Fast impedance matching for the ion cyctron resonance heating system based on capacitors at the EAST tokamak

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Abstract. This paper presents an impedance matching system based on real-time feedback control, designed to address impedance mismatching issues in radio frequency (RF) systems. The proposed system integrates a directional coupler, a double-section impedance matcher, a variable capacitor, a servo motor, and a fast real-time impedance matching feedback control system. By measuring forward and reflected power via the directional coupler, the system dynamically adjusts the capacitance to achieve optimal matching. The real-time feedback mechanism controls the servo motor to adjust the capacitor's value, thereby fine-tuning to the desired level. Experimental results show that the system can significantly reduce reflection power in less than 1 second, demonstrating fast response and high efficiency. The proposed solution is applicable in wireless communication, radar, and RF power transmission systems, offering improved system performance, reduced energy consumption, and enhanced signal quality.

1 Introduction

Plasma heating using Ion Cyclotron Range of Frequency (ICRF) waves has been extensively utilized in many magnetic fusion devices, including JET [1-3], ASDEX-U [4, 5], Alcator C-Mod [6, 7], WEST [8], EAST [9], LHD [[10, 11], ICRF waves are particularly effective for ion heating and can be applied at high plasma densities. This characteristic makes them suitable for use in next-generation fusion reactors, which will operate at high plasma densities and strong magnetic fields. As a result, ICRF heating is being considered as a potential heating method for future fusion reactors, such as ITER [12, 13].

ICRF is a crucial heating technique employed in EAST, routinely utilized to achieve long-duration discharges with optimal plasma conditions. Impedance matching plays a crucial role in optimizing the performance of radio frequency (RF) systems by ensuring maximum power transfer between components and minimizing energy loss due to reflections [14-21]. To improve system performance and achieve long pulse and high power operation, impedance matching is vital especially in dynamically changing conditions.

Traditionally, for the ICRF system in EAST tokamak, impedance matching techniques rely on liquid stubs matching system that require manual adjustment [19]. This methods is inflexible and slow. As the demand for high power and long pulse operation of the system, the need for advanced impedance matching techniques has become more pressing. Fast and automatic impedance matching is necessary to accommodate fluctuating environmental conditions in the EAST tokamak.

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2 Technical Approach

The proposed system is designed to achieve high-efficiency impedance matching between an antenna and a transmission line, which is crucial in minimizing signal reflection and maximizing power transfer in RF systems. Impedance mismatches in such systems can lead to significant signal power reflection, reduced efficiency, and potential damage to RF components. This system integrates precise measurement, mechanical adjustment, and real-time control to automatically detect and correct mismatches, adapting continuously to matching antenna impedance. As shown in Figure.1, by combining a directional coupler, a double-stub with variable capacitor, a servo motor, and a fast real-time feedback control system, the design provides a dynamic, high-precision solution for impedance matching, ensuring consistent performance across a wide range of operating conditions.

Directional Coupler: The directional coupler is an RF circuit element used to measure both forward and reflected power in the system. By analyzing these power measurements, the system can calculate the reflection coefficient, which provides information about the current impedance of the antenna and the overall transmission line. Essentially, the directional coupler acts as the "eyes" of the system, providing real-time data that enables the feedback control system to make accurate, timely adjustments to maintain optimal impedance matching.

Double-Stubs Impedance Matcher: The double-stubs impedance matcher is a common RF matching structure consisting of two parallel short or open circuit stubs. The lengths of these stubs can be adjusted to match the antenna impedance over a wide range of values. By modifying the electrical length of these sections, the matcher ensures that the impedance seen by the transmission line closely approaches the characteristic impedance, minimizing reflections and improving overall system efficiency. The dual-stub configuration allows for broad-band matching and provides flexibility in adapting to varying load conditions.

Variable Capacitor: The variable capacitor serves as the key tuning element within the matching network. Positioned at the end of the double-section stubs, it allows fine adjustments of the network's electrical length by changing its capacitance. This capability enables the system to precisely match different antenna impedances, ensuring that power transfer remains efficient even under dynamically changing conditions. Its high-resolution adjustment is critical for achieving low reflection coefficients and optimal system performance.

