MTEnergy technology – a key enabler for advanced measurement and control features in diverse RF/MW energy applications

Introduction

The advent of high-power solid-state RF/MW generators has revolutionized RF/MW energy applications, allowing for functionalities and performance levels previously unattainable with traditional RF energy technologies.

MTEnergy technology represents next evolutionary step in solid-state RF/MW energy systems, enriching the features and enhancing performance offered by these systems.

This paper aims to introduce MTEnergy technology and is organized into three parts:

Part 1: Overview of the current Solid state RF/MW energy systems- provides a brief overview of the existing architectures, compares their capabilities, and identifies functionality and performance gaps.

Part 2: Introduction to the MTEnergy technology – explains the fundamental principles of MTEnergy technology and explores implementation options.

Part 3: MTEnergy technology application examples - showcases a few RF/MW energy architectures, generators, and applications that stand to benefit from the integration of MTEnergy technology.

Part 1 - RF/MW Energy systems

1.1 Solid state RF/MW energy systems

The solid-state generators potentially offer numerous performance advantages to various RF/MW energy applications:

- accurate and agile control of all parameters of the deployed RF/MW power (frequency, phase, power level and timing)
- flexible control of important system parameters (i.e. EM field distribution in the applicator)
- reliability, lifetime, ease of use (supply voltage, EMC, etc.)
- power scalability (i.e. combining the signals from multiple power sources directly in the applicator, as shown in Fig.1., or in front of it)

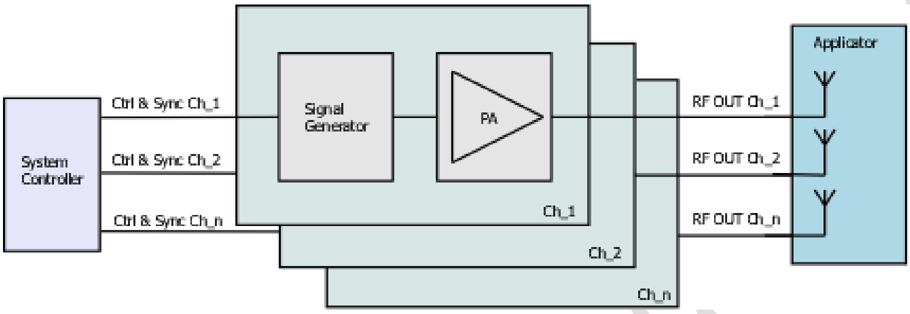

Figure.1. Simplified block diagram of a multi-channel RF energy system

The solid-state generators' capabilities enable a range of architectural options for the design of the RF/MW energy application. These options can be classifies based on several functional criteria:

- number of independently controlled RF sources
- multi- or single- frequency operation, including coherency
- open or closed loop control techniques
- CW and pulse operation
- different RF power control approaches based on: supply voltage, RF gain or time
- methods for accommodating the varying load conditions (frequency tracking vs. impedance tuning)

Let's delve into the reasoning behind these criteria.

The system can comprise of one or more channels, which independently deploy the RF energy in the application. The characteristics (frequency, phase, power, etc.) of the energy, provided by the individual channels, can be identical or diverse. For example, different channels might deliver energy at different frequencies, a scenario useful for profiling the cross-section of the thermal effect in bulk materials undergoing dielectric heating. Conversely, if multiple channels operate coherently at the same frequency, controlling the relative phases and amplitudes, offers a method for shaping the electromagnetic field throughout the applicator's volume.

The control of the signal parameters (power and phase) can be implemented based on feedback signals, sampled in the applicator or in other system's building blocks, and operate in a closed loop. Alternatively, control algorithms can be based on data obtained from prior characterization (calibration) of the system's components, without relying on feedback signals.

The applied average RF power can be controlled by adjusting the amplitude of the generated RF signal: by changing the gain of the generator's RF lineup, or by altering the supply voltage of the RF power amplifier. Alternatively, the control algorithm can change the time during which the generated power is delivered to the application—this could be achieved, for instance, applying pulse-width modulation scheme.

In certain applications, the flexibility of adjusting the frequency of the solid-state generators proves valuable for adapting the system's performance to the changing load conditions during the process execution. This approach can either supplement or bypass the dynamic impedance tuning utilizing variable matching networks.

The architectural options can be combined in numerous ways, resulting in a considerable array of potential system designs, and any attempt for systematic categorization and analysis of their features appears to be deficient.

Appendix 1. presents a comparison of the features of few architectural options, derived from the combinations of a limited set of system properties: the number of RF channels, the number of used frequencies and coherency, and the type of parameter's control. It also outlines additional HW and control requirements, imposed by the targeted functionality. For simplicity, the summary does not consider "mixed" architectures, i.e. where the power control scheme is implemented simultaneously in the amplitude- and in the time-domains.

The summary illustrates that the highly customizable solid-state system architectures offer a sufficient number of options to achieve the desired performance versus cost ratio.

It also suggests, that the most compelling architectures support coherent channel operation and closed-loop amplitude and phase control. Similar architectures require more complex HW and control provisions. The following section will demonstrate an example of a similar architecture.

1.2 RF/MW energy SS generator for coherent applications

Fig. 2. illustrates a simplified block diagram of a minimal RF architecture of an RF generator designed for operation in coherent, multichannel systems. The architecture contains only four active RF components: VCO/PLL, DCA and PA in the transmitter path, and IQ demodulator in the receiver path.

The RF signal is generated by a PLL, which is synchronized with an externally generated low-frequency reference signal – denoted as Fref. To ensure phase coherence, this signal needs to be distributed to all RF generators within the energy system. Effective phase control demands specific PLL functions related to phase adjustment and synchronization. These functions ensure that RF signals are generated with adjustable phase during operation, and eventually, possess a predictable initial phase upon resetting. Typically, these functions are realized through additional frequency dividers and control registers incorporated into more advanced PLL/VCO ICs.

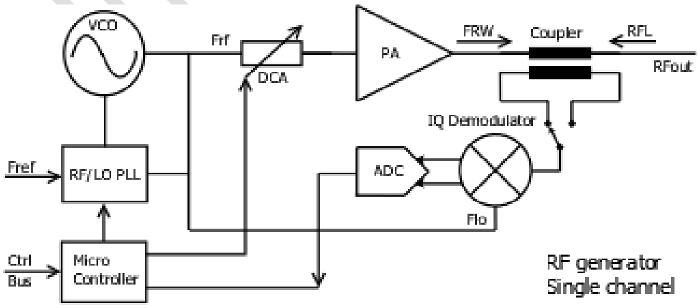

Figure 2. An example of a single channel RF generator, providing closed-loop phase and amplitude control

The amplitude of the generated RF signal – F_{RF}, which is controlled with a high-resolution, digitally controlled attenuator – DCA, is subsequently amplified by the power amplifier.

