 2020, Hobart, TAS, Australia, 29 November – 3 December 2020

Wireless-power transfer for AGVs: a comparison between ferrite and amorphous core

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***Abstract*— As the autonomous guide vehicles (AGVs) are becoming more popular in modern warehouses, there is an increase demand for a fast AGV wireless charging systems (WCS). A high-frequency high-power density wireless transformer model proposed operates at 100 kHz and has 1 kW output. Two different magnetic materials were investigated for this transformer core: ferrite and amorphous. Transformer design equations and FEM simulation were used to analysis core material feasibility. Ferrite material had 1134 W and 90% efficiency at 7 mm air gap, while amorphous material had 1184.4 W with 94% of efficiency. Investigation on power factor had shown that both magnetic materials presented an increase of reactive power for larger air gaps, resulting in lower power factor.**

Keywords—WPT, WCS, AGV, ferrite, amorphous, transformer

I. Introduction

Electric vehicles (EV) have become popular as an environmentally friendly technology. Although there are many challenges such as battery charging time and charging methods, EVs are more efficient and reliable than gas/petrol vehicles. The term EV can refer to cars or to any other vehicle which has an electric motor as well as robots.

In large storages, factories and warehouses, the implementation of Autonomous Guide Vehicles (AGV) is trend where small to medium size robots do lifting to pilling light and heavy packages. Figure 1 illustrate current AGV applications operating in a warehouse. AGV has optimized the work on storages and decreased the probability of any accidents, due to the fully programmable characteristic plus proximity sensors and iteration between machines [1]. There are two charging methods for AGVs in the market. The first one is the traditional wired method and the second wireless power transfer (WPT). In the conventional wired charging method, the AGV is connected through a physical contact to a power supply connector that can cause electric arcing, endangering humans life [2]. In addition, traditional wired charging has a slow charging process which reduces the AGV working time.

The WPT charging method is composed by two coupling coils and converter circuit [3]. The transmitter (Tx) coil is excited by an AC source, generating magnetic flux that induces AC electric current on the receiver (Rx) coil, then the current in converted into DC, charging the battery inside AGV, Figure 2. WPT has been applied to many electronic devices such as smartphones, smartwatches, vacuums, electronic toothbrush and EVs [4]. In each application, the WPT has different specifications regarding voltage, current and frequency. For AGV application, fast charging method is desirable to reduce charging time and increase the AGV daily working time. Therefore, high-frequency and high-power density transformer can be implemented as WPT for AGV.

WPT systems vary in design, as for number of coils in Tx and Rx, shape of coil (circular, square, rectangular) [3], and with or without magnetic core. This paper describes an WPT system that has circular coils and U-cores. The WPT system is capable to output 1 kW at 100 kHz. An investigation in regard to the core material has been done, in which, the conventional ferrite core and an amorphous core were compared. Transformer design calculations were initially done to analysis WPT system feasibility, followed by finite element method (FEM) simulations on COMSOL software. Furthermore, the performance of each core was evaluated in relation to the air gap distance between Tx and Rx.

Figure 1. Example of warehouse AGVs application.

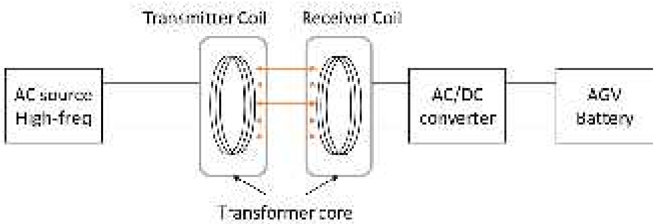

Figure 2. Diagram of WPT that has ferromagnetic cores on each end.

II. WPT Morphology

Currently, there are two methodologies for charging AGVs: dynamic and static. Dynamic wireless charging systems (WCS) is composed by multiple transmitters inside concrete and a single coil beneath the vehicle or in-wheel [5-7] as shown in Figure 3. Power transfer occurs as receiver is in range of transmitter magnetic field. Dynamic WCS requires highly cost infra-structure, besides the low efficiency due to misalignment. However, AGVs can be programmable for perfect alignment and the cost of implementing tracks inside warehouse is lower than on large motorways.

