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Research paper

Magnetic Force Calculation of Movable YBCO Superconducting Helical Coils Applicable to Electric Vehicles Wireless Power Transfer

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Abstract

Background and Objectives: Today, replacing gasoline-powered vehicles with electric vehicles (EVs) and connecting them to an electric power source have made the optimal usage of energy-saving resources. Therefore, wireless Power Transfer (WPT) outstands as an alternative technology to improve the user perception about the charging process of the EVs. Superconducting coils (SCs) with high-temperature have an applied feature in decreasing losses of wireless power transmission (WPT). The Magnetic force has effects of overall deformation modes between two current carrier superconducting coils, i.e. axial extension, torsion, and bending. Coil misalignment is a fundamental problem and its impact on wireless power transmission efficiency is very complex. The analysis of a magnetic force which is presented in this paper are beneficially for the design and application of the WPT systems. Here, a fast analytical solution is presented to obtain the magnetic force between the transmitter and receiver helical superconducting coils in different positions.

Methods: In this paper, a new method applied to solve the numerically magnetic force solutions in different superconducting coils mismatch states for WPT. Finally, for improvement of efficiency, the WPT system has been designed on the basis of mutual inductance changes which receiving helical coil was moved inside the transmitting helical coil. Hence, the magnetic force calculation of movable YBCO superconducting helical coils inside each other is presented. These models have been compared with the FEM.

Results: Results show that the presented equations are reliable as well. According to the comparing the analysis and FEM data, the obtained results indicated the errors with less than 0.0064%. Also, results show an excellent agreement with respect to the finite element method.

Conclusion: In this paper, the numerical solutions of magnetic force in different superconducting coils mismatch states were solved by a new method. The magnetic force analysis basics introduced in this paper are useful to develop and apply for wireless power transmission system. The simulation results show that only by applying some constraints, the efficiency of the transmitted wireless power will be optimized. Then, analytical models have been presented which make it possible to calculate the axial force which was exerted between two axially Helical magnetized and two thin coils in air. Also, the analytical stiffness calculation applied between these distributions of magnetic source has been presented. These models have been compared with the FEM to show an appropriate consistency.

Introduction

HTSCs have been used as variable inductors [1], a Wireless Power Transfer system [2]-[4], and electrical machines [5]. Several using benefits of HTS in traditional samples are including reduction of size and weight about 40% to 60%, almost 60% decrease wastage, repairing reduction and maintenance cost, lower environmental pollution, and decreasing fire risk [6]. HTCs also improve the efficiency of wireless power transmission by reducing resistance. The advancement of movable devices such as electric vehicles and portable equipment and also, wireless power transfer technology for charging has become even more important. In general, wireless power transfer could be considered a three-step process. I) Electromagnetic power output from direct or alternating current, e.g. 50Hz. II) Power transmission of Electromagnetic waves to distant points through free space. III) Collecting and re-converting electromagnetic waves to direct or alternating current, for example, 50 Hz at the receiver side. The total efficiency of the WPT is equal to the multiplying product of the efficiency of the above three steps. The first experiments were carried out by Hertz, developed by Tesla, and efforts to operate wireless transmission systems have continued until today [7]. According to existing papers, studies on WPT, which began in 1984 and have grown substantially in recent years. Part of these studies is introducing new applications of WPT in sectors such as industry, mining, transportation and medical engineering. Another area of study is modeling and optimizing different parts of the WPT. This paper examines the second step, which possesses a decisive role in the overall efficiency of the system. Calculations of force between superconducting coils are essential in order to achieve the optimal design of wireless transmitting systems. The calculation of the magnetic force between different types of geometric shapes of coils could be applied in widespread feasible applications which were including magnetic levitation systems, energy storage systems and flywheels, magnetic levitation vehicles and sports engineering and design of electrical machines. These apps are the reason why magnetic force calculations have been an interesting field for a number of physicists and engineers. The magnetic force calculation of thick arrays that included coaxial coils has been performed by the limited element technique [7]-[9]. Moreover, some semi-analytic setting formulas to progress of the computation accuracy of the magnetic force have been applied in the literature [10]-[11]. Formulas proposed in the literature distinguish mostly on the space base that is chosen to unlock the multiple-integral explained for the magnetic force. The space basis that was suggested by Conway was the set of Struve functions and a Mathematical program system was used for the ending estimation of the magnetic force [13]. Other works relied on single or double integration of space bases founded on Bessel functions and elliptic integrals [14]-[17]. In anticipated applications such as electric vehicles, medical implants and the aerospace industry, the receiving superconducting helical coil usually has a mismatch between the lateral and angular with the transmitting superconducting helical coil and the effect of this mismatch on power transmission efficiency has received little attention by researchers [18]-[19]. The comprehensive set presented in this paper allows the coils to move and rotate to obtain a larger mutual inductance and optimize the transmission efficiency. In this paper, a new and comprehensive set has been presented based on magnetic force analysis of the coil despite the mismatch. A theory of generalizing has been extended to estimate the magnetic force of 2- helical superconducting coils that have finite-length, depend on the analytical mutual inductance granted in [1]. Also the relation between mutual inductance and magnetic force presented in [20]-[23]. By analytical method utilization, the magnetic force of the windings can be characterized straightly and rapidly, without applying the time-consuming Finite Element Analysis (FEA). Evaluation of results, comparatively, has been helpful than the finite-element simulation results in other kinds of studies. Furthermore, the impact of the whole geometric parameters that have profoundly affected the magnetic force including pitch length, coil radius, rotation start angle and axial replacement of the coils has been researched rationally. Finally, for improvement of efficiency, the Wireless Power Transfer system has been planned in terms of mutual inductance changes in the way that the receiver helical coil was moved inside the transmitting helical coil; hence, the magnetic force calculation of movable YBCO superconducting helical coils inside each other is presented. This paper consists of the following items: inducting a pair WPT model for electric vehicle charging is presented. Also misalignment and different positions such as lateral misalignment and angular misalignment are presented. Finally, analytical equations are presented to estimate the magnetic force among two inclined HTCs when whether their axes cross at the center of one of the HTCs or their axes not cross at the center of one of them. Also, we compared analytical results with the FEM results. Also the magnetic force of two HTCs is illustrated.

