Dean&Francis
ISSN 2959-6157

Ultrasound Power Transfer for Implantable Medical Devices: Current Research and Future Directions

Yuchao Yan[1, *]

[1]School of Science, Sun Yat-Sen University, Guangzhou, China

[*]Corresponding author: yanych25@mail2.sysu.edu.cn

Abstract:

Pacemakers and neurostimulators are widely used as implantable medical devices (IMDs) in the art in recent years. Although such devices are an alternative, but they are battery dependent which must be regularly replaced, making the condition worse and costlier for surgery. Presently, traditional wireless electricity transmitting techniques including electromagnetic induction and radio frequency energy transfer are limited by short transmission distance, poor efficiency and low penetration of tissue. In recent years, Ultrasonic energy transfer (UPT), an emerging technology, is attracting extensive attention because of its superior characteristics like deep tissue penetration ability, higher energy density and high safety. This paper studies the possibility of applications for and development trends in ultrasound power transfer (UPT) technology in implantable medical devices (IMDs). UPT is touted as a potential solution to some limitations of conventional battery-powered implants. The article outlines a lot of benefits from our technology UPT, namely deep tissue penetration and safety of the application as well as figuration of its operating principles and conversion acoustic energy in electrical one. Fluid-structure coupling model, Mason model, and KLM model are three key theoretical models which affect the system efficiency. Other optimization techniques also for UPT performance improvement are examined: acoustic matching and material modification. The provided review serves to educate on the technical hurdles and promises of UPT in future medical applications.

Keywords: Implantable Medical Devices; Ultrasonic Power Transfer; Piezoelectric Effect; Acoustic Transmission; Energy Transfer Models.

ISSN 2959-6157

1. Introduction

Over the past decades, Implantable Medical Devices (IMDs) such as pacemakers and neurostimulators have been widely used in the medical field, and these devices not only effectively treat patients, but also significantly improve their quality of life. However, IMDs generally rely on battery power, and the limitation of battery life has become a major issue. Currently, batteries usually only last for a few years, after which they need to be replaced by another surgery, which increases the risk of surgery and the cost of treatment, as well as reduces the patient's life experience. Therefore, the development of an effective wireless energy transfer technology is crucial to enhance the sustainability and utility of IMDs.

Conventional wireless energy transfer methods mainly include electromagnetic induction and radio frequency energy transfer (RF) technologies. Electromagnetic induction is based on Faraday's Law of Electromagnetic Induction and transfers energy by creating a magnetic field between the transmitter and receiver coils. Its advantage lies in its high transmission efficiency over a short distance (usually a few centimeters) between the transmitter and receiver and is therefore widely used in proximity charging scenarios such as electric toothbrushes and wireless chargers. However, due to the rapid attenuation of the magnetic field strength with increasing distance, electromagnetic induction technology has a short transmission distance and strict requirements for coil alignment, which limits its application in deeply implanted medical devices.

RF energy transfer technology utilizes electromagnetic waves (usually in the MHz to GHz frequency band) for medium-distance energy transfer. Although RF energy transmission can achieve relatively long transmission distances, it has limited penetration in human tissues, has large energy losses, and is susceptible to environmental electromagnetic interference. Therefore, RF technology is also difficult to meet the power supply needs of deeply implanted devices.

To address the above challenges, Ultrasound Power Transfer (UPT) technology has emerged as a promising alternative for wirelessly powering deeply implanted medical devices. This review covers the fundamental principles, recent advancements, and future directions in UPT systems, focusing on efficiency optimization and biomedical applications. Various theoretical models are discussed in this paper, such as the Mason and KLM models, and their roles in enhancing energy transfer efficiency. Future research should aim at integrating novel materials and exploring advanced focusing techniques to further improve UPT system performance.

2. UPT

Ultrasound Power Transfer (UPT) is a wireless energy transfer technology based on the transmission of energy by sound waves. It utilizes the mechanical vibrations of ultrasound waves to transfer energy from an external source to a device implanted in the body. The process relies on the piezoelectric effect, which converts electrical energy into sound waves through an ultrasonic transducer, and then reconverts the sound waves into electrical energy through a receiver [1]. The core advantages of ultrasound energy transfer are its low energy loss, efficient tissue penetration and relatively small thermal effect [2]. The core principles and benefits of ultrasonic energy transfer are discussed in detail next.