Static WCS replaces the conventional plug-in charger systems and can be implemented at any warehouse. Composed by a single transmitter and a single receiver, this system transfer energy to any parked AGV on designated charging area, Figure 4. The system convenience prevents electrical accidents during plug of power source, also system can be implemented vertically and inside walls. AGVs are programmed to perfectly park on charging area, so that Tx and Rx are as close as possible, which decreases the air gap and increases WCS efficiency. Static system charges faster and has less losses than dynamic system, therefore the morphology developed in this paper is static WCS.

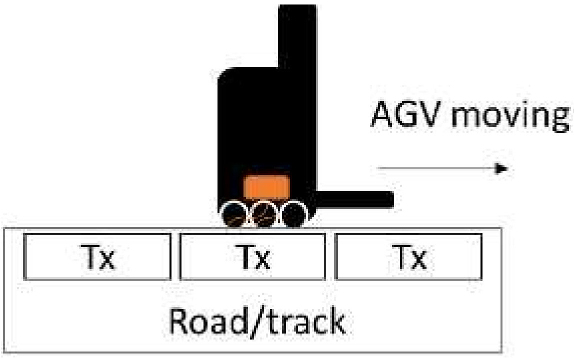

Figure 3. Dynamic WCS transferring energy to a moving electric vehicle.

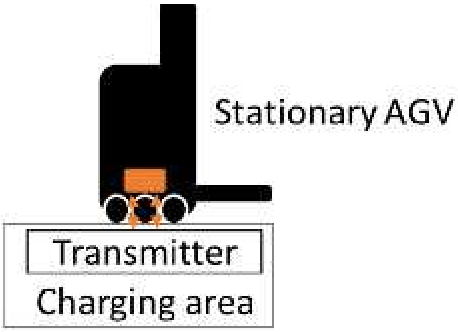

Figure 4. Static WCS recharging parked AGV.

III. WPT TRANSFORMER DESIGN

Transformer designing has many constraints that must be followed to achieve desired output, such as power output, efficiency, weight and size. Mostly one or two constraints will be dominant in the design, while others are used as trade off to achieve defined specifications. The process of designing this model started on setting the size of transformer to fit small AGVs while having minimum power output equal to 1 kW. Tx and Rx have the same dimensions, in which width is 119.90 mm, height of 89.86 mm and length of 4.80 mm. The coil is circular and has U-cores equally spaced, forming a ring that contains the coil, Figure 5. After, defining the enclosure size, the ring diameter that contains a number of U-cores and coil windings was defined as 53.54 mm and 83.40 mm, for inner and outer diameter respectively. This ring area was divided into 21 equally spaced U-cores. U-core width, height and depth are 14.34 mm, 11.21 mm and 6.42 mm, respectively.

A. *WPT transformer design considerations*

Coil winding is considered to fulfill the U concavity area, also known as Window Area (W_a) of magnetic core. The width and height of W_a is equal to 5.06 mm and 12.76 mm, respectively, thus W_a is approximately 64.57mm^2. A_c is the U-core cross-section area where the magnetic flux circulates. The A_c must to be wide enough to support designed magnetic flux. When W_a is multiplied by A_c, the result is called Area Product (A_p). A_p describes the power-handling capacity of the transformer core. This variable is commonly used by manufactures. The calculation for A_p related to core sizing is represented by Equation 1. In addition to physical equation, A_p can be calculated with transformer specifications, such as total power (P_t), flux density (B), current density (J), waveform coefficient (K_f), utilization factor (K_u) and frequency (f). Equation 2 represents the transformer calculation of A_p.

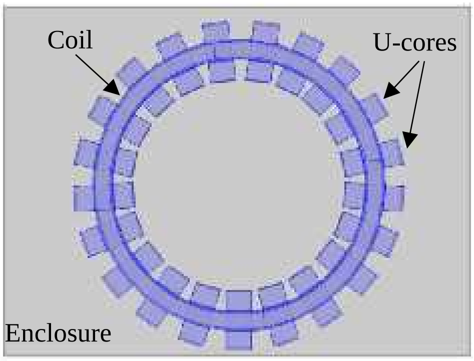

Figure 5. Top view of transformer with coil and U-cores are highlighted in blue.

$$A_p = W_a * A_c \tag{1}$$

$$A_p = \frac{P_t * 10^4}{K_f K_u B f J} \tag{2}$$

The proposed design can be considered feasible if the result of Equation 1 is equal or greater than Equation 2 as calculations of sizing limits the amount of power that the transformer can output. However, Equation 1 represents the value of A_p for a single U-cores, whereas this design has 21 U-cores, Equation 1 result must be multiplied by 21 to achieve full transformer output capacity. As a result, the total physical value of A_p is 4.30 cm^4.