At the output of the generator, a directional coupler samples both the incident (FRW) and reflected (RFL) signals, which are used in the closed-loops, controlling the amplitude and the phase of the generated RF signal. The sampled signals are down-converted (one at a time) by an IQ demodulator to DC IQ signals, which are quantized by a dual channel ADC. Using the IQ signals , the microcontroller calculates the phase and the amplitude of the analyzed signal and applies them in the control algorithms.

Figure 3. AT5g8Gen200 5.8GHz generator

Despite having some performance limitations, such as step-wise power control, this relatively straightforward generator architecture is able to fulfill the primary requirements set by a significant portion of multi-channel, coherent RF energy systems.

For instance, AndivaTech's AT5g8Gen200 5.8GHz generator, shown on Fig.3. is based on the same architecture (the phase measurements being an optional feature).

1.3 Functionality and performance gaps in the state-of-art architectures

Certainly, the RF energy applications don't necessitate the level of precision and reliability akin to the "James Webb telescope." Nevertheless, many applications do require a significant performance level. In numerous instances, heightened requirements revolve around the precision of the control algorithms and the supporting measurement functions. These demands often surpass what the existing state-of-the-art architectures and measurement techniques can adequately address.

For instance, Fig. 4. depicts a 2-channel energy system, in which both channels concurrently contribute power to an applicator, where significant cross-talk between the channels takes place.

The RFLx signals, sampled in the output branch of the couplers, contain the combination of the reflected signals (RFLx) and the signals (Sx_Rx), propagated between the channels in the applicator. When coherent channels operate simultaneously, the sampled signals become ambiguous and unsuitable for use in the control algorithms.

For example, if the parameters of the processed in the applicator object change during operation, it wouldn't be possible, without interrupting the executed process, to determine whether Sx_Rx change is due to the change of the applicator's reflection or transmission coefficients.

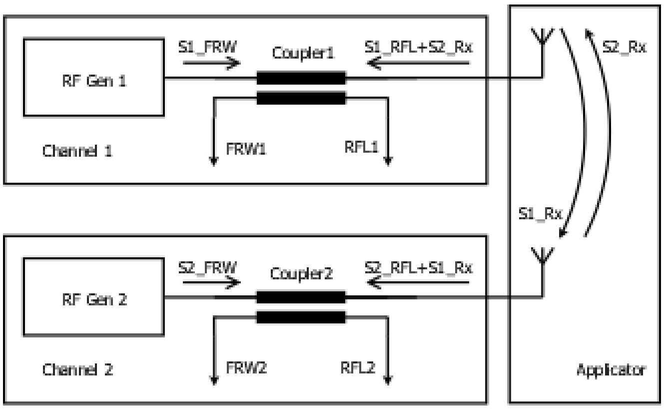

Figure 4. A 2-channel energy system with inter-channels crosstalk

As a result, the existing architectures for multi-channel coherent RF energy generators are able to detect gross changes occurring in the executed process, but lack the ability to pinpoint, in real time and without process interruptions, the exact source of the detected alternation, or decide on appropriate corrective measures. This deficiency stems from the fact that the applied measurement techniques can only quantify the parameters of the combined RF signal and not the contributions of the individual channels in it.

The subsequent section introduces MTEnergy technology, developed to address these measurement deficiencies. It provides opportunities for implementing advanced measurement and control features, such as in-process characterization of the applicator's parameters and closed-loop control of the EM field distribution to maintain or avoid local hotspots.

Part 2 - MTEnergy technology

The patent pending MTEnergy (Multi-Tone Energy) technology, developed by AndivaTech B.V, enables the measurement of the parameters of the individual RF signals, contributed by the RF sources in the multi-channel system. The analyzed signals can be sampled in any chosen point of the application. Importantly, the technology introduces no or minimal disturbances in the system's operation and performance.

The foundation of MTEnergy technology lies in the utilization of multi-tone RF signals. This approach enables a clear and unambiguous identification, as well as in-process measurement of the parameters of the analyzed signal, even in the presence of other coherent signals.

2.1 MTEnergy technology in brief

The multi-tone signals consist of a large-signal tone (S_{LS}), and several small-signal ones (S_{SS}). The high power tone - S_{LS}, generated at the common for the system F_{RF}, is phase coherent with the large-signal tones* of the other RF channels. The small-signal tones are generated on unique and channel-specific frequencies, and their parameters (both phase and amplitude) are correlated to the parameters of S_{LS}.

*NOTE: In reality, many applications do not require (and, in certain cases, it might even be undesirable) to utilize multi-tone signals simultaneously across multiple RF channels. Channels not currently under analysis can generate CW signals, which, naturally, should remain phase coherent with the large-signal tone (S_{LS}) of the channels currently being analyzed.

MTEnergy technology capitalizes on three crucial properties of the multi-tone signals:

- The S_{LS} tone in the measured multi-tone signal maintains coherence with the other RF signals employed. It carries almost all of the RF energy generated by the analyzed channel, contributing as planned, and working in tandem with the coherent signals from other channels.
- Based on their unique frequencies, the S_{SS} tones, belonging to the analyzed multi-tone signal, can be unambiguously discriminated and measured.
- The parameters of the sampled S_{LS} tone, which are of interest in the control algorithms, can be computed from the already measured parameters of the S_{SS} tones, using the relations, describing the correlation between the parameters of S_{LS} and S_{SS}.

2.2 MTEnergy technology – foundation

2.2.1 Generation of the multi-tone signals

The RF multi-tone signals (S_{MT}) can be generated in multiple types and ways. When selecting the type, an essential consideration is maintaining S_{MT} integrity, especially when amplified with non-linear or saturated power amplifiers. To achieve this, it's crucial for S_{MT} to have a constant envelope. One effective technique for generating multi-tone signals is angle (phase or frequency) modulation.

The choice of modulation signals (frequency and waveform) is primarily constrained by the limitations imposed by the selected or available circuit topology. Harmonic signals may seem like an obvious choice, but other waveforms can also be suitable.

Modulation frequencies can vary from a few KHz to tens of MHz, and the specific choice should align with the intended functionality. For example, the hot S-parameter measurement technique, as discussed later, might benefit from using a higher modulation frequency. On the other hand, if the goal is to measure the parameters of the RF signals (S_{LS}) or the S-parameters of the application at F_{RF}, a lower modulation frequency should be employed.

The selection of the modulation signal's amplitude (modulation index), involves balancing two crucial requirements:

- The amplitude needs to be low enough to prevent significant spreading of the channel's power between the large-signal (SLS) and small-signal (SSS) tones. A higher modulation index could lead to combination loss when signals from multiple channels are combined in the application. Additionally, it may introduce undesired amplitude modulation to the combined signal.
- On the other hand, the amplitude should be large enough to ensure that the signal level of the analyzed S_{SS} tones is sufficient for precise measurement of their parameters.