2.1 Piezoelectric effect and energy conversion

The piezoelectric effect is the basis for ultrasonic energy transfer. The piezoelectric effect refers to the fact that certain materials generate an electrical charge when subjected to mechanical stress and, conversely, that they deform mechanically when an electric field is applied to them [3]. This bi-directional nature of energy conversion makes piezoelectric materials the core component of ultrasonic transducers.

In ultrasonic energy transfer systems, piezoelectric materials are commonly used as transducers. First, an external transmitting transducer converts electrical energy into acoustic (mechanical) waves by inverting the piezoelectric effect. Specifically, a voltage generated by an external power source is applied to the piezoelectric material and the material undergoes mechanical vibration, which generates ultrasonic waves in the surrounding medium (e.g., air or human tissue).

In UPT systems, both the transducer and the receiver rely on the bidirectional properties of the piezoelectric effect. This property allows the external transducer to convert electrical energy into ultrasonic waves [4], while the internal receiver reconverts the sound waves into electrical energy. By carefully designing the piezoelectric materials and their geometry of the transducer and receiver, high energy conversion efficiencies can be realized. For implantable devices, receiver size is often a key limiting factor, and the use of efficient piezoelectric materials ensures that as much incoming acoustic energy as possible is captured and converted into electrical energy.

In the body, the receivers of implantable devices also use piezoelectric materials [4,5]. When a sound wave reaches the receiver, the piezoelectric material converts the mechanical vibration of the sound wave into electrical energy through the positive piezoelectric effect [6]. This electrical energy can either power the implanted device or be stored in a battery inside the device for future use.

Common piezoelectric materials include lead zirconate titanate (PZT) and vinylidene fluoride (PVDF), which each have their own characteristics [2,7]. PZT has a high mechanical quality factor and strong electro-mechanical coupling properties, while PVDF is known for its flexibility and low density, respectively, which are advantageous in specific application scenarios.

2.2 Acoustic Characteristics Selection

Ultrasonic energy transmission utilizes the properties of mechanical waves. Unlike electromagnetic waves, sound waves propagate through mechanical vibrations in a medium, which means that the transmission efficiency of sound waves is closely related to the physical properties of the medium. In the UPT system, sound waves are emitted from an external transducer and travel through different tissue layers such as air, skin, muscle, etc., and finally reach a receiver inside the body. Due to the high acoustic impedance of human tissues, ultrasound waves are attenuated during propagation, so the appropriate frequency and sound pressure level need to be selected to ensure that the energy is efficiently delivered to the implanted device [7,8].

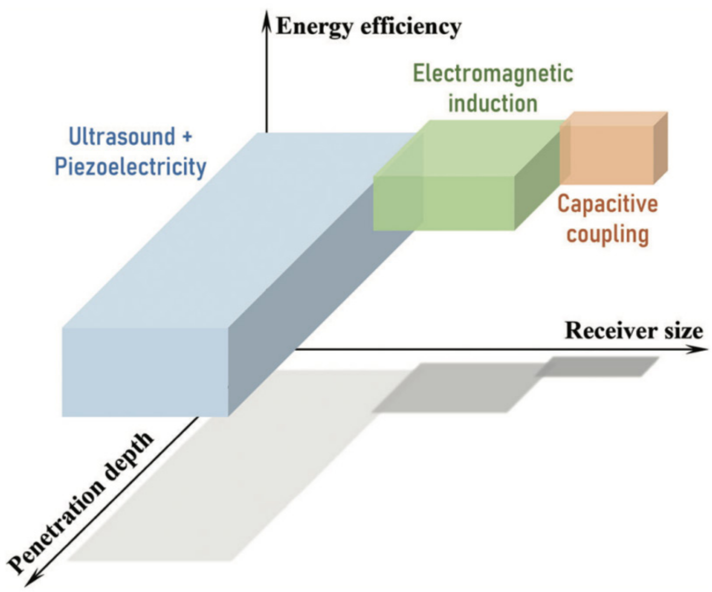

Fig. 1 Three common methods of wirelessly transmitting energy for biomedical implants. UPT has become a superior technology in terms of pentration depth and energy efficiency [8].