As described previously, the designed power output is 1 kW and the efficiency is 95 %. The AGV battery is 48 V_{dc}, thus the AC input voltage source is 68 V. Therefore, the peak current on coil will be 20.83 A and to support such current, a 3 mm diameter winding or an AWG 9 winding is ideal to this design with the total number of turns equal to 4. The turn ratio is 1:1 as the current is already high that any further current is not supported by winding of similar size plus the W_a does not fit larger windings. The waveform coefficient for sinewave is 4.44 and the window utilization factor is 0.7.

One trade-off for creating smaller size transformer while maintaining the power output is increasing the input source frequency. IEEE standard C95.1-2005 [8] specifics that for any transformer operating on frequency above 100 kHz, human exposure is not recommend due to tissue heating. Hence, the operational frequency is 100 kHz. This frequency is safe for any humans that might be on storage houses at the same that AVGs are charging.

Two core materials are used for this WPT system: ferrite and amorphous. The ferrite is a Mn-Zn selected from TDK PC90 series. This material is commonly used for switching supplies and high-frequency transformers. The Metglas AMCC series from Hitachi, is chosen as amorphous core that can also operate at high frequency. All transformer specifications discussed are listed in Table I. For each material, the A_p is calculated and compared with each other from U-core size of ferrite and Amorphous materials.

TABLE I. TRANSFORMER SPECIFICATIONS

Variable	***Value***
Power	1 [kW]
Voltage	48 [V]
Winding ratio	1:1
Window Area (W_a)	32.28 [mm^2]
Cross-sectional area (A_c)	31.73 [mm^2]
Waveform coefficient (K_f) – Sine wave	4.44
Window utilization factor (K_u)	0.7
Frequency	100 [kHz]

B. *Ferrite core*

Ferrite PC90 from TDK is a consolidate ferrite material in the market that has 2200 for initial mur and flux density of 0.35 mT for temperatures of 100 ˚C or less. This material can operate at 100 kHz without variation on the material mur characteristic. Considering the ferrite material flux density and the previous WPT specifications, the result of Equation 2 is 3.86 cm^4. Comparing the ferrite A_p value to the one calculated from transformer sizing, it is smaller, thus ferrite is suitable for this design.

C. *Amorphous core*

Amorphous materials are recently new to the high-frequency transformers market and manufactures can make different shapes out of it. The Metglas AMCC from Hitachi has U-core shape and fit the U-core size defined in this model. Typical amorphous BH-curve has higher saturation point than ferrite of 1.4 T with initial mur equal to 35000 and can be operated on higher temperatures with no additional losses. The amorphous A_p value is 0.97 cm^4. Consequently, U-cores made from amorphous material are suitable for this model plus allowing also some constraints to be readjusted.

IV. FEM SIMULATIONS RESULTS

Finite Elements Method is widely applied to simulate and describe electromagnetic physics problems, because of the simulation accuracy when tested on laboratory experiments. Hence, this proposed design is built inside COMSOL software defining the electromagnetism environment and the electric circuit of a transformer. Combined, the multi-physics analyses the structure and physical characteristics of this model plus the coupling factor between transmitter (Tx) and receiver (Rx). A load of 10 Ω represents the battery and AC/DC converter connected to Rx. The power source has the requirements discussed so far, peak of 68 V and frequency of 100 kHz. Two model are developed inside COMSOL, one in 2D and another 3D. The 2D model simulates the magnetic flux and leakage flux between Tx and Rx, while the 3D model investigates voltage, current and power of the whole WPT system.