As a general guideline: the amplitude should be < 0.1.

Considering the case of phase modulation using a harmonic signal, the multitone signal will be:

$S_{MT} = A_{RF}\cos(2\pi F_{RF}t+\phi_{RF} + S_{MOD})$ (Eq.1.),

where:

F_{RF} is the RF frequency (common for all channels),

A_{RF} and ϕ_{RF} are the amplitude and the phase of the large power signal, generated in Channel 1,

S_{MOD} is the harmonic modulation signal, used in its generation:

$S_{MOD} = A_{MOD}\cos(2\pi F_{MOD}t+\phi_{MOD}))$ (Eq.2.),

where:

A_{MOD}, F_{MOD} and ϕ_{MOD} are respectively the amplitude, the frequency and the phase of the modulation signal (multiple modulation signals can be used, as well).

Assuming small A_{MOD}, the resulting spectral components (tones) are described with Bessel functions of first kind, and their relative amplitudes are:

$cn = \frac{1}{2\pi}\int_{-\pi}^{\pi} e^{-j(\beta\sin(x)-nx)}\,dx = J_n(\beta)$ (Eq.3a.),

where:

n is the tone's integer index*

*NOTE – the applied phase modulation yields a symmetric spectrum around the carrier, thus using only the positive indexes is sufficient,

$x = 2\pi F_{MOD}t + \phi_{MOD}$ is the instant phase of the modulation signal,

$\beta = A_{MOD}$ is the modulation index,

J_n is Bessel function of first kind, n^{th} order.

The multi-tone signal components' phase is described by:

$\phi_n = \pi/2*\text{abs}(n) + \phi_{MOD}*n + \phi_{RF}$, (Eq.3b.), where:

n is the tone's integer index*,

*NOTE - the S_{LS} tones on both sides of the carrier might have different phases.

Assuming a small modulation index, the resulting phase modulated multi-tone signal will have three significant tones appearing on F_{RF} - F_{MOD}, F_{RF} and F_{RF} + F_{MOD} frequencies.

For example, if a phase modulation with the following parameters:

Example 1

$A_{RF} = 1$, $\phi_{RF} = 60^\circ$, $A_{MOD} = 0.1$ and $\phi_{MOD} = 45^\circ$ is applied, the tones' parameters will be:

S_{SS-1} (@F_{RF}-F_{MOD1}): amplitude: 0.025, phase 105°

S_{LS} (@F_{RF}): amplitude: 0.9975, phase 60°,

S_{SS-1} (@F_{RF}+F_{MOD1}): amplitude: 0.025, phase 195°.

Thus, the S_{SS} tones' level will be with about 13dB lower, then the one of S_{LS}'s one.

Since, the generation of S_{MT} could involve an IQ modulation technique, it is necessary to derive the necessary Cartesian (IQ) parameters of S_{MOD} from the parameters used in Eq.2.

Substituting in Eq.1. S_{MOD} with Eq.2., and IQ demodulating the output with F_{RF}, provide the analytical form of the required IQ signals. The obtained results contain low- and high-frequency terms. The high frequency terms of both signals cancel each other in the IQ modulation process, thus only the low-frequency terms shall be considered:

$$I_{MOD} = \cos(S_{MOD}) \qquad \text{(Eq.4a.),}$$

$$Q_{MOD} = \sin(S_{MOD}) \qquad \text{(Eq.4b.),}$$

After expanding the Eq.4a. and Eq.4b. in Taylor series, the IQ signals can be presented In a form, which is more convenient for their generations with an IQ DAC:

$$I_{MOD} = 1 - S_{MOD}^2/2! + S_{MOD}^4/4! - S_{MOD}^8/8! ... \qquad \text{(Eq.5a.),}$$

$$Q_{MOD} = S_{MOD} - S_{MOD}^3/3! + S_{MOD}^5/5! + ... \qquad \text{(Eq.5b.),}$$

Since S_{MOD} amplitude (A_{MOD}) is low, the terms containing S_{MOD} on a power higher than 2 could be neglected in most of the applications.

Note: Not surprisingly, generating the Cartesian signals requires DAC's with higher sampling rate, then generating the original S_{MOD}.

The parameters of the multi-tone signal will change, as they propagate in the system, however the ratio between the values of the S_{LS} and the S_{SS} will remain constant (providing low F_{MOD} is used), and, once the parameters of any of the S_{SS} tones are measured, the S_{LS} parameters can be calculated, as discussed in the following paragraph.

Estimating the parameters of the sampled small-signal tones

As mentioned earlier, a sample of any arbitrary RF multi-tone signal (S_{MT}) taken from the RF energy system—whether from directional couplers in the RF channels or by dedicated probes in the applicator—can be unmistakably identified and analyzed.

The processing of the sampled signals involves the application of techniques and architectures commonly used in RF communication receivers. Depending on the RF frequency used in the application, the processing can be implemented either entirely or partially in the analog and/or digital domains. For instance, in the HF ISM bands, the analyzed S_{MT} could be directly digitized using high sample rate Analog-to-Digital Converters (ADCs), while in the higher RF and MW bands, it is typically first converted down to a baseband and then digitized. The latter approach is more general, and its digital signal processing (DSP) part closely resembles the entirely digital approach. Therefore, it will be in the main focus of further discussions.

As illustrated in Fig 5, it is convenient (though not mandatory) to use an IQ demodulator in the down-conversion process. A zero- IF demodulation (F_{LO} equal to F_{RF}) is the preferred technique in applications using low frequency modulation (F_{MOD}). However, in cases where high F_{MOD} is applied - such as in hot S-parameter measurement, where F_{MOD} could be in the range of tens of megahertz - it might be more convenient to use F_{LO} close to $F_{RF} \pm F_{MOD}$. The architecture of the receiver path shown in Fig. 5 is capable of operating in both modes, as the LO signal is provided by dedicated PLL/VCO circuitry.

The IQ baseband signals also include the down-converted S_{SS}, which, in the case of zero-IF conversion, are present at frequencies $\pm F_{MOD}$. Various DSP techniques can be employed to estimate the parameters of the analyzed S_{SS}. One approach is to use a Complex Fast Fourier Transform (CFFT) algorithm, which outputs the complex parameters (amplitude and phase) of all present small-signal tones in their respective bins. The zero bin contains the parameters of the combined large-signal tones, which might serve some specific purposes, such as verifying whether the level of the combined signal aligns with the applied settings.

Alternatively, if a (digital) IQ demodulation with F_{MOD} is applied, less DSP resources are needed. In this case, only the parameters of S_{SS} located at the F_{MOD} frequency are estimated.

The subsequent step involves utilizing the estimated S_{SS} parameters to derive the parameters of the Large-Signal Tones (S_{LS}) and to calculate the applicator's S-parameters.