Inductive Pair Wireless Power Transmission System Model for Electric Vehicle Charging

Conventional methods in order to transfer energy for moving vehicles are the use of flow rails and brushes for long paths and cable transmission for short paths.

Applications of moving appliances include elevators, surface-to-air transmitters, electric vehicles and mono-rail. Inductive energy transfer based on electromagnetic induction is a new method for these applications. Fig. 1 shows a schematic of wireless power transfer method. Table 1 compares energy transfer methods. According to Table 1, the benefits of WPT[1] are low maintenance cost

[1] Wireless Power Transfer

due to non-wear parts, Insensitivity to environmental conditions, High reliability, complete electrical insulation and less environmental pollution. On the other hand, there are some disadvantages such as high complexity, low efficiency, and high installation costs [24].

These wireless power transmitting systems are similar as air core transformers whose primary connection to the power supply and the secondary connects to load. The current passing through the primary coil produces a Magnetic flux through the secondary coil that connection to the load, this flux will induce the voltage to the secondary coil, Fig. 2 displays this operation.

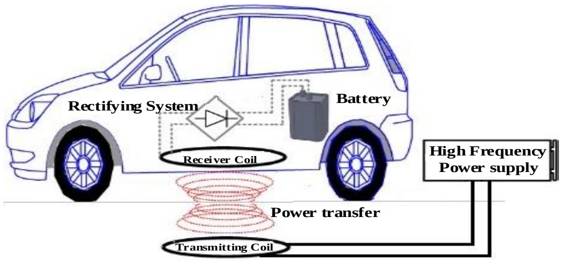

Fig. 1: Scheme of the electric vehicle wireless charging and induction coupling system.

Table 1: Comparison of different energy transfer methods [25]

Criterion	Inductive power transfer	Cable	Flow rails and brushes	Criterion	Inductive power transfer	Cable	Flow rails and brushes
Reliability	high	medium	medium	Technology	very complicated	simple	complicated
Sensitivity to the environment	No	No	Sensitive to ice and dust	Voltage and current	DC and AC high frequency	DC and AC low frequency	DC and AC low frequency
Security against electric shock	safe	safe	dangerous	Phase number	1	1 and 3	1 and 3
Electromagnetic perturbation	medium	low	low	Power conversion	Yes	No	No
Pollution	No	No	Yes, brushes	efficiency	low	high	medium
Cost Estimation	high	low	medium	Abrasion or rupture	No	Yes	Yes
Cost of installation / operation	Low/ high	Low/ Low	medium	maintenance	No	Yes	Yes

At the transmitter side, to improve efficiency, the frequency is firstly set to the resonant frequency, and the receiving side the current is converted to DC according to the load type.

Hence, promote to transmit coil, the corresponding receiving coil and the overall system are in the same resonant frequency (i.e. to achieve "electrical resonant" state) to make corresponding energy-efficient transmission.

When the system is operating at the resonant frequency, it has the smallest impedance value, and the maximum transmission efficiency point of the system can be approximated as the resonant frequency of the transmitting or receiving coil.

Therefore, in order to ensure the system work in the maximum transmission efficiency point, the circuit must ensure that the current and voltage with the same phase, in the ideal environment, current and high frequency power supply with the same phase means current and high-frequency signal generator in the same frequency phase.