A. *Computer Simulation Module of Wireless transformer*

Wireless transformer model is symmetrical considering the space between U-cores and coil windings. COMSOL software simulates a single symmetrical unit, considering and calculating all constraints as whole model by applying these variables to this unit. Plus, the user defines multiplication factor to the total number of symmetrical units the complete model has. The advantage of symmetrical modelling is reduction on computational effort, thus simulation time is greatly reduced. Thus, the model developed in COMSOL is a symmetrical section of U-cores containing Tx and Rx, as shown in Figure 6. Coils are defined homogenized multi-turn and coil excitation is created by an external source in the electric circuit physics. Ampère's Law is applied to transformer cores using material BH-curve to describe the magnetic field.

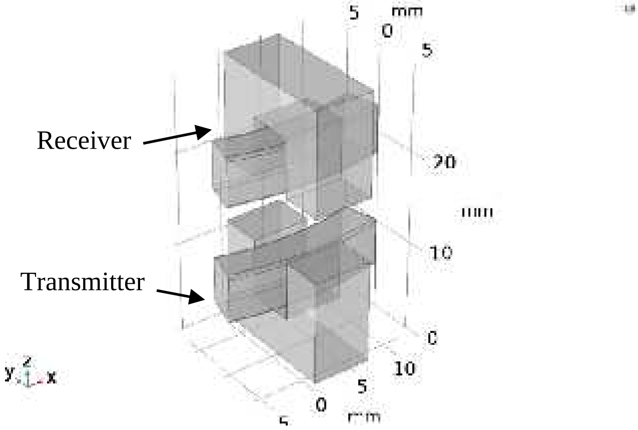

Figure 6. COMSOL module of single WPT section for 3 mm air gap.

B. *Simulation Results and Analysis*

Initial investigation compared the two selected materials when the air gap between Tx and Rx U-cores is 0 mm. As expected, both ferrite and amorphous simulations converted to similar results. The difference between ferrite and amorphous cores is power output and power efficiency for larger air gaps. The air gap of 7 mm is defined as a comparation between both core materials because it is the double size of the defined lid that encloses Tx and Rx, so that the AGV does not have to make contact between Tx and Rx devices.

Figure 7 and Figure 8 illustrate results for amorphous material 2D simulations for 0 mm and 7 mm of air gap, respectively. In Figure 7, the magnetic flux inside amorphous core has some closed loops at the receiver side (top U-core) due to the 10 Ω load. The magnetic flux is denser at receiver U-core inner corners, reaching 2.5x10^{-2} T. Ferrite core presented similar magnetic leakage flux contour, however the value was doubled, 5x10^{-2} T. For a small air gap, the transformer core magnetizing reactance and coupling coefficient is high, as a result, the current on secondary coil is almost equivalent to primary current. The transformer efficiency for 0 mm air gap is 97.26% and 98.36% for ferrite and amorphous core, respectively. There are minimum losses due to the core magnetization, core heating on high concentrate magnetic flux areas and coil copper losses.

In order to determinate the quality of this WPT design and analysing the performance of an amorphous core, a set of simulations varying the air gap from 0 mm to 10 mm with the ferrite and amorphous core was conducted. Figure 8 illustrates the magnetic flux density for an air gap of 7 mm on the amorphous core while Figure 9 shows the result for ferrite core. Both transmitter core (bottom core) has high concentrated magnetic flux on the left and at the bottom side. In addition, the leakage flux on the left side is lower than on the right. The reason behind these results is explained by the circular geometry of this model. The inner part of U-core ring is located to the left, so all U-cores compensates a little the magnetic field at the middle of coil ring, decreasing the leakage flux on the left side.

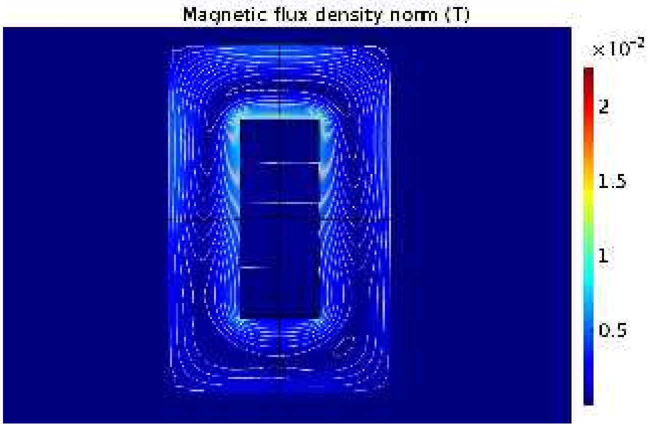

Figure 7. Magnetic flux inside amorphous core when there is no air gap between Tx and Rx. A 10 Ω load is connected to Rx.

