Automatic control of ITER-like structures

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Abstract. Abstract In ITER Ion Cyclotron System a power transfer efficiency in excess of 90% from power source to plasma in quasi continuous operation. This implies the availability of a control system capable of optimizing the array radiation spectrum, automatically acquiring impedance match between the power source and the plasma loaded array at the beginning of the power pulse and maintaining it against load variations due to plasma position and plasma edge parameters fluctuations, rapidly detecting voltage breakdowns in the array and/or in the transmission system and reliably discriminating them from fast load variations. In this paper a proposal for a practical ITER control system, including power, phase, frequency and impedance matching is described

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INTRODUCTION

In ITER, the Ion Cyclotron Heating System should routinely operate close to the nominal RF power output (20 MW) in quasi-continuous operation, with infrequent power interruptions, due to voltage breakdowns in the array and/or in the transmission system, or because of equipment failure. A reliable operation requires a control system capable of:

1) controlling the array radiation spectrum during the power pulse, so as to optimize plasma coupling and adsorption and to minimize parasitic power losses in the plasma edge;

2) establishing and maintaining the RF power flow to the plasma. This implies for all the RF power sources to automatically acquire, at the beginning of each RF pulse an impedance match suitable for an efficient RF power transfer, starting from a preset condition, and to maintain it during the whole power pulse, against significant load variations..

3) detecting and suppressing RF voltage breakdowns in the array and in the transmission system, with a time response of few microseconds, to limit the energy deposited in the arc and to avoid local equipment damage. This is usually done by a fast power interruption, with automatic recovery to normal operation, when a suitable dielectric strength is restored in the torus vacuum vessel.

4). Providing an accurate real time measurement of the plasma load.

The control method proposed here relies on the active, real time, and vectorial control, of all currents in all array elements. Currents in each element are controlled independent of those in the other ones. The method is therefore applicable to any array order.

The IC launcher described in the ITER Final Design Report is an array of eight (2 poloidal x 4 toroidal) elements, referred to as "ITER-like structure" - ILS -) powered by a 2.5 MW source, for a total of 20 MW power output. It can be shown 1) that i) if the ILS currents are controlled to be complex conjugate and symmetric with respect to the input current and ii) the input impedance of the circuit is kept not too high compared to the circuit load resistance(s), the ILS exhibits a significant tolerance to the resistive load variations such as the ones due to fast ELMs fluctuations. In a more recent CEA proposal 2) an increase of the array poloidal order (2 poloidal x 4 toroidal elements) is proposed.

CONDITIONS FOR LOAD RESILIENCE AND PERFECT MATCH

In an "ideal" ITER-like structure (i.e. with load symmetry and no inter strap coupling) the conditions for perfect match and load resilience coincide. In 3) it is shown that the same level of load resilience can be obtained for a generic ILS, for reasonable assumptions about coupling and load asymmetries, relevant to ITER IC applications, provided that the match is performed to a complex impedance $Z_{in} = R_0 - iX_{sm}$, where X_{sm} is the reactive part of the non diagonal term of the ILS impedance matrix. In short, with the ITER parameters used in the FDR report, and the notations used in 3), if $k_p = |X_{sm}|/X_s$ is of the order of percent and the ILS load asymmetries below 10%, a level of impedance matching acceptable to the specified power sources (VSWR < 2 at full power) is possible with the ILS tuning capacitors only.

In this paper however we shall derive the perfect match conditions *at* optimum load resilience for a generic ILS (i.e. with arbitrary load asymmetry and inter strap coupling). It is well known that an arbitrary complex load can be perfectly matched to a resistive input impedance R_{in} by a series/parallel combination of two reactances. Thus, for an arbitrarily loaded ILS four reactances are needed.

