FEEDBACK CONTROLLED HYBRID FAST FERRITE TUNERS

by

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ABSTRACT

A low power ANT-Bosch fast ferrite tuner (FFT) was successfully tested into (1) the lumped circuit equivalent of an antenna strap with dynamic plasma loading, and (2) a plasma loaded antenna strap in DIII-D. When the FFT accessible mismatch range was phase-shifted to encompass the plasma-induced variation in reflection coefficient, the 50 Ω source was matched (to within the desired 1.4 : 1 voltage standing wave ratio). The time required to achieve this match (i.e., the response time) was typically a few hundred milliseconds, mostly due to a relatively slow network analyzer-computer system. The response time for the active components of the FFT was 10 to 20 msec, or much faster than the present state-of-the-art for dynamic stub tuners. Future FFT tests are planned, that will utilize the DIII-D computer (capable of submillisecond feedback control), as well as several upgrades to the active control circuit, to produce a FFT feedback control system with a response time approaching 1 msec.

1. INTRODUCTION

Coupling to fast magnetosonic waves in the ion cyclotron range of frequencies (ICRF) is a prime candidate for plasma heating and current drive in present (e.g., DIII-D [1], JET [2]) and future (e.g., ITER [3], Ignitor [4]) tokamaks. Maximizing the efficiency with which ICRF power is delivered to plasma becomes increasingly more important as the size and power of ICRF systems escalate.

One way to improve the efficiency is to use a dynamic tuning system. The best example to date is the JET tuning system [5]. Variations in the ICRF frequency and stub tuner positions are feedback controlled to compensate for changes in the antenna loading. While frequency feedback changes phase in less than 1 msec, a broad bandwidth transmitter is required and/or a long (and thereby lossy) transmission line is needed to obtain sufficient phase shift. Furthermore, the JET motor-driven stub tuner is slow — taking seconds to respond to impedance changes. JET offsets this problem by varying the plasma edge position and thereby the plasma loading in tens of milliseconds. Nevertheless, there is strong

community interest in a faster (millisecond) response time, and preference for a means of impedance control that does not require plasma modification [6].

To meet this interest, TEXTOR has recently installed a variable vacuum capacitor-based double stub tuner [7]. The input power is up to 2 MW, 50 to 200 pF, capacitor voltage holdoff approaches 90 kV, and the capacitors are commercially available. The main issue is in the vacuum capacitor mechanical movement. Bellows fatigue and related lifetime limit the response time to ~ 100 msec [7].

In contrast, the hybrid FFT described herein demonstrated a new state-of-the-art 10 to 20 msec response time on DIII-D, and identified future FFT upgrades toward response times approaching 1 msec. Dummy load test results are summarized in Section 2. Section 3 presents tests with DIII-D plasma loading. Conclusions and recommendations are given in Section 4.

2. DUMMY LOAD TESTS

To validate the FFT response time in a controlled way, the simulated plasma (dummy) load and switching circuit in Fig. 1 was developed. Two electronically triggered switches with submillisecond switching times were deployed. In accordance with DIII-D plasma-loaded antenna measurements described elsewhere [8], an antenna strap with L-mode loading is simulated by a nominal 100 nH inductance with a plasma loaded resistance of 2.5 Ω . Edge localized mode (ELM)-free H-mode loading is simulated by 0.9 Ω resistance with a plasma-induced 2 Ω reduction in load reactance. ELMing H-mode loading is simulated by 5.5 Ω resistance with 9 Ω reduction in load reactance.

In a typical test, a trigger pulse from the FFT (upper trace in Fig. 2) initiated a simulated L-mode to ELMing H-mode plasma transition. This transition caused an increase in reflection coefficient to about 0.5 in less than 1 msec. The FFT response time to reduce this reflection to zero was observed by (1) measuring the coil voltages required to produce a match to the final state, (2) measuring coil voltages required to match

FIG. 1. Block diagram of FFT tests into simulated plasma loads.

to the initial state, (3) setting up the test circuit and preprogramming the FFT for the final state voltages, (4) prematching the FFT to the initial state (represented by the initial voltage level in Fig. 2, lower trace), (5) recording the transition waveform to the final state where the reflection coefficient is effectively zero (Fig. 2), and (6) observing ~ 20 msec 10% to 90% response time. The trace noise in Fig. 2 was caused by the MOSFET power supply, and did not affect the FFT operation.