Servo Motor: The servo motor provides the mechanical actuation needed to adjust the variable capacitor. By rotating the capacitor in precise steps, the servo motor effectively changes the network's capacitance according to the control commands from the feedback system. This ensures accurate, repeatable adjustments and allows the system to respond quickly to impedance variations without manual intervention.

Feedback Control System: At the heart of the system is the fast real-time feedback control mechanism. This system continuously monitors the antenna impedance using the directional coupler. When a mismatch is detected, it calculates the optimal capacitor setting required to achieve proper matching and sends control signals to the servo motor. The feedback loop operates in real time, enabling rapid correction of impedance variations and maintaining efficient power transfer. Its continuous monitoring and adjustment capabilities make the system adaptive and robust against changes in antenna load, frequency, or environmental conditions.

The feedback system operates in real-time, enabling quick adjustments to impedance mismatches. Once the system detects a mismatch, it calculates the optimal capacitor setting and directs the servo motor to the correct position, achieving an efficient impedance match.

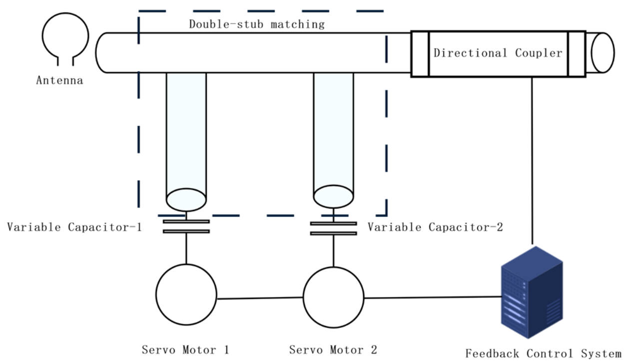

Figure 1. The schematic of impedance matching system for ICRF heating system. The system consist of a directional coupler, a double-stub impedance matcher, a variable capacitor, a servo motor, and a fast real-time impedance matching feedback control system.

3 Matching logic of the system

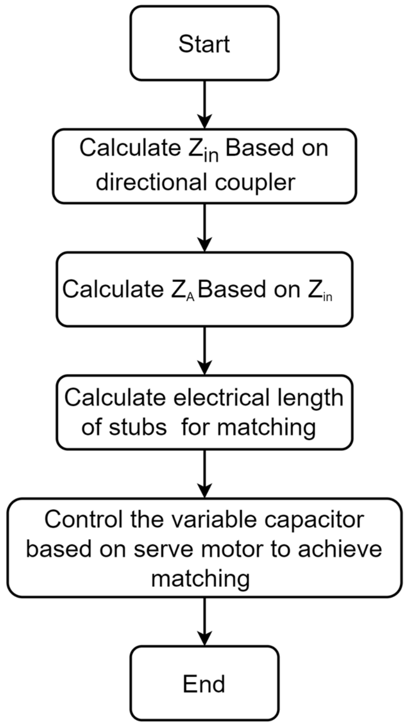

Figure 2. The logic for impedance matching of ICRF system.

In modern RF systems, achieving precise impedance matching is critical to ensuring efficient power transfer between a transmission line and an antenna, minimizing reflections, and maintaining optimal signal integrity. The process relies on careful measurement, calculation, and mechanical adjustment, and when executed systematically, it allows engineers to fine-tune antenna systems for peak performance. The logic for impedance matching of ICRF system is shown in Figure 2. Let us examine this process in detail from the perspective of a seasoned RF engineer.

Forward and Reflected Signals: The directional coupler serves as the fundamental measurement element in this system. It separates the RF signal into two distinct components: the forward signal, which propagates from the source toward the antenna, and the reflected signal, which returns due to impedance mismatches along the line or at the antenna itself. Importantly, the directional coupler provides not only the magnitude of these signals but also the phase difference between them. Both pieces of information are indispensable, as they form the basis for accurately characterizing the impedance behavior at the coupler's location. Without precise magnitude and phase measurements, any attempt at impedance matching would be largely guesswork.