2.2.2 Deriving the parameters of the S_{LS} tones

Utilizing the correlation relationships between the parameters of S_{LS} and S_{SS}, calculated using the identities from Eq. 3a and Eq. 3b, makes it straightforward to derive the parameters of the analyzed S_{LS} from the previously estimated S_{SS} parameters:

$$A_{LS} = A_{SS} * C_{LS} / C_{SS} \qquad \text{(Eq.6a.),}$$

$$\phi_{LS} = \phi_{SS} - \pi/2 - \phi_{MOD} \qquad \text{(Eq.6b.),}$$

where:

A_{SS} and ϕ_{SS} are the S_{SS} values measured at $F_{RF} + F_{MOD}$ frequency.

2.2.3 Calculating applicator’s S-parameters

The calculation of the S-parameters will be exemplified using the 2-channel system shown on Fig.4.

The directional coupler in Channel1 (coupling factor C_{PL}) samples 2 signals:

- $FRW1 = C_{PL} * S1\_FRW$ in the forward path,
- $RFL1 = C_{PL} * (S1\_RFL + S2\_Rx)$ in the reflected path.

Assuming the RF multi-tone signals S_{MT1} and S_{MT2} are generated using respectively (A_{LP1} ϕ_1, A_{MOD1}, F_{MOD1}) and (A_{LP2} ϕ_2, A_{MOD2}, F_{MOD2}), the sampled signals can be written in the following form:

$FRW1 = C_{PL} * A_{RF1}\cos[2\pi F_{RF}t+\phi_1 + A_{MOD1}\cos(2\pi F_{MOD1}t)] * G_1$ (Eq.7a.),

$RFL1 = C_{PL} * (S1\_RFL + S2\_Rx) = C_{PL} * \{A_{RF1}\cos[2\pi F_{RF}t+\phi_1 + A_{MOD1}\cos(2\pi F_{MOD1}t)] * G_1 * S_{11} + A_{RF2}\cos[2\pi F_{RF}t+\phi_2 + A_{MOD2}\cos(2\pi F_{MOD2}t)] * G_2 * S_{12}\}$ (Eq.7b.),

where G_1 and G_2 are the (complex) gains of the power amplifiers in the respective channels.

The term of Eq.7a. and the two terms of Eq.7b. are multi-tone signals. After downmixing and demodulating both signals (FRW1 and RFL1) with F_{MOD1}, the complex parameters of the forward and reflected small-signal tones can be measured - S_{SS1_FRW} from FRW1, and S_{SS1_RFL} from the first term of RFL1. Since the second term of RFL1 doesn't have a small-signal tone on F_{MOD1}, it will contribute nothing in the demodulation result. The measured values of S_{SS1_FRW} and S_{SS1_RFL} can be presented as:

$S_{SS1\_FRW} = A_{SS1\_FRW} * e^{j\phi SS1\_FRW}$, (Eq.8a.),

$S_{SS1\_RFL} = A_{SS1\_RFL} * e^{j\phi SS1\_RFL}$, (Eq.8b.),

and, the applicator's reflection coefficient, seen from output of Channel1 is:

$S_{11} = S_{SS1\_RFL} / S_{SS1\_FRW} = (A_{SS1\_RFL} / A_{SS1\_FRW}) * e^{j(\phi SS1_{RFL} - \phi SS1_{FRW})}$ (Eq.9.),

In a similar way, if one downmixes and demodulates the sampled S1_RFL and S2_FRW with F_{MOD2}, the parameters of L_{SS2_Rx} and L_{SS2_FRW} small-signal tones can be measured, and S_{12} calculated as:

$S_{12} = S_{SS2\_Rx} / S_{SS2\_FRW} = (A_{SS2\_Rx} / A_{SS2\_FRW}) * e^{j(\phi SS2_{Rx} - \phi SS2_{FRW})}$ (Eq.10.),

It is worth to emphasis, that there is no need to generate MT signals simultaneously in both channels. For instance, when the small-signal tones originating from Channel1 are analyzed, Channel2 can generate CW signal.

Another important point is, that the system can use one modulation frequency to generate MT signals in all channels, providing that only one channel generates a multi-tone signal a time. This observation is of a large significance for designing cost-effective generators and systems using MTEnergy technology.

2.3 MTEnergy technology implementation

As mentioned previously, MT signals can be generated and processed using various techniques. The following paragraphs will present two options for generating MT signals, accompanied by a discussion of a few practical aspects of implementing MTEnergy technology.

2.3.1 Generation of MT signal in the HF or VHF frequency bands

Fig. 5. depicts an RF/MW generator architecture employing MTEnergy technology within the framework of a 2-channel energy system. This architecture employs phase modulation using a Direct Digital Synthesis (DDS)/pattern generator device. The HF multi-tone (S_{MT}) signal is generated at frequencies up to a few tens of megahertz.

In the scenario where this architecture is applied in an HF ISM band generator (with frequencies up to 40 MHz), the DDS can directly synthesize the output RF signal, rendering the PLL/VCO blocks shown in Fig. 5. redundant. Consequently, the RF MT signal is directly synthesized from a waveform computed with Eq. 1.

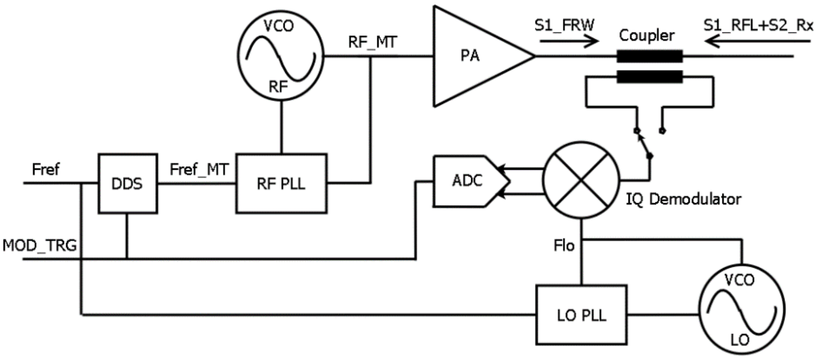

Figure 5. Block diagram of MTEnergy generator architecture with DDS/pattern generator

In the more general scenario where the generator operates at higher RF frequencies, the output RF signal is generated by PLL/VCO device. In this case, the DDS supplies the PLL with a low-frequency reference signal, which is a multi-tone signal (S_{RF_MT}) as per Eq. 1. The frequency of the F_{REF_MT} may or may not be equal to the F_{REF} frequency. The description of the output multi-tone signal is as follows:

$$S_{RF\_MT} = A_{RF\_MT}\cos(S_{MT\_REF} * N + \phi_{RF}) = A_{RF\_MT}\cos[(2\pi F_{RFF\_MT}t + S_{MOD}) * N + \phi_{RF}] =$$
$$= A_{RF\_MT}\cos\{[2\pi F_{RFF\_MT}t + A_{MOD}\cos(2\pi F_{MOD}t + \phi_{MOD})] * N + \phi_{RF}\} \qquad \text{(Eq.11.)},$$

Where: N is the frequency divider ration in PLL's feedback path – F_{RF}/F_{REF} (assuming no frequency dividers or multipliers are used in PLL's reference path).