In other words, if the receiver or transmitter adds a signal processing link into the current feedback signal, whether the system operates at the resonant frequency, the direct use of current feedback signal as a high-frequency signal generation source instead of the previous high-frequency signal generator, so the system can work directly after exemption from the previous high-frequency signal generator. The circuit equivalent to the inductive-pair wireless power transmission system is shown in Fig. 3. The variable *d* is the distance between the two coils, M is the mutual inductance of the two coils, and U_{in} is the potential source.

The values of $\mathrm{R_P}$, $\mathrm{R_S}$, $\mathrm{C_P}$, and $\mathrm{C_S}$ are parasitic resistance and capacitance of primary and secondary coils respectively in high frequency, and $\mathrm{L_P}$ and $\mathrm{L_S}$ are self-inductance of two-coil.

$\mathrm{R_L}$ is also the load resistance. The total resistance of lead-acid batteries is considered R_L= 1/44 Ω [26] In order to reduce the parasitic capacitive effects, coils are usually made of a single-layer helical coil in a wireless power transmitting system. In a wireless power transmitting system, an inductive frequency resonant pair can transmit power from the primary transmitter coil (T_x) to the secondary receiver coil (R_x) for the purpose of changing the magnetic field [27].

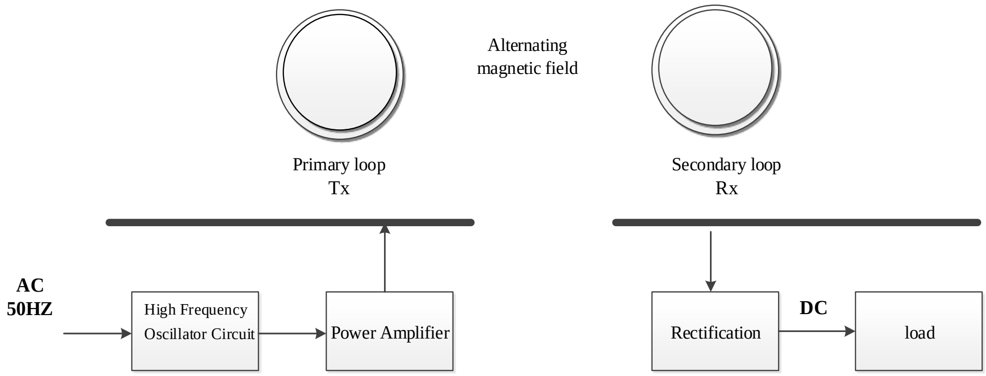

Fig. 2: The structure of the wireless power transmission system.

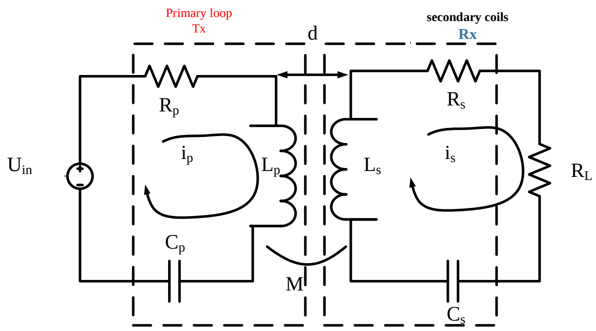

Fig. 3: Model of wireless power transmission system.

Assuming the system is operating at frequency ω, the KVL relationships for the primary and secondary circuits could be calculated from Fig. 3 as below:

$$\begin{bmatrix} R_p + jX_p & j\omega M \\ j\omega M & R_s + R_L + jX_s \end{bmatrix} \begin{bmatrix} I_p \\ I_s \end{bmatrix} = \begin{bmatrix} U_{in} \\ 0 \end{bmatrix} \quad , \qquad (1)$$

$$\begin{cases} X_p = \omega L_p - 1/(\omega C_p) \\ X_s = \omega L_s - 1/(\omega C_s) \end{cases}$$

The transmitted power efficiency in this paper is defined by the ratio of the output power P_{out} in R_L load to the produced input power P_{in} of the primary coil:

$$P_{in} = \frac{u_{in}^2 Z_s}{Z_p Z_s + (\omega M)^2}, P_{out} = \frac{u_{in}^2 (\omega M)^2 R_L}{[Z_p Z_S + (\omega M)^2]^2} \qquad (2)$$

$$\eta = \frac{P_{out}}{P_{in}} = \frac{(\omega M)^2 R_L}{Z_S [Z_P Z_S + (\omega M)^2]^2} \times 100\%$$

In the case of resonance existence in two coils, the maximal power transfers to the R_L and reactance losses would be eliminated. Thus, for η it could be written:

$$\eta = \frac{(\omega M)^2 R_L}{(R_s + R_L)[R_p(R_S + R_L) + (\omega M)^2]} \times 100\% \qquad (3)$$

From (3) the effect of the mutual inductance and resistance of coils on transmission power could be observed clearly.

