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A NEW AUTO FREQUENCY TUNING ALGORITHM

Abstract

One countermeasure to fast plasma impedance variations is auto frequency tuning where on a sub-millisecond timeframe the RF-power generator sets its fundamental to a frequency value with better matching. Conventional solutions for auto frequency tuning work with a trial and error algorithm that jumps to a new frequency, tests the reflected power and decides to either proceed or turn back, or use complex impedance measurement to deduce the tuning information. These solutions, however, suffer from inadequate performance and occasionally get stuck. In our new approach the RF fundamental is constantly FM-modulated with a selectable modulation frequency. If this modulated RF hits the "matching slope" of the chamber the reflected power will not only be frequency modulated but also amplitude modulated. Special double demodulation yields a signal representing the steepness and sign of the matching slope, i.e. its derivative, which may readily be used as tuning information. The algorithm is tweaked to not get latched at local reflection minima while displaying a smooth and tempered behaviour close to the tuning optimum.*

Introduction

Matching the source (generator) to the load (plasma) is an important yet often underestimated link in the RF supply chain. Due to the variable process parameters a constant re-tuning is usually necessary. For fast plasma process changes mechanical matchboxes are not fast enough. One solution to this challenge is auto frequency tuning (AFT) where the generator sets its fundamental to a frequency value with better matching. The objective was to provide a more reliable and self-controlling frequency tuning that ensures the location of the correct frequency independently of any cable length even with complicated and constantly changing reflection behavior. The natural drawback of frequency tuning is that this method only covers one dimension in the two-dimensional impedance domain and only has a narrow frequency range; hence it can only compensate for limited impedance offsets. Thus, auto frequency tuning is either installed together with a conventional tuning matchbox or a fixed match.

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While auto frequency tuning in combination with a tuning matchbox is the optimal solution for covering both, an extended impedance range and fast changes, one of the challenges is to prevent competing matching operations of the matchbox and the frequency tuning that might drive either technique to its dead end.

Algorithm

Conventional solutions for AFT work with a trial and error algorithm that jumps to a new frequency, tests if the reflected power has increased or decreased and thus decides to either proceed into this direction to turn back. The frequency step width is adjusted, i.e. decreased while tuning advances or increased while tuning deteriorates. Once a sufficient matching has been achieved, the algorithm stops until the reflected power rises above a predefined threshold.

An alternative technique uses complex impedance measurement (in-phase/quadrature, V/I, Γ/φ) to deduce the tuning information. These solutions, however, suffer from inadequate performance and occasionally get latched at a frequency border or some area without sufficient Γ (reflection)-slope. The latter method also shows a principal cable length dependency.

The herein chosen approach [1] uses frequency modulation. The RF fundamental is constantly FM-modulated with a selectable modulation frequency. The frequency of this "tone" may be anything from some hertz up to a fraction of the fundamental; a typical modulation frequency may be 16 kHz. The waveform can be anything, but a sine wave or a rectangular are of advantage due to their defined bandwidth or their significant frequency impact, respectively.

If the fundamental including this FM hits a "matching slope" the reflected power P_r will not only be frequency modulated but also amplitude modulated. The magnitude of the resulting amplitude modulation is defined by the slope of the matching curve. The detector diode attached to the directional coupler demodulates this AM. At its output one can “listen” to the modulation "tone".

The “sign” of the demodulated tone (i.e. its phase) readily defines the orientation of the slope, an in-phase signal stands for a rising curve, a 180° out-of-phase signal a falling curve as depicted in Figure 1. To get this information a second demodulation is performed by mixing the received tone with the original modulation waveform. The resulting DC represents the steepness and sign, i.e. the derivative dP_r/df of the matching slope. This signal is a perfect tuning indicator with a zero crossing right in the tuning optimum.

This algorithm automatically pulls the fundamental frequency downhill the matching slope to the minimum where the missing gradient prevents generation of almost any AM. With sufficient FM deviation a tone at twice the modulation frequency may be observed but this is cancelled at the second phase-sensitive demodulation in the mixer.

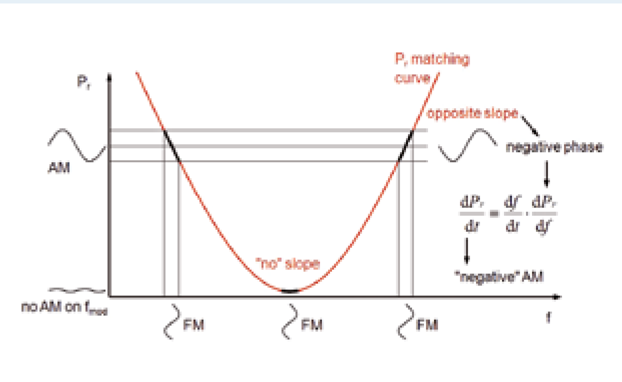

Fig. 1: A frequency modulation results in an amplitude modulation on P_r if the matching curve is not flat. The double-demodulated AM represents a signal whose strength and sign represent the derivative of the P_r matching slope (straight inclined line).