From Eq.11. is evident that S_{RF_MT} tones - S_{LS} and S_{SS}, remain spaced with F_{MOD}, albeit with a large modulation index, denoted as $A_{MOD} * N$. To achieve the same amplitude ratio between the generated S_{LS} and S_{SS}, as determined with Eq.1. and Eq.3a., A_{MOD} in Eq.11. should be divided with a factor of N.

An important consideration in this architecture is the need to keep F_{MOD} within the bandwidth of the PLL, in order to preserve the modulation's integrity. The PLL's bandwidth is typically chosen within the range of one or a few hundred KHz.

This implementation offers a significant potential for cost optimization. A single S_{REF_MT} signal can be generated and used across the whole RF energy system. S_{REF_MT} can be "easily" distributed amongst the RF channels of the system, together with the CW F_{REF} and the modulation trigger signal - MOD_{TRIG}. In this scenario, the RF generators in the remaining RF channels, aside from the one generating the S_{MT_REF} signal, will resemble the conventional generator architecture shown in Fig. 2. An additional component needed in those generators is a multiplexer, which selects the low-frequency reference signal to be used (S_{MT_REF} or F_{REF}), depending on whether or not the MT RF signal of that channel is currently measured.

2.3.2 Generation of RF MT signal

As previously detailed, the RF IQ modulation technique provides an alternative for generating RF MT signals, as illustrated in Fig. 6.

The MT modulation waveform is generated using an IQ DAC according to Eq. 5a and Eq. 5b. The RF_MT signal is obtained by modulating the RF Carrier (RF_CW) with the IQ waveforms. The RF_CW signal, generated by PLL and VCO, also serves as a LO signal for the IQ demodulator.

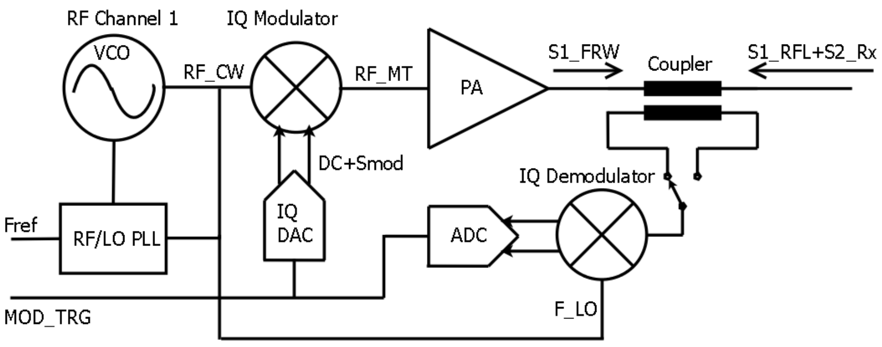

Figure 6. Block diagram of MTEnergy generator architecture with IQ modulator

Particular features of this approach:

- It allows a fast and easy switching between the generation of CW or MT RF signal - if the IQ DAC outputs only DC voltages, the RF_MT signal will turn into a CW one.
- No strict frequency limitations on the used IQ waveforms (F_{MOD}). The possibility to use higher frequencies is useful in implementing the hot S-parameter measurement technique.
- In the particular implementation, shown on Fig.6, the analyzed RF S_{MT} signals are mixed down to zero_IF baseband ($F_{LO} = F_{RF}$). When the technology is used for realizing hot S-parameter technique, an F_{LO} closer to the frequency of analyzed S_{SS} ($F_{RF} \pm F_{MOD}$), could be desirable in order to reduce the bandwidth of the analyzed baseband signal. In that case a dedicated PLL/VCO would be required to generate the required F_{LO} signal.

2.3.3 Practical aspects of MTEnergy technology implementation

While the MTEnergy technology is designed to minimize adverse impacts on processes within the RF energy system, several application aspects must be considered to further mitigate potential effects.

Critical factors are the number of MT signals employed in the system and their time of deployment.

As previously discussed, individual MT signals possess a constant envelope. However, the summation of multiple MT signals, generated with coherent carriers and varying modulation frequencies, results in an undesired amplitude modulation.

Assuming equal amplitude (A_{RF}, Eq. 1) and modulation index (A_{MOD}, Eq. 2) for all S_{MT} signals, the amplitude of the resulting AM modulation can be calculated using:

$$A_{AM} = \frac{n}{N} * \left[1 - \cos\left(\frac{Amod}{2*\pi}\right)\right] \qquad \text{(Eq.12.),}$$

where:

N is the number of active channels, n of which generate S_{MT} signals.

Therefore, in order to maintain A_{AM} small*, preferably A_{MOD} should be below 0.1, and only one or few channels should use S_{MT} signals (if A_{MOD} <0.1, the maximal A_{AM} is minor anyway ~ 0.5%).

In certain scenarios, the processes being executed may demand rapid measurement and control of the regulated RF signals. To minimize measurement time, such cases might necessitate the use of higher modulation index (A_{MOD}) to ensure a high Signal-to-Noise (S/N) ratio of the analyzed S_{SS} and simultaneous analysis of multiple MT signals. A solution in this context could involve employing the S_{MT} signals in short bursts while generating CW RF signals for the majority of the time.

Appendix 2. depicts spectrograms of MT signals, generated by a two channel 5.8 GHz demonstrator. The demonstrator's MW generators are based on the architecture shown on Fig. 5.

Part 3 - MTEnergy technology application examples

This section highlights the advantages offered by the MTEnergy technology in number of RF/MW energy applications.

3.1 MTEnergy technology in high-power RF/MW generators

A notable example of MTEnergy technology's potential lies in the optimization options it enables in the high power generator architectures, resulting in cost and performance benefits.

Different application require RF power level, provided from a single generator, exceeding the capabilities of the available RF power devices. To fulfill these requirements, the generator must combine the signals of few RF line-ups, as shown on Fig.7.

