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Optimal control of wireless energy transfer system via decreasing frequency

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Abstract: In order to solve the multiple power extreme value point problem caused by system frequency splitting during wireless energy transmission at short distances, a transmission model of the system is established. With the comprehensive consideration of the resonance frequency, load parameters and the coupling between coils, the internal factors of frequency splitting and boundary conditions are discussed. The results show that under the condition of the fixed load, the higher the natural resonance frequency, the easier the frequency splitting. As the frequency splitting occurs, the frequency of the maximum power transfer is no longer with the natural resonance frequency, which can make the system unstable and the transfer power more difficult to control. Therefore, a decreasing-frequency method is proposed to avoid the system frequency splitting. And decreasing the system resonance frequency can make the system successfully withdraw the frequency splitting area at a short-distance range. Under the fixed load condition, the transmission power of the system can be increased by 400%, and the transmission efficiency is reduced by only 14%, which greatly improves the transmission performance of the system.

Key words: optimal control; wireless energy transfer; decreasing frequency

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Wireless energy transfer is critical to many emerging applications and it is commonly realized by means of near-field magnetic resonance coupling. In 2007, the wireless energy transmission research group at MIT proposed the technology of magnetically coupled resonance wireless energy transmission and the research results[1]. This technology has attracted attention by many scholars and gradually become an important research direction in the field of energy transmission. In the subsequent long period of time, this technology has been used to study the long-range energy transmission (The transmission distance is much greater than the geometric dimensions of the coil size), in which case the coupling of transmitting and receiving coils is weakened, and the frequency splitting phenomenon is not obvious or rarely occurs. For this reason, this phenomenon has not attracted much attention by researchers anymore.

Actually, wireless energy transmission technology has been widely used in various fields[2], and the transfer distance may be close to the radius of coils or smaller than the radius of coils. The coil size and the transmission distance are roughly of propinquity. According to relative theory, the system will be working in strong coupling regions, and the transmitting and receiving coils are prone to strong coupling, which makes the system work in the frequency splitting region. Meanwhile, the extreme transmission power will be split[3]. This splitting leads the power transmission at the natural resonance frequency to decline rapidly, sometimes even up to 50% or more [4-5], which is extremely unfavorable to the transfer of power. Meanwhile, the extreme value of transmission power is deviated from the natural resonance frequency, which means controlling power by stabilizing the natural resonance frequency is no longer suitable.

So far, it is necessary to propose a reasonable frequency splitting solution when the system is working in the frequency splitting region, which is not only to explore the transmission mechanism of the system, but also is more conducive to the promotion and application of this transmission technology. For this reason, many researchers have also suggested some solutions. For example, Sample et al. [4] changed the coupling between two coils (i. e. changed the angle between the coils) in the strong coupling region to make the system withdraw the frequency splitting region. Actually, the problem of resonance frequency splitting is complex and involves lots of parameter optimizations of the system. By studying the power transmission model of the system, we find that the system frequency splitting is mainly determined by the coupling coefficient between two coils and the natural resonance frequency, and the coupling coefficient between the two coils is affected by the transfer distance. As a result, in this paper we propose a solution based on decreasing the frequency to control the resonance frequency splitting.

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The simulation and analytical results favourably confirm to the practical measurements obtained from the design.

1 Model and Power Splitting

To facilitate the design and analysis, we assume that the transmitting and receiving coils have the same electrical and mechanical parameters (namely coils winding, radii, turns and external compensation capacitance, etc.). Then we have $L_1 = L_2 = L$, $C_1 = C_2 = C$, where L and C are the inductance and capacitance values of the coils. According to the equivalent mathematical model[5-7] as shown in Fig. 1, the system can be described as

$$\begin{bmatrix} V_s \\ 0 \end{bmatrix} = \begin{bmatrix} R_1 + R_s + jX & j\omega M \\ j\omega M & R_2 + R_L + jX \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \end{bmatrix} \tag{1}$$

where $X = \omega L - 1/(\omega C)$; V_s and R_s are the external power source and the internal resistance, respectively; R_1 and R_2 are the equivalent resistances of transmitting and receiving coils, respectively; I_1 and I_2 are the current of two coils (transmitting and receiving coils); ω is the system working frequency. The load receiving power can be obtained by

$$P_L = \frac{|V_L|^2}{R_L} \tag{2}$$

where V_L is the voltage of the load and it can be computed by

$$|V_L|^2 = \frac{(\omega M R_L |V_s|)^2}{T(X, M)} \tag{3}$$

where R_L is the load resistance; M is the mutual inductance between two coils, which is related to the transmission distance with coil parameters fixed. $T(X, M)$ is a variable varying with frequency and mutual inductance, which can be calculated by

$$T^2(X, M) = [(R_1 + R_s)(R_2 + R_L) - X^2 + (\omega M)^2]^2 + [X(R_1 + R_s + R_2 + R_L)]^2 \tag{4}$$