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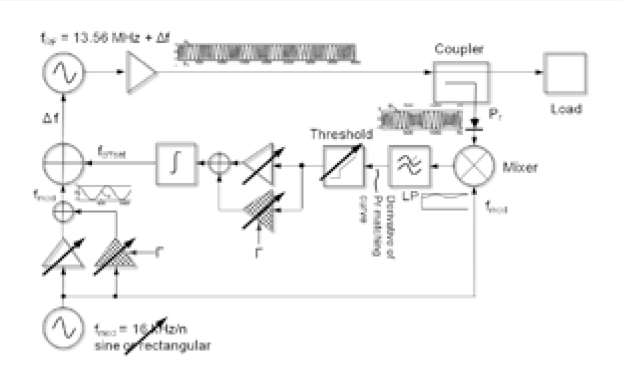

Fig. 2: Frequency modulation of 13.56 MHz, resulting amplitude modulation at P_r, demodulation by the detector at the P_r-port of the directional coupler. The main oscillator (upper left) has a frequency control input from the bottom. Downstream of the P_r detector diode a mixer is used to demodulate the "tone" to get a value for the derivative (inclination) of the matching slope. An integral control unit adds up this error voltage and then acts as f_{offset} on the same frequency control input as the modulation f_{mod}. The main tuning parameters are (each Γ-dependent [checkered] and Γ-independent [blank]) deviation and loop gain. An optional threshold and the control of the modulation frequency complete the settings. The modulation frequency and waveform may be adjusted to meet special purposes.

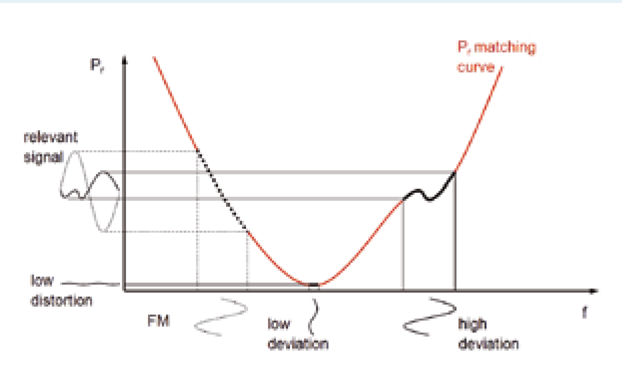

Fig. 3: A Γ-dependent frequency modulation deviation prevents the tuning to be trapped at local minima while at the optimal position only residual modulation remains.

Implementation

Figure 2 shows the complete functional block diagram. Modulation and the double demodulation may be implemented in software or hardware or any mixture thereof. It may be favourable to use dedicated hardware for the first AM demodulation, e.g. a rectifying diode or an amplitude detector as long as there is no direct sampling of the RF (or IF) waveform. The mixer of the second AM demodulation only processes the lower modulation frequency and may easily be realized in software as well as the following control path. Generating a frequency modulation is easy with oscillators that have a frequency control input, e.g. voltage controlled oscillators; a more sophisticated way is to use a direct digital synthesizer module (DDS) and control the frequency digitally.

How to control? Reflection-dependent parameters

It is desirable to initially have a large FM deviation while at the tuned-in position the deviation should be small to prevent influence of the modulation to the matchbox or the process. A Γ (reflection)-dependent modulation parameter solves this problem; the rather wide modulation range at high Γ assures a pull even at elevated plateaus and at local minima en route while at the final position only a residual FM warrants an always correct frequency. Likewise the loop gain may be Γ-dependent to speed up the tuning process in the initial phase while constituting a smooth and quiet behavior at and near the optimal frequency as indicated in Figure 3. Both parameters, deviation and gain, also retain a Γ-independent part.

Results

The algorithm has proven to be fast in initial tuning, stable during operation and smooth. The example in Figure 4 illustrates how the f-tuning process can compensate a mistuned C_L capacitor (C_T is held at optimal position).
The actual tuning speed depends of the P_r matching slope, on deviation and gain settings and on the modulation frequency, i.e. how fast the inclination of the matching curve can be obtained:

$$\text{Speed} = (\text{Gain} + \Gamma \cdot \text{RelGain}) \cdot (\text{Modulation} + \Gamma \cdot \text{RelModulation}) \cdot \text{Slope} \cdot f_{mod}$$

Even with low modulation frequencies of a few 10 kHz tuning times of far less than 1 ms (13.56 MHz ±5 %) can be obtained.