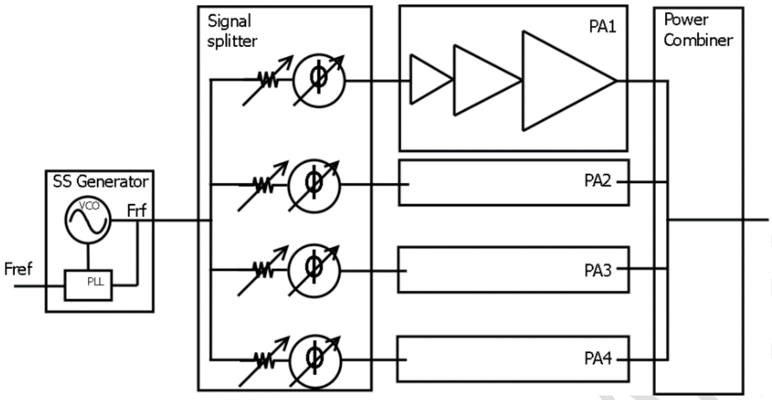

Figure 7. Block diagram of a 4-channels, high power solid-state RF generator

RF line-ups, particularly in the higher microwave bands such as S and C, tend to experience significant parameters spread. This variability can lead to substantial combination losses, introducing numerous complications in the system. State-of-the-art architectures address this issue through measures like amplitude and phase compensation implemented in the signal splitter. These measures aim to equalize the amplitudes and phases of the signals outputted by the channels, thereby mitigating the occurring combination loss. However, the effectiveness of this approach heavily relies on extensive calibration efforts. Parameters of the splitter, PAs, and power combiner need to be calibrated against variations in multiple domains, including frequency, power, temperature, and supply voltage. Despite the meticulous calibration process, this approach has inherent drawbacks. Calibration can only be performed at the component level, and any differences in performance that emerge upon integration into the system cannot be detected by the employed open-loop control algorithms.

To address these drawbacks, additional detectors, such as IQ demodulators, can be added to the outputs of PAs, enabling closed loop control. However, apart from the increased hardware complexity, the control loops still rely on calibration data of the power combiner—a component remaining outside the control loops. More critically, the control loops are still susceptible to parameter variations in the feedback paths, including directional couplers and IQ demodulators.

These problems are circumvented by MTEnergy technology-enabled generator architectures. Fig.8 shows one possible embodiment.

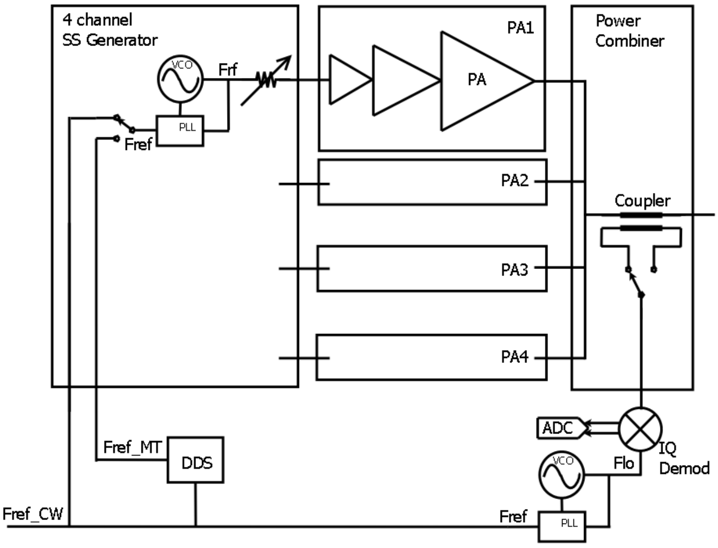

Figure 8. Block diagram of a 4-channels, MTEnergy-enabled high power solid-state RF generator

In this architecture, the single channel small-signal RF source and the signal spitter from Fig.7, are replaced with a 4 channel SS generator. The generator utilizes two low-frequency F_{REF} signals: F_{REF_CW} and F_{REF_MT}, which are multiplexed at the inputs of every PLL. F_{REF_CW} is predominantly used, while F_{REF_MT} is selected when the parameters of the respective channel are measured. The measurement device comprises of directional coupler at the generator's output, and IQ demodulator, which LO signal is supplied by a dedicated PLL/VCO. The closed-loop control algorithms, aimed at equalizing the parameters of the signals delivered by the 4 channels, require no calibration. This is because all measurement are performed by a single device and on a signal sampled in the same point. In most cases, one F_{REF_MT} signal will suffice, as there is no need to measure the signal generated by all channels simultaneously. Importantly, the amplitude and phase measurement, performed on the MT (or CW) output RF signals, can be used by the close-loop power and phase control algorithms of the complete generator.

3.2 MTEnergy technology in surfaguide MW plasma sources

A surfaguide generator comprises a waveguide applicator and a discharge tube, penetrating through the center of the applicator. The waveguide applicator has two ports. Typically, the surfaguide source is powered with MW energy provided by a magnetron generator, connected (via a directional coupler and a tuner) to one of the ports. The other port is loaded with a tunable short, which ensures, that the maximum (E-field) of the standing wave coincides with the axis of the discharge tube.

However, this configuration is not optimal for generating plasma in the entire cross-section of the discharge tube. The non-symmetric excitation confines the plasma to the portion of the tube facing the magnetron [2].

To achieve symmetric plasma excitation, it is feasible to excite the surfaguide through both ports using two coherent microwave generators. These generators would excite the maximum E-field in the center of the discharge tube. A schematic representation of a similar system is depicted in Fig. 9.

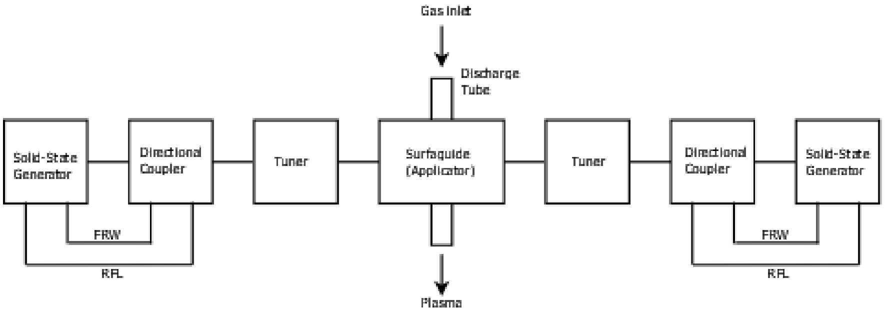

Figure 9. Surfaguide plasma sources enabled by MTEnergy technology

The FRW and RFL signals, sampled by the directional couplers, should be used by the algorithms, controlling the parameters (amplitude and phase) of the MW generators in order to optimize the applicator’s EM field distribution, and also to control the tuners.

The application of MTEnergy technology enables the simultaneous excitement of plasma with high density, and the achievement of optimal impedance matching between the surfatron and the microwave sources.

3.3 MTEnergy technology in RF/MW mediated hyperthermia applications

Fig. 10. schematically illustrates a 4-channel solid-state RF/MW energy system, applicable for localized heating of targeted cancer tissue in hyperthermia therapy. Traditionally, to achieve the intended localized heating effect, similar systems apply a predefined control scheme for managing the amplitude and phase relations between the RF power signals, delivered by the individual RF/MW sources[1].