Ultrasonic energy transfer typically operates in the frequency range of tens of kilohertz to several megahertz. The choice of frequency depends on several factors, including depth of tissue penetration and energy loss. In general, lower frequencies (e.g., tens of kHz) facilitate deeper penetration of sound waves into tissues because there is less attenuation. However, too low a frequency may result in less efficient energy transfer. Conversely, higher frequencies (e.g., a few MHz) provide higher energy density but have limited depth of penetration, making them suitable for shallowly implanted devices [9].

2.3 Focused Ultrasound Technology

Focused Ultrasound is one of the key technologies for improving the efficiency of ultrasound energy transfer. By concentrating acoustic energy into a small area, Focused Ultrasound can significantly increase the efficiency of energy transfer, reducing the scattering of sound waves in the tissue and energy loss [6,8].

Focused ultrasound is achieved through specially designed transducers or acoustic lenses. These devices can converge the emitted ultrasound waves into a small area such that the energy of the sound waves creates a high sound pressure at the receiver. For example, curved transducers or multiple transducer arrays significantly increase the energy density received at the receiver by controlling the phase and intensity of the emitted waves so that all the sound waves are focused on a specific depth.

Transducer Arrays are one of the most important tools for realizing focused ultrasound. By using multiple transducer units, arrays can emit multiple ultrasound waves simultaneously, which are focused on a target area by phase control and interference effects, thus increasing the intensity of the sound waves in that area. Array transducers also allow dynamic tuning of sound waves to different depths and directions in response to variations in implantation

ISSN 2959-6157

depths and tissue environments [4].

Focused ultrasound not only increases the concentration of energy transmission, but also reduces the scattering and attenuation of sound waves during propagation. Therefore, energy loss can be minimized by optimizing the path of ultrasound. For example, an acoustic matching layer can be incorporated into the design of the transducer to minimize the reflection of sound waves at the interface of different media (e.g., skin and muscle), thereby improving the overall energy transfer efficiency [6].

2.4 Optimization of energy transfer efficiency

The efficiency of ultrasonic energy transfer depends on several factors, including the frequency of the sound wave, the design of the transducer, the acoustic properties of the medium, and the size and construction of the receiver. To improve the efficiency of energy transfer, these parameters need to be optimized for different application scenarios [10,11].

Acoustic matching layer is one of the key designs to improve the efficiency of energy transfer. When ultrasonic waves are transmitted from one medium to another (e.g., from air to skin), reflections and scattering occur due to differences in acoustic impedance, resulting in energy loss. By adding an acoustic matching layer to the surface of the transducer, the reflection of sound waves between different media can be reduced, thus improving the efficiency of energy transfer.

The geometric design of the receiver is also critical to improving energy conversion efficiency. A smaller receiver, while it may fit within the size constraints of the implanted device, may capture less acoustic energy. By optimizing the shape and materials of the receiver, it is possible to improve the receiver's ability to capture energy without increasing its size. For example, a receiver using a curved design can better receive focused ultrasound waves, resulting in improved conversion efficiency [7,12].

2.5 Advantage

UPT has excellent tissue penetration capabilities, a feature that has allowed it to be used in a wide range of medical applications, such as ultrasound imaging and High Intensity Focused Ultrasound (HIFU) treatments, which take advantage of ultrasound's ability to penetrate multiple layers of tissue in the human body and to focus on specific locations. Similarly, UPT technology reduces energy loss in the tissue by using lower frequencies (typically in the range of tens of kHz to a few MHz), allowing for efficient energy transfer to deeply implanted devices. For example, ultrasound maintains a lower attenuation coefficient at lower frequencies compared to the rapid attenuation of RF energy delivery at high frequencies, allowing more energy to be delivered at a higher power density [7,12].