The transmission efficiency is directly proportional to the mutual inductance. Therefore, selection of superconducting materials as coils conductors leads to remarkable increase in efficiency of wireless power transmitting systems. The maximum power transfer theorem results in maximum power transfer across the circuit, and not maximum efficiency. Efficiency can be higher if the charge resistance creates larger than the source resistance, since a very high percentage of the source power is shifted to the charge, but the load power value is lower since the whole of the circuit resistance goes up. Is the load resistance more similar than the source resistance, then much of the power ends up being dissipated in the source, and though the whole power dissipated is higher, because of a lower entire resistance, it turns out that the amount dissipated in the charge is decreased. The quality factor (Qs) of the coils determines the coil efficiency. Certainly, the Qs can be related to material and shape of coils, track width, and number of turns [28]-[29].

Misalignment Between Superconducting Helical Coils

Coil orientation is a basic parameter in designing wireless power transmission systems. In practical applications, coils misalignment is common and can be in one of the following three forms:

- Lateral misalignment: in this case both coils are in parallel plates and have a vertical distance of d but, coils centers have the lateral distance of Lx along the axis of x or the lateral distance of Ly along the axis of y (Fig. 4-a).
- Angular misalignment: in this case the angle of coil plate Tx changes as the same as θ (Fig. 4-b).
- Combined misalignment: in this case both misalignments (lateral along x-axis or lateral along y-axis and angular) exist in coil at a same time (Fig. 4-c).

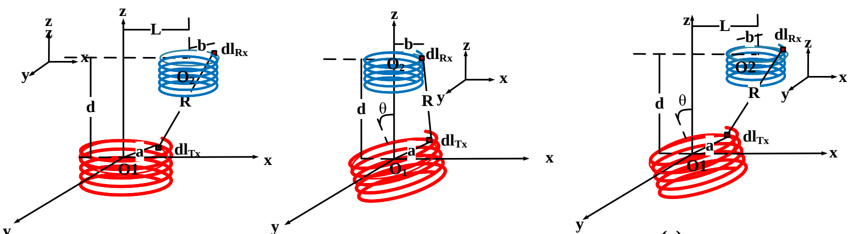

Fig. 4: The figure of two helical coils a) lateral misalignment without arrangement (x-axes cross but not at the center of each other) b) angular misalignment c) non-alignment (axes intersect but not at the center of each other and Angular misalignment).

A common case of misalignment in transmitting and receiver superconducting coils has been presented in Fig. 4.

Magnetic Force Calculation between Two Superconducting Helical Coils

The general expression for their mutual inductance drive the magnetic force between two coils including current-carrying. Solving equation assesses superconducting helical coils [20]:

$$F_{21} = -I_1 I_2 \nabla.M \tag{4}$$

where [24]:

$$M = \frac{\mu_0}{4\pi} \oint_{c_1} \oint_{c_2} \frac{\overrightarrow{dc_1}.\overrightarrow{dc_2}}{r} \tag{5}$$

dc_1 and dc_2 are tiny integration elements and r is the space from dc_1 to dc_2 line element. The φ coordinate of the point where the helical coil cross the plane $Z = 0$ by φ_0, the parametric equations according to Fig. 9 the helical line due to the parameter $\varphi(\varphi_0 \le \varphi \le (2\pi l/h) + \varphi_0)$ and with $\varphi(\varphi_0 \le \varphi \le (2\pi l/h) + \varphi_0)$ are:

$$\begin{aligned} x_1 &= a_1 \cos\varphi_1 , & x_2 &= a_2 \cos\varphi_2 + L_x \\ y_1 &= a_1 \sin\varphi_1 \cos\theta , & y_2 &= a_2 \sin\varphi_2 \cos\theta + L_y \\ z_1 &= \frac{h_1}{2\pi}(\varphi_1 - \varphi_{01})\sin\theta , & z_2 &= \frac{h_2}{2\pi}(\varphi_2 - \varphi_{02})\sin\theta + d \end{aligned} \tag{6}$$

To use (5), beneficial expressions for $\overrightarrow{dc_1} . \overrightarrow{dc_2}$ must be found:

Different lengths, radius, and pitch lengths of two right-handed superconducting helical showed that in Fig. 9. To solve the integral of equation can analytically tackle the mutual inductance (5), as explained in the following.

$$\overrightarrow{dc_1}.\overrightarrow{dc_2} = \left[a_1 a_2 \cos(\varphi_1 - \varphi_2) + \frac{h_1 h_2}{4\pi^2}\sin^2\theta \right] d\varphi_1 d\varphi_2 \tag{7}$$