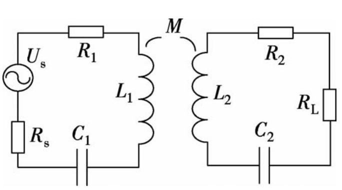

Fig. 1 Circuit model of transmission system

If ω_0 meets the relation $\omega_0 = \frac{1}{\sqrt{L_1 C_1}} = \frac{1}{\sqrt{L_2 C_2}}$, namely ω_0 is the natural resonance frequency, then $X(\omega_0) = 0$. $T(X, M)$ determines the change trends of the load receiving power. In order to investigate the load receiving extreme power, we can calculate the derivative of $T(X, M)$, and make the derivative of $T(X, M)$ equal to zero.

$$\frac{\partial T(X, M)}{\partial X} = 0 \tag{5}$$

The conditions that satisfy Eq. (5) are

$$X = 0 \tag{6a}$$

$$[(R_1 + R_s)^2 + (R_2 + R_L)^2 + 2X^2 - 2(\omega M)^2] = 0 \tag{6b}$$

In the case of $X = 0$, there clearly exists an extreme point of the load receiving power. It is not difficult to find that the receiving power of the load may also meet two other extreme points when Eq. (6b) is valid. Meanwhile, $X \neq 0$, $\omega_0 \neq \omega$, which means that in addition to ω_0, there are two other frequencies which make the load receiving power achieve the two extreme values, respectively. These two frequencies are distributed on both sides of the natural resonance frequency.

So, it is not difficult to calculate Eq. (6b) in the solvability condition.

$$\omega \geqslant \sqrt{\frac{[(R_1 + R_s)^2 + (R_2 + R_L)^2]}{2M^2}} \tag{7}$$

Actually, Eq. (6b) is not expected to have solutions and the analysis error should be considered. The correction factor K_m is introduced. So the condition of the system has only one stable resonance frequency which is

$$\omega_0 \leqslant K_m \sqrt{\frac{[(R_1 + R_s)^2 + (R_2 + R_L)^2]}{2M^2}} \tag{8}$$

If the radius of the coils is r, the number of turns is N. The mutual inductance[8] between the transmitting and receiving coils can be calculated by

$$M = \mu_0 N^2 r \left[\left(\frac{2}{\delta} - \delta \right) K(\delta) - \frac{2}{\delta} E(\delta) \right] \tag{9}$$

where $K(\delta)$ and $E(\delta)$ are complete elliptic integrals of the first and the second kind, respectively; and δ is

$$\delta = 2\sqrt{\frac{r^2}{d^2 + 4r^2}} \tag{10}$$

where d is the transmission distance.

In order to simplify calculation, $K(\delta)$ and $E(\delta)$ can be expanded into the form of an infinite series:

$$K(\delta) = \frac{\pi}{2}\left[1 + \left(\frac{1}{2}\right)^2 \delta^2 + \left(\frac{1 \times 3}{2 \times 4}\right)^2 \delta^4 + \left(\frac{1 \times 3 \times 5}{2 \times 4 \times 6}\right)^2 \delta^6 \dots \right] \tag{11}$$

$$E(\delta) = \frac{\pi}{2}\left[1 - \left(\frac{1}{2}\right)^2 \delta^2 - \left(\frac{1 \times 3}{2 \times 4}\right)^2 \frac{\delta^4}{3} - \left(\frac{1 \times 3 \times 5}{2 \times 4 \times 6}\right)^2 \frac{\delta^6}{5} \dots \right] \tag{12}$$

2 Frequency Control Scheme and Feasibility Analysis

The above analysis results show that the system has two working statuses. One is the system working on the natural resonance frequency and it has only one resonance frequency, and then the load can receive the maximum power. The other state is that the system meets the frequency splitting condition, and the load receiving maximum power meets the occurrence of splitting. In another sense, the higher the natural resonance frequency, the larger the frequency splitting region, and the lower the natural resonance frequency, the system is less prone to show the resonance frequency splitting. From the results of the above studies, if we do not make any change in the coupling between coils or the load resistance, and just simply reduce the system's natural resonance frequency, the system is also possible to withdraw the conditions of frequency splitting. This discovery is very important for the system design and control, which means that we can make the system work out of the frequency splitting region by decreasing the natural resonance frequency.