UPT offers a higher level of safety. Compared to electromagnetic induction and radio frequency energy transfer, ultrasound is safer to transmit in the human body and has significant advantages in avoiding electromagnetic interference (EMI). Electromagnetic induction and radiofrequency energy transfer systems generate electromagnetic fields when they operate, which can interfere with the normal operation of other electronic devices, and IMDs in practical medical environments often contain metal devices. In contrast, ultrasonic energy transfer utilizes mechanical waves that do not generate electromagnetic interference, and the power density and sound intensity of ultrasound can be controlled by precisely adjusting the frequency and intensity of the sound waves, thus ensuring sufficient energy transfer while reducing potential damage to the tissue [12,13].

UPT has excellent focusing capabilities. By using focused ultrasound technology, UPT can concentrate the acoustic energy into a very small receiving area, thus significantly improving the efficiency of energy transfer. Focused ultrasound utilizes a specially designed transducer or acoustic lens to concentrate ultrasonic energy in a targeted area, which not only improves the concentration of energy, but also reduces scattering and attenuation in the surrounding tissue [13]. This concentrated energy delivery makes UPT particularly appropriate when it is needed to power small implantable devices such as neurostimulators or drug delivery devices.

UPT has a low thermal effect. In wireless energy transfer, excessive power density may lead to increased tissue temperatures around the implanted device, which may cause tissue damage or other side effects. Electromagnetic induction and radiofrequency energy transmission typically produce significant thermal effects at high power transmissions, especially when the device size is small and the ability to dissipate heat is limited, which may lead to overheating at the implant site. In contrast, ultrasonic energy delivery, at appropriate frequencies and power levels, has a lesser thermal effect and heat buildup can be further minimized by adjusting the pulse pattern and spacing of the sound waves, thus ensuring safe operation of the implanted device [11-13].

3. Theoretical model and analysis

The operation of ultrasonic energy transfer systems involves several physical processes, including the piezoelectric effect, acoustic wave propagation, and the attenuation and reflection of acoustic waves in different media. More detail energy attenuation as shown in Figure 1. To deeply understand and optimize this energy transfer processes; researchers have developed a variety of theoretical models to help predict and improve the efficiency of the system. Theoretical models not only accurately describe the propagation behavior of ultrasonic waves in complex media, but also provide guidance for practical design and experimentation. In this section, several commonly used theoretical models and their applications will be highlighted, including the Fluid-Structure Interaction (Fluid Structure Interaction, FSI), the Mason Model [14,15] and the KLM model [16,17]. UPT energy link is divided into five subsections, as illustrated in lower right of Fig. 2.