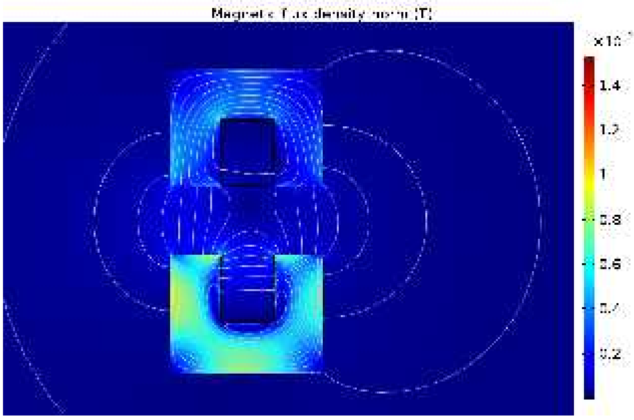

Figure 8. Magnetic flux density on amorphous core with 10 Ω load when the air gap is equal to 3.5 mm.

Ferrite core has higher magnetic flux density than the amorphous core at the U-cores inner edges, closer to the transmitter coil windings. Therefore, losses from magnetization and heating of this areas are higher on ferrite material. Figure 10 illustrates the power efficiency results for both material over the different air gaps. As expected, the ferrite material has lower efficiency than amorphous, because the flux density limit for ferrite is lower than amorphous. In addition, the previous calculation of A_p demonstrate that ferrite core is closer to the physical limitation of this wireless transformer design. At 7 mm air gap, ferrite has power output of 54 W for single U-core and 1134 W for the entire wireless transformer, while amorphous has 56.4 W for single U-core and 1184.4 W for the entire system. Both core materials have achieved the power output designed of 1 kW.

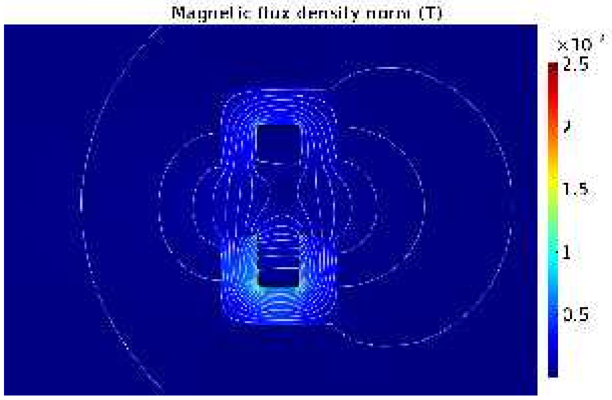

Figure 9. Magnetic flux density on ferrite core with 10 Ω load when the air gap is equal to 3.5 mm.

Figure 10. Variation of power efficiency over air gap for ferrite and amorphous cores.

The efficiency for 7 mm air gap was above 90% for both core materials. However, this efficiency result is related to the active power of this wireless transformer. Further investigation was conducted to analysis the power factor of the designed system. Amorphous core and ferrite core presented similar behaviour for the power factor. Table II lists the simulation results for air gap that vary from 0 mm to 10 mm for amorphous core. The excitation current is increasing with the air gap as the transformer requires more energy in the primary inductor to generate magnetic field. Consequently, the reactive power on primary increases, also decreasing the input power factor. For 7 mm, the primary power factor is close to 0. This reactive power is wasted on the primary inductor as the secondary is not absolving this energy, on the contrary, the reactive power on secondary is decreasing with the air gap. The active power at 7 mm air gap correspond to less than 3% of apparent power, which means that almost all energy introduced into the system is being wasted into reactive power. Although the wasted input reactive power, active power transmitted from primary to secondary is highly absolved which resulted in the highly efficient transformer. Compensation circuit decreases the reactive power on primary side, improving the primary power factor and coupling coefficient.