In order to achieve system transmission power stability at a single natural resonance frequency to solve the frequency splitting caused by strong coupling between the coils, decreasing the natural resonance frequency can be used. Sometimes, the system operating frequency often works in a high state (MHz level), which makes the system strong-coupling region large, thus the system can easily enter the frequency splitting region at short-distance transmission. Therefore, decreasing the natural resonance frequency and narrowing the frequency splitting region are very necessary. Fortunately, decreasing the system natural resonance frequency does not obviously reduce the system transfer efficiency at close range transmission[9], so by decreasing the frequency control to solve the frequency splitting is feasible in theory.

3 Simulation and Experimental Study

3.1 Simulation

The system simulation and experimental parameters are: $V_s = 200$ V, $L = 350$ μH, $R_L = 5$ Ω, $r = 0.2$ m, r is the radius of coils. Fig. 2 shows that in the case that the natural resonance frequency ω_0 and the load resistance R_L are 830 kHz and 5 Ω, respectively, the load receiving power changes with the frequency of the external power source. From Fig. 2, we can find that the load receiving power has only one maximum value when the system works at the natural resonance frequency (830 kHz) in the long-distance transmission ($d \gg 0.25$ m). With the transmission distance continuing to decrease, the load receiving power will achieve a maximum value at a certain transmission distance, which is mainly due to the fact that the system equivalent internal resistance matches the internal resistance of the source at the natural resonance frequency[9].

With the transmission distance decreasing ($d < 0.25$ m), the load receiving power enters the frequency splitting region, and the natural resonance frequency ($\omega_0 = 830$ kHz)

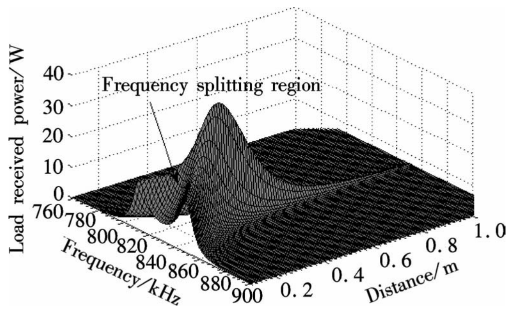

Fig. 2 Load receiving power splitting at nature resonance frequency of 830 kHz

is no longer the maximum power frequency, instead of being a saddle point for the load receiving power.

In order to verify the feasibility of the control program for the resonance frequency splitting, we do some simulation studies by Matlab/Simulink and COMSOL electromagnetic module. Fig. 3 and Fig. 4 show that at the load of 5 Ω and the natural resonant of 830 and 200 kHz, the load receiving power changes with transmission distance and frequencies. The results of Fig. 3 show that with the increase in the coupling strength of two coils (i. e. the distance is reduced), the frequency splitting threshold distance is about 0.25 m.

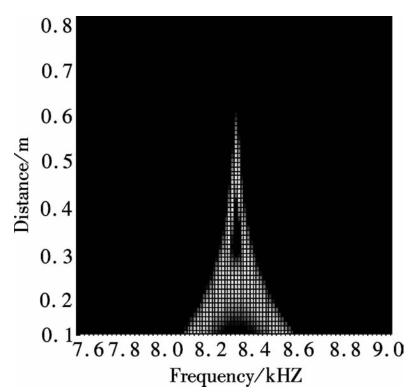

Fig. 3 Load receiving power with distance and frequency changing at natural resonance frequency of 830 kHz and the load resistance of 5 Ω

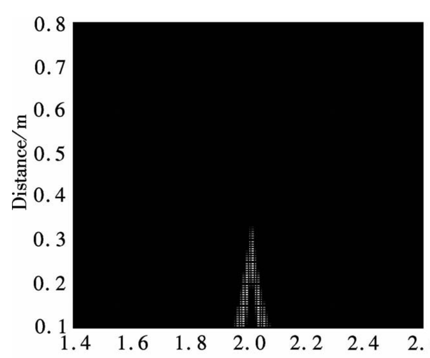

Fig. 4 Load receiving power with distance and frequency changing at natural resonance frequency of 200 kHz and load resistance of 5 Ω

The results of Fig. 4 show that at the natural resonance frequency of 200 kHz, the frequency splitting threshold distance is about 0. 12 m, in spite of the fact that the lowering of the system resonance frequency can greatly weaken the ability of long-range power transmission. But at close range transmission, the transmission power can still become very high. What's more, the system is out of the frequency splitting region, and the threshold value of the transmission distance is smaller.