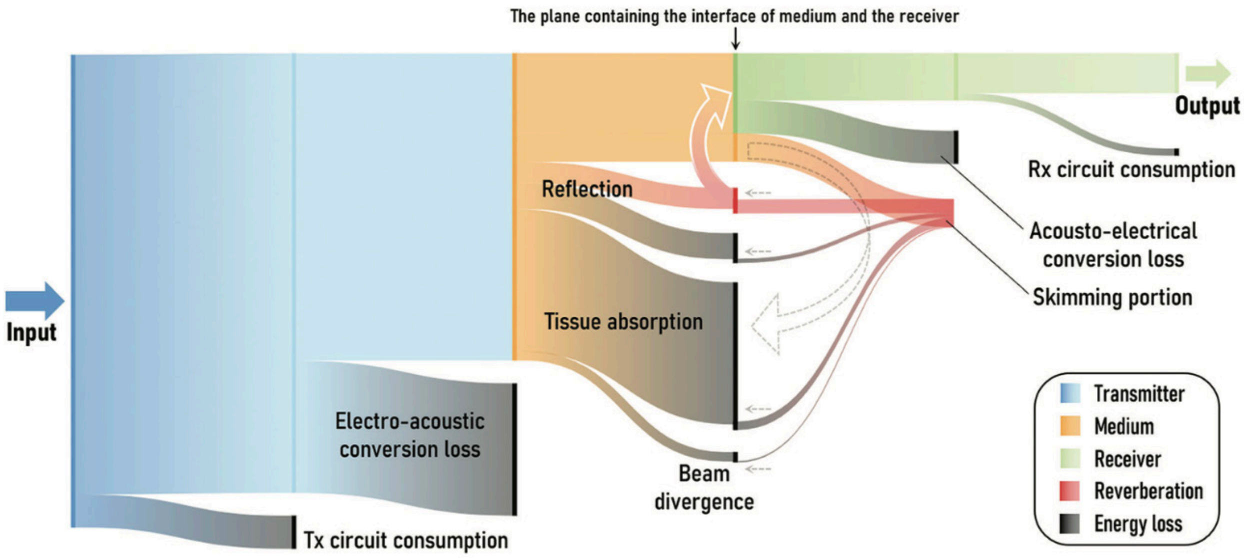

Fig. 2 Energy flow attenuate diagram of a general UPT system.

3.1 Fluid Structure Interaction Model

Fluid Structure Interaction (FSI) is one of the most important fundamental models for ultrasonic energy transfer systems, which is used to describe the propagation of ultrasonic waves in different media and the interaction between the ultrasonic waves and the receiver. The FSI model can accurately predict the energy transfer efficiency by considering the interplay between pressure fluctuations of the acoustic waves and the mechanical response of the receiver. interactions between the pressure fluctuations of the acoustic wave and the mechanical response of the receiver, the FSI model can accurately predict the energy transfer efficiency [14].

3.1.1 Acoustic wave propagation in fluids

In an ultrasonic energy delivery system, sound waves propagate from the transmitting transducer to the receiver of the implanted device. The process involves propagation of sound waves through a fluid medium such as water and tissue [14,15]. The sound waves in the fluid satisfy the fluctuation equation with the following expression:

$$\frac{\partial^2 p}{\partial t^2} = c^2 \nabla^2 p \qquad (1)$$

Where p is the sound pressure, c is the propagation velocity of the sound wave in the fluid, and ∇^2 is the Laplace operator. This equation describes the pattern of change of sound pressure with time and space. In practical applications, the attenuation and scattering of sound waves through liquid media such as water or human tissue must also be considered [15]. By introducing the attenuation coefficient, the improved fluctuation equation can be expressed as:

$$\frac{\partial^2 p}{\partial t^2} = c^2 \nabla^2 p \qquad (2)$$

Where α is the attenuation coefficient, which describes the energy loss of sound waves in a medium. Typically, the attenuation coefficient is proportional to the frequency, so that low-frequency sound waves can travel farther in a tissue, while high-frequency sound waves are better suited for energy transfer over short distances [14,15].

3.1.2 Acoustic response in structures

When sound waves reach the receiver of an implanted device, the piezoelectric material generates mechanical vibrations and converts the energy of the sound waves into electrical energy. The vibration of the receiver can be described by the equations of electrodynamics, which have the basic form [14]:

$$\rho \frac{\partial^2 u}{\partial t^2} = \nabla \cdot \sigma + f \qquad (3)$$

Where ρ is the density of the receiver material, u is the displacement vector, σ is the stress tensor, and f is the ex-

ISSN 2959-6157

ternal body force. In this equation, the pressure effect of the acoustic wave is applied to the surface of the receiver through boundary conditions. Since the receiver material is usually piezoelectric, it is necessary to couple the electric field to the mechanical deformation to describe the piezoelectric effect [14,15].

3.1.3 Coupled equation

In piezoelectric materials, there is a coupling effect between the mechanical strain and the electric field, and the basic equation of the piezoelectric effect can be expressed as:

$$\begin{aligned} T_{ij} &= c_{ijkl} S_{kl} - e_{kij} E_k \\ D_k &= e_{kij} S_{ij} + \epsilon_{kl} E_l \end{aligned} \tag{4}$$

Where T_{ij} is the stress tensor, and S_{kl} is the strain tensor, and c_{ijkl} is the modulus of elasticity, and e_{kij} is the piezoelectric constant E_k is the electric field, and D_k is the potential shift. The above equation describes the interaction between electric field and strain: an electric field can initiate mechanical deformation, and conversely, mechanical stress can generate an electric charge. This bi-directional coupling property is one of the core mechanisms of ultrasonic energy transfer [14,15].