Reflection Coefficient: From the forward and reflected signals, we can calculate the reflection coefficient (Γ) at the coupler's position. The reflection coefficient is a complex quantity representing both the amplitude and phase of the reflected wave relative to the incident wave. Its significance cannot be overstated: it directly quantifies the degree of impedance mismatch. A reflection coefficient of zero indicates perfect matching, while larger values signify increasingly poor matching. Understanding the reflection coefficient allows the engineer to make informed decisions about the required adjustments to bring the system toward optimal performance.

Transmission Line Theory: Using well-established transmission line theory, the reflection coefficient measured at the coupler can be mathematically translated into the input impedance at the antenna. This step is crucial because the input impedance dictates how efficiently energy is transferred from the transmission line to the antenna. The closer the antenna's input impedance is to the characteristic impedance of the line, the less power is reflected and the more energy is radiated effectively. Knowledge of the input impedance forms the cornerstone of any impedance-matching strategy.

Impedance Matching: Once the input impedance is determined, the next step is to match it to the system's characteristic impedance. This is typically achieved using a matching network, often implemented with stubs or reactive elements. By adjusting the electrical length of the matching stub, engineers can introduce the exact reactance required to cancel the reactive component of the antenna's impedance, bringing the overall system into resonance. This step transforms a potentially lossy connection into an efficient power-transfer pathway, dramatically reducing reflected power and improving overall system efficiency.

Stub Electrical Length and Capacitance: The electrical length of the matching stub is directly related to the capacitance required for compensation. This relationship can be empirically measured using a network analyzer, as described in prior work [20]. The relationship between the stub electrical length and the number of turns of the capacitor is shown in Figure 3. Once the required capacitance is determined from the stub length, it can be used as the control parameter for the mechanical tuning element in the system. This step bridges theoretical calculations with practical hardware implementation.

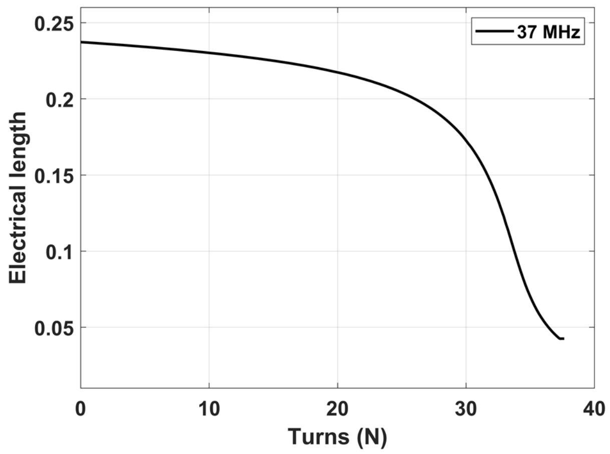

Figure 3. The stub electrical length corresponding to different numbers of turns of capacitor.

Motor Adjustment: The final stage involves precise mechanical adjustment using a servo motor, which controls the variable capacitor in the matching network. The calculated capacitance value dictates both the number of turns the motor must make and the direction of rotation. By executing these controlled adjustments, the motor modifies the capacitance with high precision, thereby tuning the stub and completing the impedance match. The process can be repeated dynamically in real time, allowing the system to continuously respond to changing antenna characteristics or environmental factors.

This systematic approach—measuring forward and reflected signals, calculating the reflection coefficient, determining input impedance, computing required stub lengths and capacitance, and precisely adjusting the motor—embodies decades of RF engineering practice. By following this methodology, engineers can ensure that antennas operate with minimal reflection, maximum efficiency, and reliable performance under varying conditions. The beauty of this approach lies not just in its theoretical foundation but in its practical, repeatable application, bridging the gap between precise measurement, calculation, and mechanical control to achieve optimal signal transmission and reception.

4 Reliability of Automatic Matching Technology in the EAST Experiment

To validate the proposed system, experiments were conducted on a test platform, simulating various impedance matching scenarios. The system was configured with a directional coupler to measure forward and reflected power. Based on these measurements, the feedback control system adjusted the variable capacitor in real-time to match the impedance.