3. 2 Experimental results

The experimental device is designed as shown in Fig. 5. The internal resistance of the system power supply is 50 Ω, and the output frequency can be adjusted manually. Fig. 6 shows that the load receiving power changes with the load of 5 Ω, a transmission distance of 0. 2 m and a natural resonance frequency of 830 and 200 kHz, respectively. In order to facilitate the analysis, we make 830 and 200 kHz as the system reference frequencies, respectively, and then normalize the operating frequency to the reference frequency. In the case of the natural resonance frequency of 830 kHz, the system is obviously in the frequency splitting region, and if we reduce the system operating frequency to 200 kHz, the system load receiving power will be withdrawn from the frequency splitting region as shown in Fig. 6. From Fig. 6, we also know that the system frequency splitting can be effectively suppressed by decreasing the natural resonance frequency in the frequency splitting region. The method for reducing the natural resonance frequency is provided in Ref. [10], and it will not be repeated here.

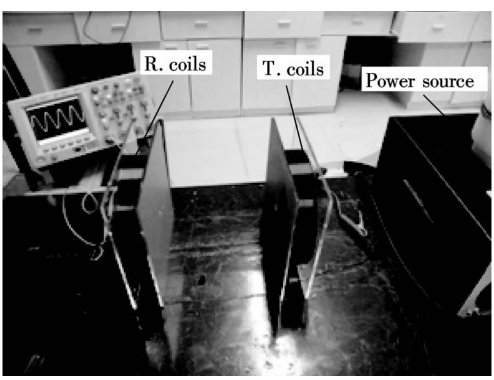

Fig. 5 Experimental device

From Fig. 6, we can also see that at the same distance (d = 0. 2 m), the natural resonance frequency reduces from 830 to 200 kHz, and the load receiving power is from 6 W up to 30 W at the natural resonant, which increases about 400% . Fig. 7 shows that the system transmission efficiency changes regularly with the natural frequency. From Fig. 7, we can find that the system resonance frequency reduces from 830 to 200 kHz, and the theoretical transfer efficiency only drops from 70% to 61% . The actual measurement results are basically consi-

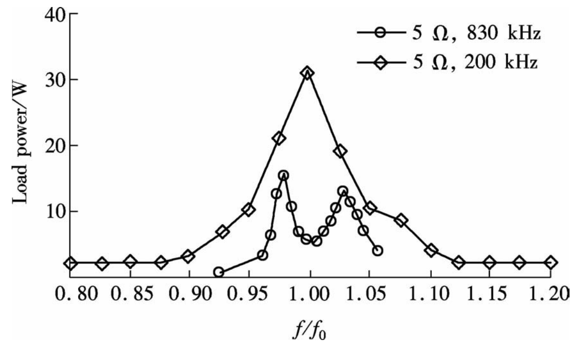

Fig. 6 Frequency splitting result from the experiment

stent with theoretical calculations at 200 and 830 kHz. Results from Fig. 7 show that decreasing the system natural frequency to control the transfer power will have a little effect on the transmission efficiency, which is just 14% . Compared with the transmission power increased by 400% , the efficiency loss by the decreasing frequency can be ignored.

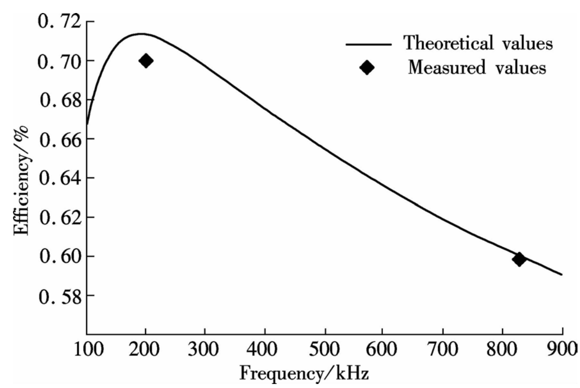

Fig. 7 Transmission efficiency of system changes

If we consider the impedance matching, the load receiving power will be greatly increased. On the other hand, decreasing the natural frequency not only can reduce system power requirements under a close transfer distance, but can also help the transfer system to reduce heat dissipation and space dissipation.