3.2 Mason Model and KLM Model

In addition to fluid-structure coupling modeling, equivalent circuit modeling is also a commonly used approach in the analysis of ultrasonic energy transfer systems. By equating the physical system to a circuit model, the analysis of the energy transfer process can be simplified, and the efficiency and power output of the system can be quantified [14].

Both the Mason model and the KLM model are important tools for analyzing ultrasonic energy transfer systems. The Mason model is suitable for simple linear system analysis, while the KLM model is more suitable for complex multi-frequency systems [15]. In practical applications, researchers can choose the appropriate model according to the specific system requirements. For example, when designing high-frequency systems, the KLM model can better capture the effect of frequency on the energy transfer efficiency [14,15].

3.2.1 Mason Model

Based on transmission line theory, the Mason model equates the piezoelectric transducer to a transmission line with mechanical impedance and uses an ideal transformer to describe electroacoustic conversion behavior [14].

In the Mason model, the piezoelectric transducer is equated to a transmission line with mechanical impedance whose electroacoustic conversion behavior is represented by an ideal transformer. The ratio of this transformer is related to the electro-mechanical coupling coefficient of the piezoelectric material. Specifically, the equivalent circuit in the Mason model can be represented by the following components:

1. Mechanical impedance: The propagation of acoustic waves in piezoelectric materials is described by mechanical impedance, which is related to the density, elastic modulus and geometry of the material.
2. Electroacoustic converters: Electroacoustic converters represent the conversion of piezoelectric materials between mechanical and electrical energy. The mechanical impedance is converted into electrical impedance by means of an ideal transformer.
3. Electrical Imppedance: Electrical impedance is used to describe the process of transferring electrical energy in a circuit.

The advantage of the Mason model is that it can be used to solve for the energy transfer efficiency and the electrical characteristics of the system through standard circuit analysis methods. However, the model assumes that the system is linear and lossless, so its prediction accuracy may be limited in certain complex scenarios [14-16].

3.2.2 KLM Model

The KLM model refines this by introducing frequency-dependent elements in the acoustic transmission line, providing a more accurate description of the system's response at different frequencies [16,17].

At the heart of the KLM Model is the division of a piezoelectric transducer into multiple physical parts, each represented by an equivalent circuit element. For example, the mechanical response of a piezoelectric material can be modeled equivalently as a transmission line, while its electrical response is represented through capacitance and inductance [17]. In this way, the KLM model can more accurately analyze the frequency response and power transfer efficiency of the system [16,17].

3.3 Analysis of energy transfer efficiency

An important application of theoretical models is to predict and optimize the efficiency of ultrasonic energy transfer systems [18]. By analyzing the propagation of acoustic waves in a medium and the response of the receiver, the key factors affecting the efficiency of the system can be found and corresponding optimization schemes can be proposed [19-21].

3.3.1 Optimization of transmission paths

In ultrasonic energy transfer systems, the propagation path of sound waves has a decisive influence on the efficiency of energy transfer. To maximize the energy transfer, sound waves should try to avoid excessive reflection, scattering or absorption in the propagation medium. Therefore, the design of reasonable acoustic wave propagation path is an important means to improve the efficiency of energy transmission [18,19].

• Frequency selection of sound waves: Frequency is one of the key parameters affecting the efficiency of energy transmission. Lower frequency ultrasound waves have less attenuation in the medium and can penetrate thicker tissue layers, but too low a frequency may result in a weakened response from the receiver. Conversely, higher frequencies help to increase the sensitivity of the receiver, but the depth of penetration of the sound waves in the tissue is limited [18]. Thus, frequency selection requires a balance between energy density and tissue penetration.