3. DIII-D PLASMA TESTS

The FFT was inserted in the ICRF system on DIII-D as shown in Fig. 3. The FFT accessible mismatch range (i.e., the range of variation in complex reflection coefficient within which a match can be achieved) was rotated in phase to overlay the phase quadrant wherein

the plasma-induced changes in reflection typically took place (as observed using a Smith chart display). A 10 to 100 W oscillator-amplifier source was deployed to permit measurements of reflected power with the 70 dB couplers on DIII-D, as well as protect the source oscillator against arcing due to spurious plasma-induced transients. The pressurized coaxial line A on DIII-D was connected to the source via a type N to 9-in. coax adapter. Similarly, the output of the 9-in. dc break on line A was connected to the input of strap No. 3 in DIII-D using another 9-in. coax to N adapter and a length of N cable. The other three straps not in use were determined by terminating them in their 25 Ω matched load.

A total of 17 shots into DIII-D plasma were made. Changes in the amplitude and phase of the reflection coefficient during transitions from vacuum to plasma, and from L-mode to H-modes with and without giant or grassy ELMs were observed. Data fell into two categories: (1) Shots 76193 through 76195 with stub A in the neutral position; and (2) Shots 76184 through 76192 and 76196 through 76201 with stub A and stretcher A pretuned to vacuum. As expected, all shots exhibited significant mismatch excursions during the few hundred millisecond delay time required for network analyzer and computer system to digitize and process information. Once the FFT coils received the feedback control voltages, however, a match (to within the desired 1.4 : 1 VSWR) typically occurred within 20 msec. This response time is comparable to that measured during the dummy load tests discussed in Section 2.

FIG. 2. Evidence of a 20 msec FFT transition time from a simulated L-mode load to an H-mode load with grassy ELMs.

FIG. 3. Block diagram of FFT tests into plasma in DIII-D.

Shot 76196 is a good worst-case demonstration of the FFT dynamic matching capability. This is because strap No. 3 pretuned to vacuum prior to the shot, thereby causing a greater initial mismatch. Normally, ICRF experiments in DIII-D benefit from pretuning to a reasonably close match.

The density variation for shot 76196 is exhibited in Fig. 4 (upper trace). This variation effectively correlates the time that the plasma is present with the reflection coefficient variation exhibited in the lower trace. Notably, the reflection coefficient varies around 0.6 to 0.8 during the few hundred millisecond computer processing time. Once the power supply received the control voltages, however, a rapid transition to a nearly perfect match occurred. To more accurately measure this transition time, the 450 to 550 msec time-window was expanded as shown in Fig. 5. The self-evident 13 msec 10% to 90% transition time represents the fastest of the data recorded during these tests. The phase of the reflection coefficient during this period is also shown in Fig. 5. Notably, there is less than a 90 deg phase change during the transition from a mismatch to a match. This is within the FFT accessible mismatch range. The increased phase fluctuation after achieving a good match is because the FFT control circuit is not locking onto the corresponding low reflected power (and does not need to).

4. CONCLUSIONS AND RECOMMENDATIONS

An ANT-Bosch low power FFT demonstrator has been successfully validated into a lumped circuit equivalent of an antenna-strap with simulated dynamic plasma loading, and an isolated antenna strap in DIII-D with both vacuum and plasma loading. The FFT accessible mismatch range has been effectively rotated in phase to

FIG. 4. The variation of plasma density and reflection coefficient magnitude during FFT operation on shot 76196.

FIG. 5. Magnitude and phase variation of reflection coefficient on shot 76196 (expanded time window).

encompass the observed range of plasma loaded reflection coefficients. Matching to a 50Ω source to within an acceptable 1.4 : 1 VSWR has been demonstrated.

Four upgrades to reduce the FFT response time to (1 msec or less) were identified:

- Incorporate the DIII-D computer system, or an equivalent megahertz operating speed digitizer and computer microprocessor to effectively eliminate the 100 to 400 msec data processing time.
- Increase the 200 V maximum coil voltage and thereby effectively eliminate the estimated few milliseconds delay therein.
- Effectively eliminate the 5 to 6 msec time delay caused by eddy currents in the FFT enclosure, by replacing

the brass with copper-coated stainless steel.

- Upgrade the power supply insulation to handle voltage risetimes less than 2 msec, and thereby remove the need for a protection filter (with 2 msec delay time).

While working recently at the four European tokamak facilities for a couple of months, one of us (D.A.P.) discussed with many scientists the FFT test results described herein and the need for a millisecond response time dynamic tuner, such as an FFT [6]. Everyone responded with the benefits to plasma load matching that an FFT represents. They also identified many technology issues that could be resolved by a high power demonstration. Based on the above discussions, the low power FFT test results described herein, prior FFT publications [9], and ferrite circulator experience at high power [10], ANT-Bosch engineers project with confidence that a high power FFT prototype with millisecond response time can now be built. Consequently, GA has submitted a proposal to DOE to perform a high power FFT demonstration on DIII-D in 1994.

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