4 Conclusion

The load receiving power of the wireless energy transmission system with the frequency changing is studied and the influencing factors of the system transmission power are analyzed in this paper. The mechanism and the boundary conditions of the system frequency splitting are proposed. For a given load, the scheme which by decreasing the system natural resonance frequency has been proposed to solve the frequency splitting problem. However, decreasing the natural resonance frequency can lead transmission distance and transmission efficiency to decrease, but it can increase the system power transmission. Sometimes we must ensure that the system does not cause frequency splitting and that the system transfer distance and efficiency reducing remains in an acceptable range.

This research work is only a solution for the frequency splitting and verifies its feasibility, so we did not involve the scheme optimization. In practical applications, the external resistance should perfectly match the internal resistance of the system. In order to achieve maximum power transmission, the resonance frequency will have an optimal value in different transmission distances. Therefore, in the process of system designing and controlling, we should coordinate with the load, transfer efficiency, and transfer distance. In this way, the system can not only effectively withdraw the frequency splitting region and it will be easy to control, but it can also achieve maximum power transfer at a close transfer distance. However, the work of this paper can provide an effective solution for frequency splitting control.

References

[1] Kurs A, Karalis A, Moffatt R, et al. Wireless power transmission via strongly coupled magnetic resonances [J]. *Science Express*, 2007, **317**(5834): 83 – 86.

[2] RamRakhyani A K, Mirabbasi S, Chiao M. Design and optimization of resonance-based efficient wireless power delivery systems for biomedical implants[J]. *IEEE Trans Biomed Circuits Syst*, 2011, **5**(1): 48 – 63.

[3] Tak Y D, Park J M, Nam S W. Mode-based analysis of resonant characteristics for near-field coupled small antennas[J]. *IEEE Antennas Wireless Propag Lett*, 2009, **8**(11): 1238 – 1241.

[4] Sample A P, Meyer D A, Smith J R. Analysis, experimental results, and range adaptation of magnetically coupled resonators for wireless power transfer [J]. *IEEE Trans Ind Electron*, 2011, **58**(2): 544 – 554.

[5] Cheon S, Kim Y, Kang S, et al. Circuit model based analysis of a wireless energy transfer system via coupled magnetic resonances[J]. *IEEE Trans Ind Electron*, 2011, **58**(7): 2906 – 2914.

[6] Kurs A, Moffatt R, Soljacic M. Simultaneous mid-range power transfer to multiple devices[J]. *Appl Phys Lett*, 2010, **96**(4): 044102-1 – 044102-3.

[7] Casanova J J, Low Z N, Lin J S. A loosely coupled planar wireless power system for multiple receivers[J]. *IEEE Trans Ind Electron*, 2009, **56**(8): 3060 – 3068.

[8] Maxwell J C. *A treatise on electricity and magnetism* [M]. New York: Dover, 1954.

[9] Fu Wenzhen, Zhang Bo. Maximum efficiency analysis and design of self-resonance coupling coils for wireless power transmission system[J]. *Proceedings of the CSEE*, 2009, **29**(18): 21 – 26. (in Chinese)

[10] Tan Linlin, Huang Xueliang, Huang Hui. Transfer efficiency optimal control of magnetic resonance coupled system of wireless power transfer based on frequency control [J]. *Science in China Series E: Engineering and Materials Science*, 2011, **54**(6): 1428 – 143.

基于降频的无线能量传输系统优化控制

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摘要：为了解决近距离传输时无线能量传输系统出现频率分裂导致多个功率极值点的问题，建立了系统的传输模型. 综合考虑谐振频率、负载大小、两线圈间的耦合强度等参数，探讨了频率分裂现象发生的内在因素和边界条件. 结果表明：在负载大小不变的情况下自然谐振频率越高，越容易发生频率分裂，当频率分裂现象发生时，系统的最大传输功率将不在线圈的自然谐振频率处，给系统稳定性及功率优化控制带来了困难. 为此提出了一种近距离传输时通过降低谐振频率来解决频率分裂的方法，当传输距离减小时降低系统的谐振频率可使系统成功退出频率分裂区域，并在负载不变的情况下传输功率可提高 400% ，而传输效率仅下降约 14% ，极大地提高了系统的传输性能.

关键词：优化控制；无线能量传输；降频

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