We consider the circuit in Figure 1, where the generic ILS, including the two tuning capacitive reactances X_{C1} and X_{C2} (Pretuner) is connected to the series/parallel combination of two reactances X_S and X_P (Trimmer). The system is described by the equations:

$$\begin{aligned}(R_{s1} + i\cdot X_1)\cdot\iota_1 + (R_{sm2} - i\cdot X_{sm2})\cdot\iota_2 &= (R_0 + i\cdot X_0)\\ (R_{sm1} - i\cdot X_{sm1})\cdot\iota_1 + (R_{s2} + i\cdot X_2)\cdot\iota_2 &= (R_0 + i\cdot X_0)\end{aligned} \quad \text{with} \quad \iota_1 = \frac{I_1}{I_{in}} \quad \iota_2 = \frac{I_2}{I_{in}} \quad \iota_{in} = \iota_1 + \iota_2 = 1 \qquad 1)$$

If we impose to the current ratios to be complex conjugate and :

$$\begin{aligned}\iota_1 &= \iota_0\cdot(\cos(\phi) + i\cdot\sin(\phi))\\ \iota_2 &= \iota_0\cdot(\cos(\phi) - i\cdot\sin(\phi))\end{aligned} \quad \text{or} \quad \iota_1 + \iota_2 = 2\cdot\iota_0\cdot\cos(\phi) = 1, \text{ i.e. } \iota_0 = \frac{1}{2\cdot\cos(\phi)} \qquad 2)$$

substitution in 1) leads to :

$$\Delta X_C = \Delta X_s \pm \sqrt{\left(2 \cdot R_0 - R_s - R_{sm}\right) \cdot \left(R_s - R_{sm}\right)} + \Delta X_{sm}$$

$$\tan\phi = \pm\sqrt{\frac{\left(2 \cdot R_0 - R_s - R_{sm}\right) \cdot \left(\Delta X_C - \Delta X_s - \Delta X_{sm}\right)}{\left(R_s - R_{sm}\right) \cdot \left[\left(\Delta X_C - \Delta X_s\right) + \Delta X_{sm}\right]}} + \Delta X_{sm} \qquad 3)$$

$$X_C = \left(X_C + X_{sm}\right) - \mathrm{cotan}(\phi) \cdot \left(\Delta R_s - \Delta R_{sm}\right)$$

$$X_0 = \frac{1}{2} \cdot \left[(\tan(\phi) + \mathrm{cotan}(\phi)) \cdot \Delta R_s + (\tan(\phi) - \mathrm{cotan}(\phi)) \cdot \Delta R_{sm}\right] - X_{sm}$$

where R_s, X_s, R_{sm}, X_{sm} are the arithmetic average of $R_{sk}, X_{sk}, R_{smk}, X_{smk}$ (k = 1,2) and ΔR_s, ΔX_s, ΔR_{sm}, ΔX_{sm} the relative asymmetries. On the other hand, from Figure 1 it is deduced that:

$$X_0 = \sqrt{R_0 \cdot \left(R_{in} - R_0\right)} - X_s \qquad R_0 = R_{in} \cdot \frac{X_p^2}{\left(R_{in}^2 + X_p^2\right)} \qquad 4)$$

From 3) it is seen that, if current symmetry and input resistance R_0 are imposed to in a generic ILS for optimum load resilience, a reactive input mismatch (X_0) depending on both circuit asymmetry and coupling is generated.

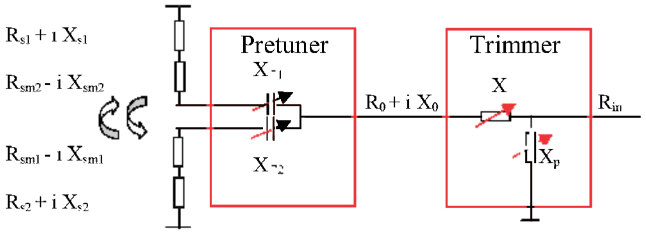

Figure 1 Layout of the tuning system

If unacceptable to the RF power source, the mismatch can however be easily corrected by the Trimmer circuit. In practice, for a moderate mismatch, it may be convenient to locate the trimmer at the generator end and use a wideband multi section transformer at the Pretuner input to bring the (low) R_0 value close to the transmission line characteristic impedance Z_c.