In the illustrated example, the solid-state generators deliver their energy through four separate antennae. The parameters (amplitude and phase) of all FRW and RFL signals (these signals and the sampling couplers are not depicted in Fig. 10.) are continuously measured by one or more generators.

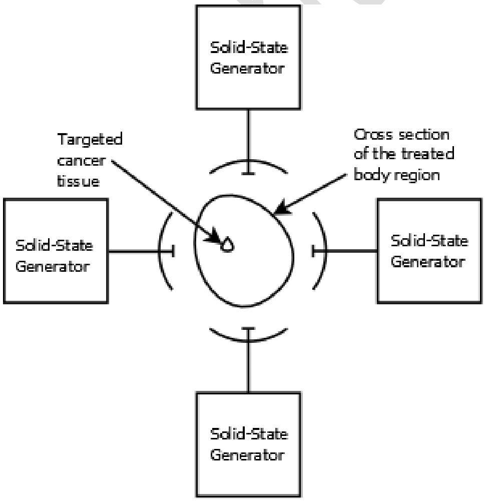

Figure 10. RF/MW hyperthermia system

MTEnergy technology offers the capability for real-time measurement of the complex parameters of the individual signals, present on each generator output, regardless whether they are incident, reflected or transmitted. The measured parameters serve as inputs for the control algorithms, allowing the calculation of the corrections, necessary to sustain the planed heating profile. Consequently, MTEnergy technology improves the efficiency of the hyperthermia therapy and provides a cost-effective solution for real-time estimation and control of:

- the spatial distribution of the EM field intensity and actually absorbed thermal energy
- the resulting hot-spot alignment with the targeted cancer tissue

3.4 MTEnergy technology as Hot S-parameters measurement technique

The preceding discussion has focused on the application of MTEnergy technology in characterizing multi-channel RF/MW applications. However, this technology is also well-suited for implementing the Hot S-parameters functionality, a valuable technique for non-invasive characterization and optimization of various RF energy applications.

For instance, certain plasma sources generate plasmas that interacts with the treated matter in the plasma active zone or its vicinity. That interaction might alter the operational conditions of the plasma source.

Traditional RF/MW generators can only measure the plasma source’s reflection coefficient at the instantaneous frequency of operation, lacking information on its frequency response. Consequently, tuning the frequency of operation for better impedance matching might lead to process disturbances.

This limitation is addressed by the Hot S-parameter measurement technique.

Fig. 11. illustrates an example of a conventional Hot S-parameters setup, applied for the characterization of a plasma-jet application. This technique employs a multi-tone signal provided by two different sources: the large-signal tone from a high-power RF energy generator and the small-signal one from a vector network analyzer. The latter sweeps the small-signal across the frequency range, in which the reflection coefficient of the plasma source is analyzed [3],[4].

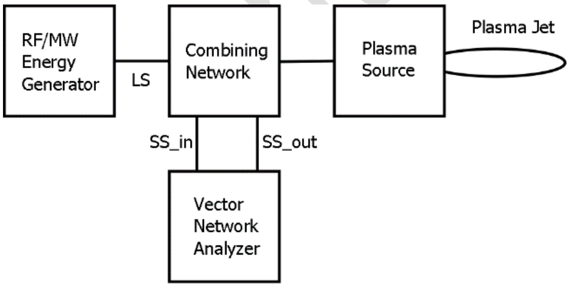

Figure 11. Conventional setup for Hot S-parameters measurements

The Hot-S parameter measurement functionality is inherent to the MTEnergy technology. Consequently, generators equipped with MTEnergy can conduct continuous and non-intrusive measurements of the plasma source input impedance and its frequency response.

The Hot-S parameter functionality involves sweeping* the F_{MOD} used to produce the MT signal). Importantly, this sweep changes only the frequencies of the small-signal tones, ensuring that the process of plasma generation remains undisturbed during the measurement of the reflection coefficient. The reflection coefficient is then calculated using the parameters of the analyzed small-signal tones on $F_{RF+}F_{MOD}$ and F_{RF}-F_{MOD} frequencies. Subsequently, if necessary, the frequency of the large-signal RF/MW tone can be tuned to the obtained optimal value.

In situations where an external tuner is utilized for impedance matching between the generator and the plasma source, the measured parameters could be employed to govern the dynamic impedance matching.

*NOTE: As discussed earlier, the IQ modulator-based architecture (Fig.6) is better suited for generating MT signals with the higher modulation frequency (up to few tens of MHz), which may be required by many of the applications using the Hot S-parameters technique.

**NOTE: The Hot S-parameters technique is applicable and useful also in systems where the MTEnergy technology is applied for different purposes, such as the surfatron plasma generator application.

Summary

The developed MTEnergy technology presents a significant innovation in the techniques, used for analysis and control of the solid-state RF/MW energy systems.

It provides a real-time, non-disruptive tool for measuring the parameters of signals, applied in coherent, multi-channel RF/MW energy systems—a feature hitherto unattainable with state-of-the-art architectures.

The technology uses multitone-signals, consisting of one large- and a few small-signal tones. These tones are generated using an appropriate technique, such as angle modulation, resulting in a constant envelop RF signal with correlated parameters of its tones.

The large-signal tone is coherent with the RF signals, delivered by other channels in the system. It carries the vast portion of the RF power, generated in the channel, and contributes to the executed process.

However, in the presence of multiple coherent signals, there is no way for explicit measurement of the RF parameters of any large-signal tone, as required by the process control algorithms governing the application. The associated small-signals tones offer an indirect solution. Because the small-signal tones are generated on unique, channel-specific frequencies, their parameters can be measured using standard frequency discrimination and signal analysis techniques. Utilizing the measured values and the correlation relations between tones of the MT signal, the parameters of every large-signal tone, present in the analyzed signal can be calculated.

Furthermore, the measured parameters of the small-signal tones provide all the necessary information to calculate the transmission and the reflection coefficients (S-parameters) to and from any port in the application.

Additionally, at no extra cost, the technology offers an efficient implementation option for the Hot-S paraments measurement technique, which proves useful in the characterization and operational phases of the RF energy applications.