Finally, the mutual inductance between two coaxial helical superconductors with different finite lengths of l_1, l_2, different pitch lengths of h_1, h_2, different coil shifts of $\varphi_{01}, \varphi_{02}$, and the distance between the starting point (0, 0, 0) of transmitting coil and the ending point (x,y,d) of the receiver one along the Z-axis (d), X-axis (Lx), Y-axis (Ly) and different windings radius a_1, a_2, takes the form:

$$F_{12}(h_1, h_2, a_1, a_2, \varphi_{01}, \varphi_{02}, d, L_x, L_y, \theta) = -I_1 I_2 \nabla.\frac{\mu_0}{4\pi}\left[\frac{\tau_x}{18}\frac{\tau_y}{18} \sum_{i=1}^{n}\sum_{j=1}^{n} Q(s_i, s_j) \right] \tag{8}$$

where

$$\begin{aligned} Q(s_i, s_j) = [&\lambda_1.G(C_i, C_j) + \\ &\lambda_2.G(C_i, A_j) + \lambda_1.G(C_i, D_j) + \\ &\lambda_2.G(A_i, C_j) + \lambda_3.G(A_i, A_j) + \\ &\lambda_2.G(A_i, D_j) + \lambda_1.G(D_i, C_j) + \\ &\lambda_2.G(D_i, A_j) + \lambda_1.G(D_i, D_j)] \end{aligned} \tag{9}$$

$$\tau_x = \frac{2\pi l_1}{n.h_1}, \tau_y = \frac{2\pi l_2}{n.h_2} \tag{10}$$

where λ1, λ2 and λ3 are 25, 40 and 64, respectively [30], and

$$G(\varphi_1, \varphi_2) = \Omega(\varphi_1, \varphi_2, h_1, h_2, a_1, a_2) \times \Phi_m^{-0.5}(\varphi_1, \varphi_2, h_1, h_2, a_1, a_2, d) \tag{11}$$

To use formula (11), beneficial expressions for $\Omega(\varphi_1, \varphi_2, h_1, h_2, a_1, a_2)$ and $\Phi_m(\varphi_1, \varphi_2, h_1, h_2, a_1, a_2, \varphi_{01}, \varphi_{02}, d)$ must be found:

$$\Omega(\varphi_1, \varphi_2, h_1, h_2, a_1, a_2, \theta) = \left[a_1 a_2 \cos(\varphi_1 - \varphi_2) + \frac{h_1 h_2}{4\pi^2}\sin^2\theta \right] \tag{12}$$

$$\Phi_m(\varphi_1, \varphi_2, h_1, h_2, a_1, a_2, \varphi_{01}, \varphi_{02}, d, L_x, L_y, \theta) = \left[\begin{aligned} &(a_2\cos\varphi_2 + L_x - a_1\cos\varphi_1)^2 + \\ &(a_2\sin\varphi_2\cos\theta + L_y - a_1\sin\varphi_1\cos\theta)^2 \\ &+(\frac{h_2}{2\pi}(\varphi_2 - \varphi_{02})\sin\theta + d - (\frac{h_1}{2\pi}(\varphi_1 - \varphi_{01})\sin\theta))^2 \end{aligned} \right] \tag{13}$$

where:

$$
\begin{aligned}
&C_i = -\sqrt{\frac{3}{5}}\cdot\frac{\tau_x}{2} + A_i\,; C_j = -\sqrt{\frac{3}{5}}\cdot\frac{\tau_y}{2} + A_j\,;\\
&D_i = \sqrt{\frac{3}{5}}\cdot\frac{\tau_x}{2} + A_i\,; D_j = \sqrt{\frac{3}{5}}\cdot\frac{\tau_y}{2} + A_j\,;\\
&A_i = \frac{\varphi_{1(i)} + \varphi_{1(i+1)}}{2}; A_j = \frac{\varphi_{2(j)} + \varphi_{2(j+1)}}{2}\\
&\varphi_{1(i)} - \varphi_{1(i+1)} = \frac{2\pi l_1}{n}\\
&\varphi_{2(j)} - \varphi_{2(j+1)} = \frac{2\pi l_2}{n}
\end{aligned}
\tag{14}
$$

Theory-based studies for investigating magnetic force in coils misalignment modes will be very complicated due to the existence in equations (8)-(14). Thus, achieving analytical solutions is almost impossible. The New method is employed to calculate force magnetic in different misalignment modes and considering the distance (d) of two coils equal to 50 and 60 cm according to Fig. 4.

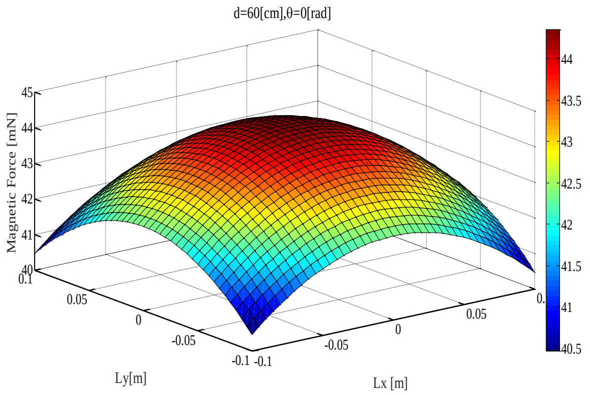

Fig. 5: Magnetic force in lateral misalignment along x and y axes with distance z equal to 60 cm, R_{Tx}=0.3 m, R_{Rx}=0.2 m, N_{Tx}=13, N_{Rx}=16 and resonance frequency =0.56 MHZ.