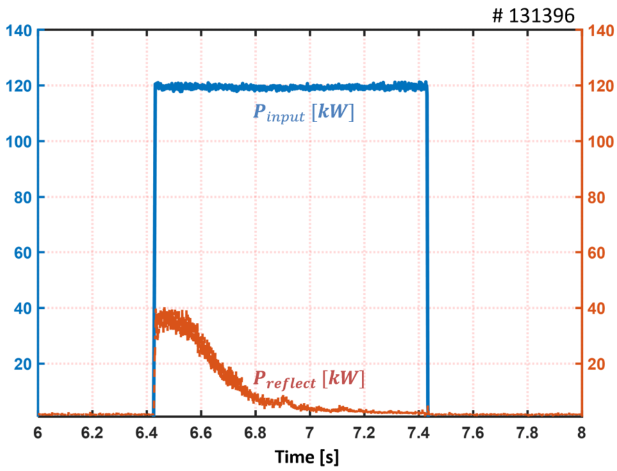

Figure 4. Test results from the EAST 131396 experiment (L mode discharge) demonstrate the effectiveness of the automatic matching technique. The reflected power decreases from 30% to below 1% within 1 second, showing the fast response and high reliability of the automatic impedance matching system under dynamic conditions.

Figure 4 illustrates the reflection power measured over time in L mode discharge. Initially, when the system is activated, the reflection power is high (approximately 30%). Within 0.4 seconds of initiating the feedback loop, the reflection power drops below 5%. After 1 second, the reflection power is reduced to below 1%, indicating that the system has achieved optimal impedance matching. For H-mode discharge, as shown in Figure 5, the reflected power decreases from more than 30% to below 5% in 1s and remains below 5% for the last 5s, even though the fluctuation is stronger compared with L-mode discharge.

These results demonstrate the rapid response and effectiveness of the real-time feedback control system in achieving impedance matching. The system's ability to respond quickly to changing conditions in achieving optimal impedance suggests that it can be applied in real-world RF systems.

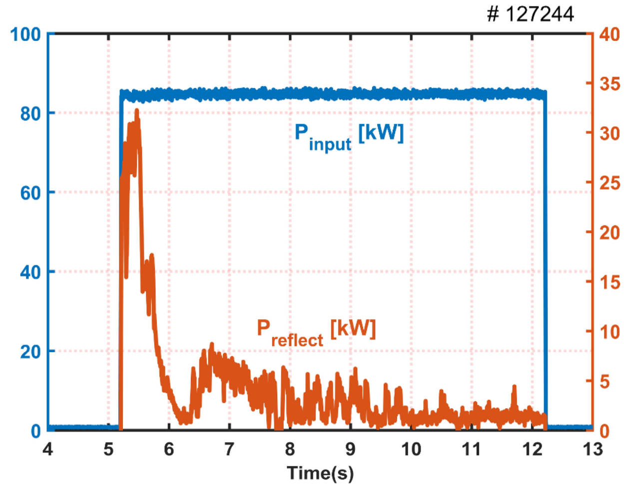

Figure 5. Test results from the EAST 127244 experiment (H mode discharge) demonstrate the effectiveness of the automatic matching technique. The reflected power decreases from more than 30% to below 5%.

5 Discussion

The proposed system offers several advantages over traditional impedance matching techniques. The most significant is its real-time response capability, which allows for fast adaptation to changing conditions. The automation of the impedance matching process also eliminates the need for manual adjustments, reducing operational costs and complexity.

Moreover, the system's use of a servo motor and variable capacitor enables precise control over the impedance, which enhances system performance. The integration of a feedback loop ensures that the system remains in an optimal state, even when environmental or load conditions change.

However, there are certain limitations to the system. One limitation is that the speed of response is still dependent on the hardware and the processing time for the feedback loop. Future work could focus on improving the response time further by optimizing the control algorithms and hardware components. Additionally, the system's performance in more complex environments with multiple reflection sources or highly dynamic load conditions needs further exploration.

6 Conclusions

This paper presents a novel impedance matching system based on real-time feedback control. By integrating a directional coupler, double-section impedance matcher, variable capacitor, and servo motor, the system automatically adjusts impedance to ensure optimal performance in RF applications. Experimental results demonstrate that the system can significantly reduce reflection power within a short time frame, highlighting its potential for use in wireless communication, radar, and RF power transmission systems. The proposed system offers an automated solution to impedance mismatching, improving efficiency, reducing energy consumption, and enhancing system stability. Future research will focus on optimizing the control algorithms and exploring broader application scenarios.

Acknowledgements

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