Appendix 1. Solid-state RF/MW energy systems: comparison of architectures and features

Architecture					Additional HW requirements	Additional control requirements	Features	Drawbacks
Number of channel	Phase control	Phase control loop	Power control parameter	Power control loop				
Single	na	na	Amplitude	Open	na	na		No EM field control pssible, inaccurate PLC**
				Closed	Directional coupler, RF power detectors	na	Accurate PLC, load tracking***	No EM field control
			Time (i.e. by PWM)	Open	na	na	High efficiency ****	No EM field control pssible, inaccurate PLC, limited power control range
				Closed	Directional coupler, RF power detectors	na	Higher efficiency, accurate PLC, load tracking	No EM field control pssible, limited power control range
Multiple	No	na	Time (i.e. by PWM)	Open	na	Pulse synchonization	High efficiency, limited EM field control	Inaccurate PLC, limited power control range
				Closed	Directional coupler, RF power detectors		High efficiency, accurate PLC, load tracking, limited EM field control	Limited power control range
	Coherent	Open	Amplitude	Open	IQ modulator	LF or RF Reference	Complete EM field control	Inaccurate PLC and phase control
				Closed	IQ modulator, Directional coupler, RF power detectors	LF or RF Reference	Complete EM field and PL control, load tracking	Inaccurate phase control
			Time (i.e. by PWM)	Open	IQ modulator	LF or RF Reference, pulse synchonization	Complete EM field control, high efficieny	Inaccurate PLC and phase control, limited power control range
				Closed	IQ modulator, Directional coupler, RF power detectors*	LF or RF Reference, pulse synchonization	Complete PLC and EM field and PL control, load tracking	Inaccurate phase control, limited power control range
		Closed	Amplitude	Open	IQ modulator, Directional coupler	LF or RF Reference	Complete EM field control	Inaccurate PLC
				Closed	IQ modulator, Directional coupler, RF power detectors	LF or RF Reference, pulse synchonization	Complete EM field and PL control, load tracking	none
			Time (i.e. by PWM)	Open	IQ modulator, Directional coupler	LF or RF Reference	Complete EM field control, high efficiency	Complete EM field control, high efficiency
				Closed	IQ modulator, Directional coupler, RF power detectors	LF or RF Reference, pulse synchonization	Complete EM field and PL control, load tracking, high efficiency	Limited power control range

* The IQ demodulator is an excellent amplitude detector. However, it might be complicated to use it simultaneously in the power and phase control algoritms, esspecially in PWM scheme.

** Power level control

*** Load tracking means tuning of the frequency of the applied RF power for mantaining optimal load's impedance matching

**** PWM-based power control scheme allows maintaining high efficiency at lower power levels

Appendix 2. MTEnergy signals examples

The spectrograms depict the signals generated in a two channel system. CH1 generates MT signal: F_{LS}=5.801GHz, F_{MOD}=39.0625KHz. CH2 generates a CW one: F_{CW}=5.801GHz, approximately on the same power. The two signals are combined by a power combiner. The blue traces represent the spectrum of the RF MT signal, while the green traces represent the combined signal.

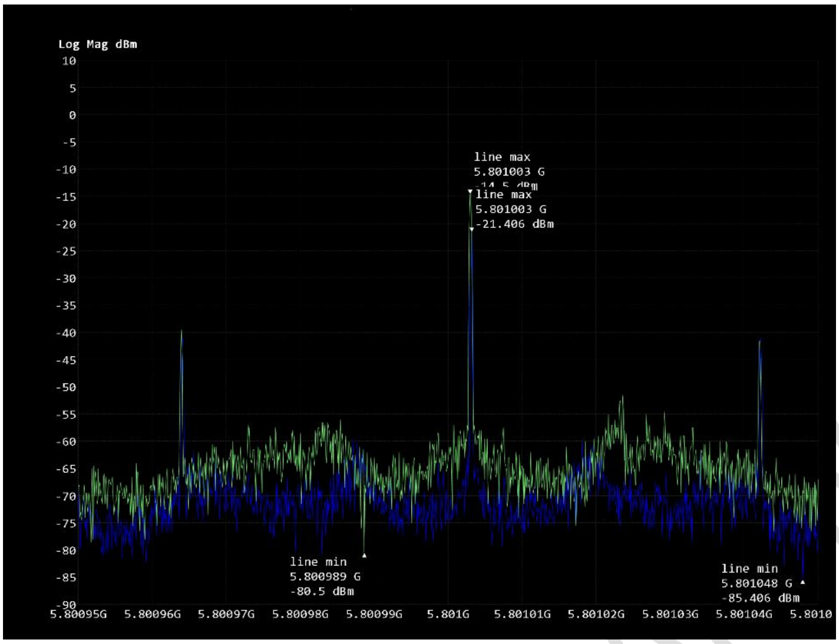

Figure 12. The CW and the L_{SS} signals are out of phase.

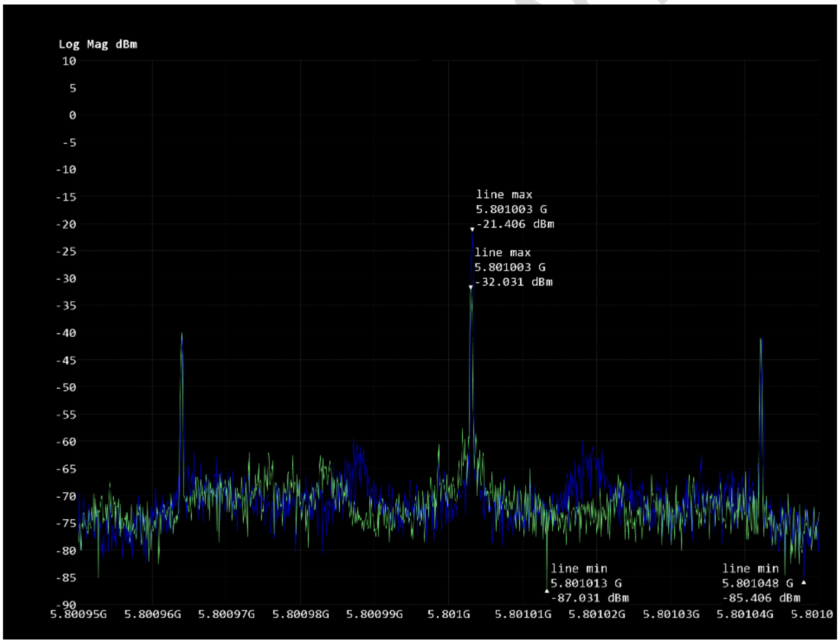

Figure 13. The CW and the L_{SS} signals are in phase.

The comparison of the two spectrograms makes evident, that the amplitude of the combined large signal exhibits significant variations. However, the amplitude (and, naturally, also the phase) of the small-signals remains constant. As a result, the parameters of the of the MT signal generated by CH1 can be measured in both scenarios.

About AndivaTech B.V.

AndivaTech is a company, specialized in the field of radio-frequency (RF) and microwave technologies, dedicated to delivering high-quality products, technologies, and services to a diverse clientele, including industrial, scientific, and business customers, engaged in the production or application of Solid-State RF/MW Energy Systems.

Our product portfolio encompasses a range of offerings, from generic, multi-market products to customized solutions tailored to specific applications.

In addition to the product offerings, AndivaTech provides various consultancy, R&D and engineering services to meet the diverse needs of our clients.

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