In Fig. 5 positive and negative values of L_x and L_y aim only to allude the orientation in special coordinate system. Obviously, an increase in lateral distance results in a decrease of magnetic force in lateral misalignment mode. In combined misalignment mode magnetic force is changed with respect to the lateral distance of L_x and L_y as well as rotation angle θ and there are relative optimal solutions in the shown range. Besides, considering the constant distance between two coils, peak values of magnetic force in Figs. 6 and 7 are not achieved in a full coils alignment. It could be understood that there are a number of constraints in inductive coupling wireless power transmission systems that ensure the possibility of maximum transmission power in a full alignment. Also, Fig. 8 demonstrates the efficiency based on lateral distance and rotation angle with respect to equations (1)-(3). According to (3), the efficiency of the system of WPT is maximized when the mutual inductance between two coils is maximum.

Finally, the WPT system has been planned based on changes of the mutual inductance in the way that the receiver coil was transferred inside the transmitting coil; therefore, the mutual inductance of the system was become to realize the maximum amount of the efficiency.

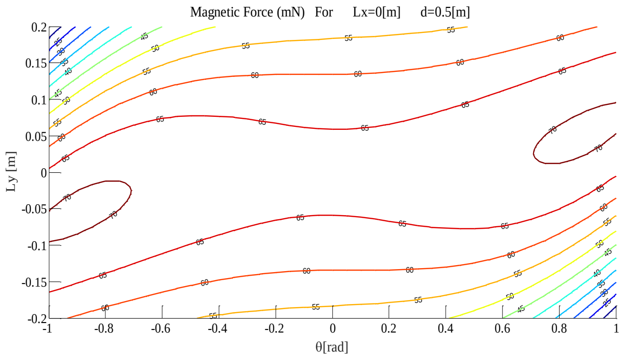

Fig. 6: Magnetic force in combined misalignment in x lateral and rotation angle θ with distance z equal to 50 cm with R_{Tx}=0.3[m], R_{Rx}=0.2[m], N_{Tx}=13, N_{Rx}=16 and resonance frequency =0.56 [MHZ].

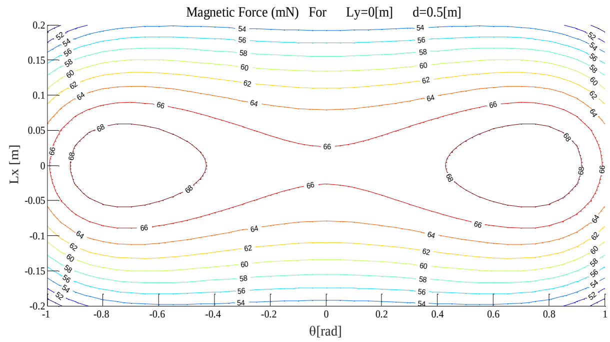

Fig. 7: Magnetic Force in combined misalignment at lateral distance x and rotation angle θ with distance z equal to 50 cm, R_{Tx}=0.3 m, R_{Rx}=0.2 m, N_{Tx}=13, N_{Rx}=16 and resonance frequency =0.56 MHZ.

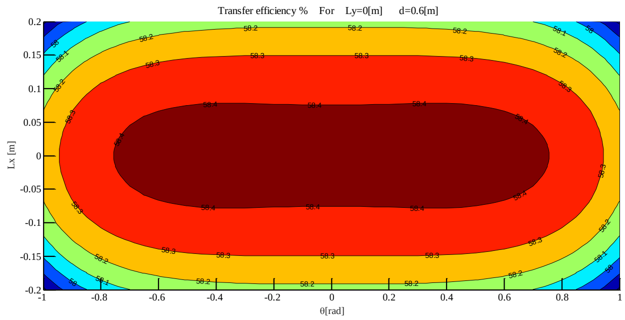

Fig. 8: Efficiency of compound mismatch at lateral distance x and rotation angle θ with distance z equal to 60 cm.

If two superconducting coils have the same length when they are fully intertwined, they have the highest mutual inductance, and if one of them is shorter than another, the coil with the shorter length must be in the middle of the larger coil to achieve the highest mutual inductance [1]. The Magnetic force has effects of overall deformation modes between two current carrier superconducting coils, i.e. axial extension, torsion and bending. Fig. 9 shows the case studied in the present paper containing two superconducting helical coils which were located coaxially in the Cartesian coordinate system (x, y, z).

It has been confirmed that the mentioned parameters were adaptable with the program FEM, in keeping with the limitation of the computer calculation power, they have been designed so that minimal errors occurred in the calculations.