• Reflection and Scattering of Sound Waves in a Medium: During propagation, sound waves are reflected and scattered when they encounter interfaces in different media (e.g., from air to skin). These phenomena lead to energy losses [19]. Therefore, when designing a system, reflections can be reduced, and the penetration of sound waves can be improved by adding an acoustic matching layer. The role of the matching layer is to smooth out the acoustic impedance differences between different media and reduce reflection losses at the interface, thus improving the overall energy transfer efficiency [18-20].

• Focused ultrasound applications: Focused ultrasound can concentrate acoustic energy in the receiver through an array of acoustic lenses or transducers. This not only significantly increases the acoustic energy density, but also reduces energy loss in non-targeted areas. Focused ultrasound technology is particularly important for powering deeply implanted devices, as it can effectively improve the transmission efficiency of the system [19].

3.3.2 Optimization of receiver design

The design of the receiver is also critical for improving the efficiency of energy conversion. The geometry, material selection and electrical properties of the receiver all affect its efficiency in receiving sound waves [18,20].

• Piezoelectric Material Selection: Commonly used piezoelectric materials include lead zirconate titanate (PZT) and vinylidene fluoride (PVDF.) PZT has a high electromechanical coupling coefficient and can provide high energy conversion efficiencies. However, PZT is stiff and not easily bendable, which can be a limitation in certain application scenarios where flexibility is required. In contrast, PVDF has better flexibility and is suitable for implantable devices with complex shapes. In addition, studies have shown that energy conversion efficiency can be further improved by using multilayer piezoelectric material designs or 1-3 type piezoelectric composites [18-20].

• Effect of receiver size: The size of the receiver is usually limited by the size of the implanted device. Smaller receiver sizes, while easily implantable, may not receive enough energy. Therefore, when designing a receiver, it is often necessary to optimize its geometry and materials to maximize its ability to capture energy. For example, curved surfaces or focused receivers may better capture sound waves from different angles, thereby improving energy capture [20,21].

• Optimization of circuit design: After the receiver converts acoustic waves into electrical energy, it needs to stabilize the output voltage and supply power to the implanted devices through rectifier and energy storage circuits. Optimizing the circuit design of the receiver to reduce the loss in the power conversion process is also a key step to improve the overall efficiency of the system [19,21].

3.3.3 Analysis of overall system efficiency

The efficiency of an ultrasonic energy transfer system depends on several components, including the emission, propagation, reception, and conversion of the sound waves to electrical energy. The efficiency of each link has an impact on the final energy transfer efficiency [21]. To improve the overall efficiency, the following aspects need to be considered:

• Efficiency at the transmitter side: The efficiency at the transmitter side depends primarily on the design of the ultrasonic transducer and the efficient conversion of the input electrical energy. By optimizing the electro-acoustic conversion efficiency of the transducer, it is possible to ensure maximum conversion of electrical energy into mechanical sound waves [19].

• Influence of the propagation medium: The nature of the propagation medium (e.g., speed of sound, attenuation coefficient, etc.) affects the propagation efficiency of sound waves. Especially in human tissues, attenuation and reflection of sound waves lead to energy losses, which can therefore be reduced by frequency selection, focusing techniques and the design of matching layers.

• Receiving end efficiency: The design of the receiver not only affects its ability to receive sound waves, but also directly affects its efficiency in converting sound waves into electrical energy. The use of efficient piezoelectric materials and optimized circuit design can improve the energy conversion efficiency at the receiver end [20,21].

• System Integration Optimization: Effectively integrating all these elements into a single system and ensuring the efficient operation of each link is the ultimate goal of improving the overall efficiency of the system [20]. In this process, it is necessary to balance the parameters of the transmitter and receiver and optimize the design for differ-

ISSN 2959-6157

ent application scenarios.

4. Conclusion

This paper provides a detailed review of the application of wireless energy transfer technology in implantable medical devices, focusing on the principles and advantages of ultrasonic energy transfer (UPT) and its potential in practical applications. It covers the fundamental principles, recent advancements, and future directions in UPT systems, focusing on efficiency optimization and biomedical applications. Various theoretical models are discussed in this paper, such as the Mason and KLM models, and their roles in enhancing energy transfer efficiency. UPT is an ideal choice for wireless power supply of deeply implantable devices due to its excellent tissue penetration capability, efficient energy focusing characteristics, and low thermal effect. Combined with technologies such as focused ultrasound and acoustic matching layer, the energy transfer efficiency of UPT is significantly improved, especially in complex human environments showing good adaptability and safety.