TABLE II. AMORPHOUS U-CORE POWER RESULTS FOR SINLGE MODULE

Air Gap (mm)	*Input Apparent Power (VA)*	*Input Reactive Power (VAR)*	*Input Active Power (W)*	*Power Factor*
0	373.56	74.77	366	0.980
0.5	477.28	380.59	288	0.603
1	598.08	546.49	243	0.406
1.5	670.95	637.24	210	0.313
2	720.48	696.59	184	0.255
3	812.80	800.30	142	0.175
4	874.48	867.02	114	0.130
5	897.00	892.27	92	0.103
6	931.68	928.74	74	0.079
7	948.66	946.76	60	0.063
8	975.00	973.72	50	0.051
10	984.27	983.65	35	0.036

V. CONCLUSION

A study in regard to core material for of WPT transformer has been conducted. This WCS model can fit on current AGV applications and operates on high-frequency, outputting 1 kW. Two core material were investigated, a ferrite from TDK series PC90 and an amorphous from Hitachi series Metglas AMCC. First evaluation of material feasibility was conducted using transformer design equations for area product W_a. The physical W_a is 4.30 cm^4, ferrite had 3.86 cm^4 and amorphous 0.97 cm^4. Both core material was suitable for the transformer. As expected, ferrite material had lower performance than amorphous material in relation to power output and power efficiency, therefore amorphous is better core material for the proposed wireless charge system. However, both materials had an increase of reactive power for larger air gaps, which requires the addition of a compensation circuit to improve power factor. Further investigations will be made on the improving of coupling coefficient and power factor on primary side by introducing a compensation circuit to this transformer.

REFERENCES

[1] D. P. Kar, S. S. Biswal, P. K. Sahoo, P. P. Nayak, and S. Bhuyan, "Selection of maximum power transfer region for resonant inductively coupled wireless charging system," *International journal of electronics and communications,* vol. 84, pp. 84-92, 2018, doi: 10.1016/j.aeue.2017.11.023.

[2] S.-J. Huang, T.-S. Lee, W.-H. Li, and R.-Y. Chen, "Modular On-Road AGV Wireless Charging Systems Via Interoperable Power Adjustment," *IEEE transactions on industrial electronics (1982),* vol. 66, no. 8, pp. 5918-5928, 2019, doi: 10.1109/tie.2018.2873165.

[3] J. Zhang, Z. Wang, Y. Liu, C. Cui, S. Cui, and C. Zhu, "Research on the transmission characteristics of various coupling structures based on Various Wireless Power Transfer Technology," 2019, no. Conference Proceedings: IEEE, pp. 1-6, doi: 10.1109/ICEMS.2019.8921795.

[4] K. Kadem, Y. Le Bihan, M. Bensetti, E. Laboure, A. Diet, and M. Debbou, "Reduction of the shielding effect on the coupling factor of an EV WPT system," 2019, no. Conference Proceedings: IEEE, pp. 21-24, doi: 10.1109/WoW45936.2019.9030652. [Online].

[5] C. Panchal, S. Stegen, and J. Lu, "Review of static and dynamic wireless electric vehicle charging system," *Engineering science and technology, an international journal,* vol. 21, no. 5, pp. 922-937, 2018, doi: 10.1016/j.jestch.2018.06.015.

[6] C. Jiang, K. T. Chau, C. Liu, C. H. T. Lee, W. Han, and W. Liu, "Move-and-Charge System for Automatic Guided Vehicles," *IEEE transactions on magnetics,* vol. 54, no. 11, pp. 1-5, 2018, doi: 10.1109/tmag.2018.2829727.

[7] M. Sugino and T. Masamura, "The wireless power transfer systems using the Class E push-pull inverter for industrial robots," 2017, no. Conference Proceedings: IEEE, pp. 1-3, doi: 10.1109/WPT.2017.7953901. [Online].

[8] I. Xplore, *C95.6-2002 - IEEE Standard for Safety Levels With Respect to Human Exposure to Electromagnetic Fields, 0-3 kHz* (no. Book, Whole).