Equations (4)-(14) were applied in order for the calculation of the magnetic force analysis. The whole of the analytical imagery outcomes for n=100 moreover, the rotation direction and current direction of both of the coils are similar too. The dependence of coils radius (a_1, a_2) on the magnetic force has been shown in Table 2. The length of the winding is l_1, l_2 = 50 cm, the pitch length is h_1=h_2=h=5mm and the coil shift is ϕ_{01}= ϕ_{02}=0. Table 2 shows the computed outcomes by two techniques.

To verify the analytical resulting validation, the magnetic force between the two superconducting coils has been simulated by FEM program. By adopting the analytical expression, the magnetic force for the transmitting coil radius of 80 mm and the receiver coil radius of 34 mm is 1936.987 mN with 0.89 s. The finite element method has given the magnetic force of 1949.962 mN with 178.09s for the same parameters. The entire outcomes attained by the FEM and analytical techniques are in considerable agreement. Table 3 showed the pitch length (h1, h2) dependence of the force magnetic. Hereunder, it has considered the dimensions of two coils in the test example: transmitting coil radius a2= 0.050 m, receiver coil radius a1=0.025 m, length of coils: l1=l2= 50 cm, and coil shift: ϕ01=ϕ02= 0 degrees. From Tables 2 and 3, it could be realized that the effect of coil radius is much further than the impact of pitch length on increasing the percentage of the force magnetic between the superconductor helical coils. The FEM and the analytic solutions are exactly comparable with each other. Table 3 has listed the results from the analytical and FEM methods.

Table 2: Results of the magnetic Force [mN] with length of coils 50 cm, pitch length 5mm, coil shift 0 degree versus Receiver and Transmitting coil radius[mm], using FEM and the analytical methods

Receiver pitch length [h1]	7		12		17	
Transmitting pitch length [h2]	FEM	Analytical method	FEM	Analytical method	FEM	Analytical method
7	574.5458	570.7234	337.2187	335.0751	239.7773	238.1579
12	337.3201	335.0751	199.0587	197.7359	142.0145	141.0701
17	239.7526	238.1579	141.9725	141.0701	101.8992	101.2217
22	186.3775	185.1389	111.025	110.2832	79.84501	79.31591
27	152.9403	151.9241	91.40861	90.82759	66.14274	65.6977

As seen in Table 3, the analytical expressions and the FEM for h_2=22 mm and h_1=12 mm give the Magnetic Force of 110.2832 mN with 0.51s and 111.0324 mN with 1267s, respectively. relating to the results of Table 4, Firstly, it must be noted that FEM and analytical method are different by ~0.66%. Secondly, for loosely-wound coils (having large pitch), It is evident that for a given accuracy, the analytical method has a low computational cost compared to the FEM method. In the design process of wireless power transmission with fixed pitch length, the part of received coil has moved inside the sender coil which has a greater effect on magnetic force as well as the radiuses of two coils with constant distance.

The relationship between magnetic force and distance is inverse, therefore, the optimal design for wireless power transmitting system is a condition that two receiver and sender coils have the least distance. In The geometric parameters of movable wireless power transmitting are listed in Table 4 for n=100.

Two right-handed superconducting helical with different lengths, different radius, and different pitch lenghts are shown in Fig. 3. Analytical computational carry out by MATLAB and finite element results were obtained using ANSYS Maxwell software with ASPIRE 4752 G. In the case, the electric boundary condition (E [t] = 0) was applied and the distance between the boundary and the winding was about 4 times higher than the model height. Yttrium barium copper oxide (YBCO) superconductor and two existing ports have been applied as coil material and excitation source, respectively. For this model on the magnetic commencement, Triangular meshes have been spontaneously created. Further, as the helical winding is an open circuit, instead of a closed one like a round winding, to avoid the error in the finite element method, the terminal leads were assembled on the model to connect the end of the coil with the boundary, as shown in Fig. 10 (b). In addition, the magnetic energy between two coils is shown in Fig. 10 (a).

As shown in Fig. 10 (a), the magnetic energy around the receiving coil is greater than transmitting coil, so the receiver radius should be larger than the transmitter radius.

Table 3: Results of the Magnetic Force [mN] with length of coils 50 cm, Receiver coil radius 50mm, transmitting coil radius 25mm, coil shift 0 degree versus pitch length [mm], using FEM and the analytical methods.