Future research can enhance the efficiency and stability of UPT by further optimizing the design of the transducer, improving the conversion performance of the piezoelectric material, and developing more accurate theoretical models to promote its wide application in medical implantable devices.

References

[1] C Y. Hu, X. Zhang, J. Yang, Q. Jiang, IEEE Trans. Ultrason. Ferroelectr. Freq.Control 2003,50,773.

[2] X. Bao, W. Biederman, S. Sherrit, M. Badescu, Y. Bar-Cohen, C.Jones, J. Aldrich, Z. Chang, in Industrial and Commercial Applicationsof Smart Structures Technologies 2008, SPIE, San Diego, US 2008, pp.291-298.

[3] H. Basaeri, D. B. Christensen, S. Roundy, Smart Mater. Struct. 2016, 25,123001.Ma Kunlong. Short term distributed load forecasting method based on big data. Changsha: Hunan University, 2014.

[4] K. Agarwal, R. Jegadeesan, Y.X. Guo, N.V. Thakor, IEEE Rer. Biomed.Eng. 2017, 10, 136.Fangfang. Research on power load forecasting based on Improved BP neural network. Harbin Institute of Technology, 2011.

[5] L. Jiang, Y. Yang, Y. Chen, Q. Zhou, Nano Energy 2020, 77, 105131.

[6] S. R. Khan, S. K. Pavuluri, G. Cummins, M. P.Y. Desmulliez, Sensors2020, 20, 3487.

[7] A. Denisov, E. Yeatman, in 2010 International Conference on BodySensor Networks, IEEE, Singapore 2010, pp.84-89.

[8] V.T. Rathoa, Sensors 2020, 20, 4051.

[9] T. Inoue, M. Ohta, S. Takanashi, IEEE Trans. Ultrason. Ferroelectr.Freq. Control 1987, 34, 8.

[10] E. Waffenschmidt, T. Staring, in 2009 13th European Conference onPower Electronics and Applications, IEEE, Barcelona, Spain 2009, Pp.1-10.

[11] A. lbranim, M. Meng, M. Kiani, IEEE Sens. J. 2018, 18, 3813.

[12] B. Jaafar, J. Neasham, P. Degenaar, IEEE Rev. Biomed. Eng. 2021, 16, 357.

[13] M. Gao, Y. Yao, F. Yang, J. Ye, G. Liu, B. Wang, S. Liu, P. Wang, Y. Lu, Device 2023,1.

[14] W. P. Mason, Electromechanical Transducers and Wave Filters, VanNostrand 1942.

[15] D. A. Berlincourt, D. R. Curran, H. Jaffe, Physical Acoustics: Principlesand Methods 1964, 1, 202.

[16] S. Sherrit, M. Badescu, X. Bao, Y. Bar-Cohen, Z. Chang, in SmartStructures and Materials 2005: Smart Sensor Technology and Measure-ment Systems, SPIE, San Diego, US 2005, pp.362.

[17] R. Krimholtz, D. A. Leedom, G. L. Matthaei, Electron. Lett. 1970, 13, 398

[18] T. Maleki, N. Cao, S. H. Song, C. Kao, S. C. Ko, B. Ziaie, IEEE Trans.Biomed. Eng. 2011, 58,3104.

[19] S. H. Song, A. Kim, B. Ziaie, IEEE Trans. Biomed. Eng. 2015, 62, 2717.

[20] A. Arbabian, T. C. Chang, M. L. Wang, J. Charthad, S. Baltsavias, M.Fallahpour, M. J. Weber, IEEE Microw. Mag. 2016, 17, 39.

[21] M. M. Ghanbari, R. Muller, IEEE Trans. Biomed. Circuits Syst. 2020, 14. 1381.