From the above considerations the matching algorithms for the Pretuner are:

$$[\arg(I_1)-\arg(I_{in})] + [\arg(I_2)-\arg(I_{in})] = 0 \quad \text{acting on } X_C \qquad 5)$$

and

$$\mathrm{Re}(Z_p) = R_0 \quad \text{acting on } \Delta X_C. \qquad 6)$$

where Z_p is the Pretuner input impedance. The Trimmer algorithms are straightforward from equations 4). In Figure 2 the two relations 5) and 6) are plotted against the tuning reactances X_{C1} and X_{C2}, for typical ITER values $R_s = 1\Omega$, $X_s = 30\Omega$, $R_{sm} = 0.5\ \Omega$, $X_{sm} = 0$ and 0.3Ω mapped against the module of the reflection coefficient. In this case $\Delta R_s = \Delta X_s = \Delta R_{sm} = \Delta X_{sm} = 0\ \Omega$ for simplicity. In the first case (Figure 2a) optimum resilience and perfect match conditions coincide, as expected. In the second case, they do not because of the term $X_0(R_s,X_s,R_{sm},X_{sm},\Delta R_s,\Delta X_s,\Delta R_{sm},\Delta X_{sm})$.

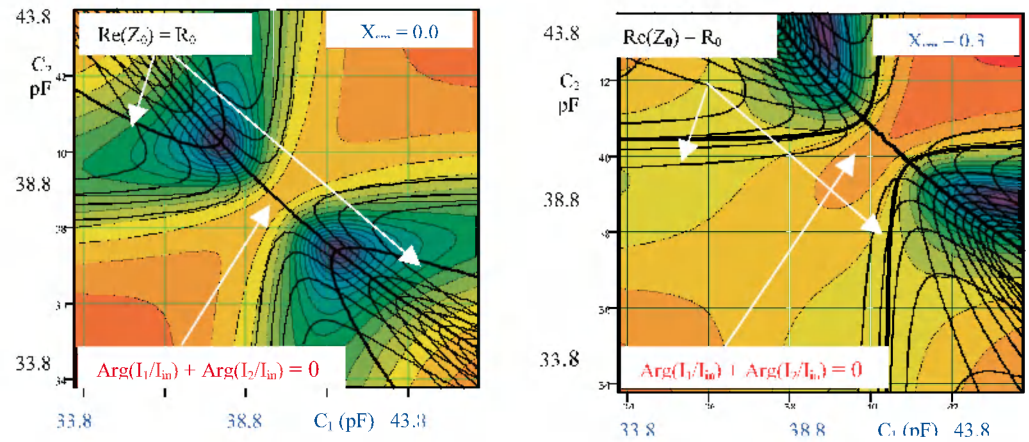

Figure 2 Conditions for perfect match and load resilience mapped against X_{C1} and X_{C2} : a) $X_{sm}= 0\Omega$; b) $X_{sm}= 0.3\Omega$.

The two control loops of the Pretuner should operate with different time constants so that the ΔX_C loop tracks the X_C loop. In the same way the Trimmer control loops (if any) should track the Pretuner loops. Finally, the tuning loops should track the phase and power control loops.

CONCLUSIONS

In conclusion, a simple matching algorithm for a generic ILS is proposed. The method requires the vectorial detection of the ILS currents. The design of a suitable vectorial current monitor cannot be included here for lack of space, but it is discussed in the companion poster. As the strap currents are symmetrically controlled with respect to the input current by the feedback system, a matched ILS behaves as a single matched strap. Therefore the extension of this method to a complex array can be performed as for an array of single straps. As all array currents are actively controlled to predictable values, phase instabilities described in $^{3)}$ can be avoided .

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