Transmitting coil radius	68		80		86	
Receiver coil radius	FEM	Analytical method	FEM	Analytical method	FEM	Analytical method
10	177.4619	175.081	171.8124	170.722	169.6836	168.6056
16	444.3941	441.437	433.6612	430.7759	428.2169	425.5788
22	836.679	831.3583	816.8203	811.3859	807.0962	801.6469
28	1354.742	1345.594	1321.972	1313.175	1305.686	1297.384
34	1998.464	1985.165	1949.962	1936.987	1925.433	1913.57

Table 4: The parameters of two superconducting helical coils

Parameter	Symbol	Value
Receiver coil radius	a_1	200 mm
Transmitting coil radius	a_2	300 mm
Receiver coil shift	ϕ_{01}	0 rad
Axial displacement along y axis	L_y	0
Axial displacement along x axis	L_x	0
Rotational angle relative to x axis	θ	0
Transmitting coil shift	ϕ_{02}	0
Receiver coil pitch length	h_1	35 mm
Transmitting coil pitch length	h_2	60 mm
Number of Resivier coil turns	N_1	3
Number of Transmitting coil turns	N_2	6
Receiver coil length	l_1	105 mm
Transmitting coil length	l_2	360 mm
Current	I	5 A
resonance frequency	f	0.56 MHz

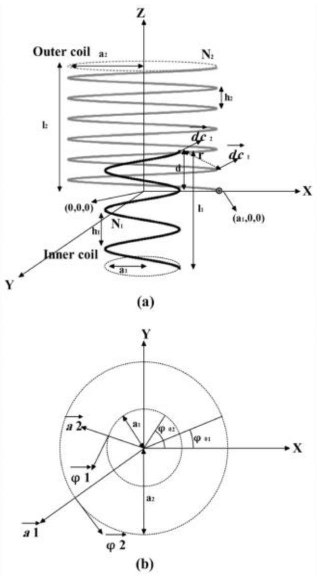

Fig 9: Overview of two superconductivity helical coils a) Two helical superconductor of winding radius a_1 and pitch length h_1, and winding radius a_2 and pitch length h_2 b) Cross-sectional view of two superconducting helical of winding radius a_1 and a_2.

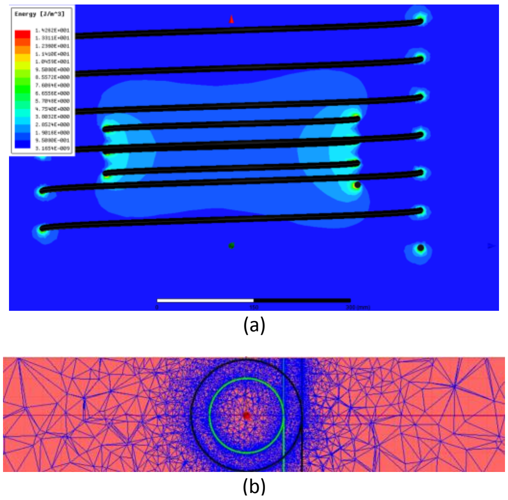

Fig. 10: Three-dimensional modeling a) magnetic Energy of the coils b) x-y view of meshing of the two superconducting helical coils in ANSYS Maxwell software.

Table 5 shows the Magnetic Force dependence on the common length of the coils (d). According to this table, it can be seen that (8) is in good agreement with the results of the finite element method, for all of linear distances (d). However, when the transmitting coil is located thoroughly in the middle of the receiver coil, the force magnetic is maximized.

Conclusion

In this paper, a new method used to solve the numerical solutions of magnetic force in different superconducting coils mismatch states. The fundamentals of the analysis of magnetic force which is reported in this paper are beneficial for the design and implementation of the wireless power transmission systems. the simulation results show that only by applying some constraints, the efficiency of the transmitted wireless power will be optimized if it is aligned. Then, analytical models have been presented which make it possible to calculate the axial force exerted between two Helical axially magnetized coils in air. These models have been compared with the FEM. Comparing the analytical and FEM results shows that the obtained errors are less than 0.0064%. Therefore, the proposed equations are highly reliable.

Table 5: The magnetic force [mN] calculated by the analytical and FEM methods according to moving of Receiver coil inside Transmitting coil on Z-axis [mm]

d(**mm**)	Magnetic Force (**Analytical method**(**mN**))	Magnetic Force (**Finite Element Method**(**mN**))	Discrepancy $e_{F-A}=\frac{\lvert F_F-F_A\rvert}{F_F}$
0	102.5494	103.2096	0.0064
35	110.5849	111.2722	0.00618
70	116.1429	116.6745	0.00456
100	118.8403	119.2582	0.0035
130	119.6315	120.0024	0.00309
160	118.5239	118.9615	0.00368
215	109.0618	109.7117	0.00592
255	102.5494	103.212	0.00642

Author Contributions

Iman Soltani in collaboration with Mohammad Reza Alizadeh Pahlevani and Arash Dehestani, designed, simulated and carried out the data analysis, and Iman Soltani collected the data and interpreted the results and wrote the manuscript.

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Conflict of Interest

The authors declare no potential conflict of interest regarding the publication of this work. In addition, the ethical issues including plagiarism, informed consent, misconduct, data fabrication and, or falsification, double publication and, or submission, and redundancy have been completely witnessed by the authors.

Abbreviations

EVs	Electric Vehicles
FEM	Finite Element Method
WPT	Wireless Power Transfer
SCs	Superconducting Coils
YBCO	Yttrium Barium Copper Oxide

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