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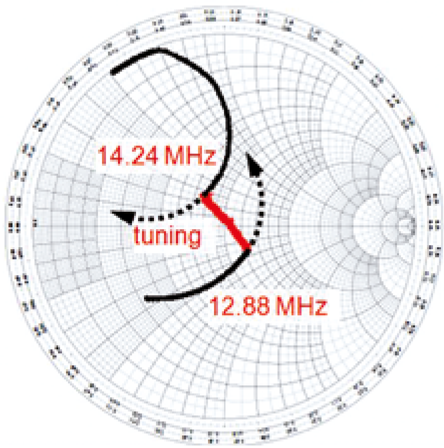

Fig. 4: The C_L capacitor of a matchbox attached to a plasma process is manually tuned end to end and back. In the extreme capacitor ranges the AFT hits the frequency limits but still reduces the reflected power compared to the center frequency of 13.56 MHz (circle segments). In a wide capacitor span the frequency tuning almost compensates the incorrect C_L position (center line).

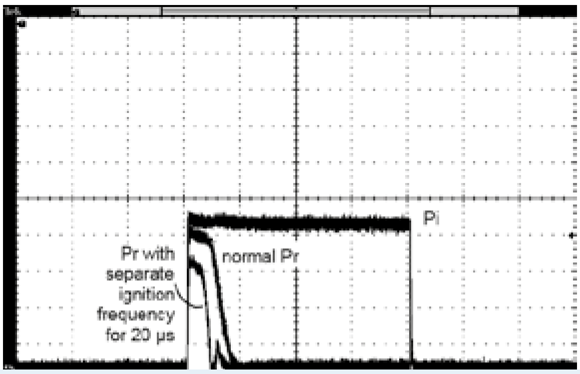

Fig. 5: An ignition frequency 300 kHz higher than the achieved optimum matching frequency was set for 20 µs to sped up plasma ignition of the 160 µs wide pulse.

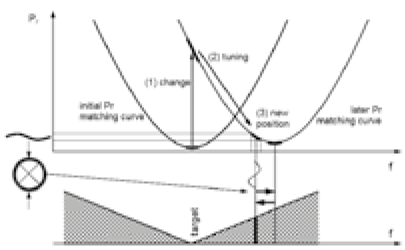

Fig. 6: Upon a process change match is lost (1) and regained by frequency tuning (2). However, the new frequency will not be in the minimum of the new matching curve. A superimposed intentional adjustment voltage ("bowl", shaded curve) pulls the new frequency slightly towards the set target frequency until this adjustment voltage and the tuning error signal are in equilibrium.

In pulsed operation the AFT suspends operation during the pulse pauses. The FM changes the output frequency during pulse-on time. If pulses are shorter than one modulation period it takes several pulses for a full period. If pulses are longer, the modulation proceeds as long as possible. The tuning speed is directly multiplied with the duty factor.

Additional features

The ignition period of pulses may result in incorrect tuning information due to high P_r values. An adjustable tuning delay time relative to the rising pulse edge prevents such incorrect data.
Plasma ignition requires a high voltage peaking rather than a perfect match to the dark plasma chamber. This peaking may require a differ-ent frequency than the later on desired match during processing. To ease reignition in pulse mode operation it may be advantegous to deliberately set such an ignition frequency at the beginning of each pulse for a defined time before resuming the tuning operation for best match. Separate frequency and timing registers allow for such operation that can significantly speed up ignition time and also reduce reflected power during the initial phase of each pulse. The effect is shown in Figure 5.

Although auto frequency tuning is a favorable way to react quickly to plasma process changes, it only covers a limited range of one dimension in the two-dimentional reactance domain of the system. Thus a conventional matchbox might be necessary as well. If the automatic matchbox also tries to find an optimal setting of its reactances the independent and concurrent actions of the two tuning systems, namely matchbox and frequency, may lead to an interdependent build up of settings and thus may end at either a frequency limit or a capacitor setting limit. In order to prevent such a self-excitation the new AFT algorithm has the option to perform an imperfect match always having a tendency of pulling the frequency back to a predefined target. This "detuning on purpose" always gives the matchbox a stimulus to also act into the correct direction. The frequency offset algorithm is virtually superimposed by a "bowl" function (Figure 6).

Conclusion

The presented concurrent rather than consecutive algorithm for automatic frequency tuning based on frequency modulation enables optimal and fast matching of the RF power generator to the plasma process. The principal control is self-reliant by adjusting the parameters according to the observed reflected power. Delayed tuning and choice of a separate ignition frequency allow for easy pulse mode operation. The pullback feature enables an easy and unconcerned parallel operation of an automatic matchbox as a second independent tuning system.

Literature

[1] C. Bock, M. Glück, F. Maier, WO2012/142998, Method for impedance matching and high frequency power supply. Priority April 18, 2011.

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