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## **High-Efficiency RF Power Amplifier Design Atlas** (*H2ID* Complementary Waveform Framework)

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## Executive Summary

This document presents a curated atlas of complementary intrinsic current and voltage waveforms derived across the Second-Harmonic Input Distortion (*H2ID*) design space for high-efficiency RF power amplifiers.

The atlas provides a structured mapping between the *H2ID* vector (magnitude and phase) and:

- Complementary intrinsic voltage and current waveforms
- Achievable waveform efficiency
- Conduction angle
- Associated intrinsic harmonic load impedances

This approach enables a waveform-centric design methodology, in which amplifier operation is defined directly in terms of intrinsic voltage and current waveforms, rather than predefined amplifier classes.

### Key Observations

- Efficiencies exceeding 90% are achievable for small *H2ID* magnitudes, while efficiencies up to ~87% are achievable at higher distortion levels.
- Classical Class-B and Class-F-like behaviour emerge naturally within the *H2ID* framework.
- Additional high-efficiency operating modes exist beyond classical classes, including inverse Class-F-like operation.
- Class-F-like operation is not supported in certain regions of the *H2ID* plane, where negative harmonic resistance would be required.
- Efficiency is strongly dependent on both the magnitude and phase of the *H2ID* vector.
- Certain regions of the *H2ID* design space inherently yield poor efficiency and should be avoided in practical design.
- In some regions, negative intrinsic source resistance is required, highlighting practical implementation constraints.

This document is intended for:

- RF power amplifier designers
- Microwave engineers
- Academic researchers in waveform engineering

The dataset provided can be used to augment load-pull, harmonic tuning, and waveform engineering workflows, enabling faster and more informed design decisions.

## Why This Atlas Is Valuable

Traditional RF power amplifier design relies heavily on:

- Iterative load-pull simulations
- Harmonic tuning experiments
- Trial-and-error optimization

These approaches can be time-consuming and provide limited physical insight into the underlying waveform behaviour.

This atlas introduces a fundamentally different approach:

### Waveform-First Design

Instead of searching for optimal impedances, the designer can:

1. Select a desired waveform behaviour
2. Identify the corresponding *H2ID* operating point
3. Directly calculate the required intrinsic harmonic impedances

### Key Advantages

- Reduced design time through structured pre-synthesis of solutions
- Direct mapping: *H2ID* → waveform → impedance → implementation
- Identification of high-efficiency regions and design avoidance regions
- Insight into non-classical operating modes beyond Class-B and Class-F
- Compatibility with practical limited-harmonic implementations ( $\leq 3$ rd harmonic)

This transforms amplifier design from a purely numerical process into a guided, insight-driven methodology.

## H2ID Complementary Waveform Method

The approach presented in this atlas is based on the following principles:

### 1. H2ID-Defined Current Waveform

The intrinsic output current waveform is determined uniquely by the second-harmonic input distortion (*H2ID*), characterised by its magnitude and phase.

### 2. Complementary Voltage Waveform Synthesis

A complementary intrinsic voltage waveform is synthesized such that:

- Voltage and current waveforms minimally overlap in high-power regions
- Efficiency is maximized
- Voltage and current constraints are respected

### 3. Limited Harmonic Content

Waveforms are constructed using a limited number of harmonics (DC, fundamental, 2nd, and 3rd), ensuring practical realizability.

### 4. Harmonic Impedance Calculation

For each operating point, the required intrinsic harmonic load impedances are derived:

- Fundamental impedance ( $Z_{L1}$ )
- Second-harmonic impedance ( $Z_{L2}$ )
- Third-harmonic impedance ( $Z_{L3}$ )

### 5. Harmonic-Aware Design Insight

The method reveals that:

- Small deviations from ideal harmonic terminations can significantly affect efficiency
- In some cases, non-zero or even resistive harmonic components can improve performance
- Classical amplifier classes represent only a subset of a broader design space

## Overview

Efficiency is a primary constraint in RF power amplifier design, directly affecting thermal performance, reliability, and system cost.

High efficiency requires control of:

- Fundamental-frequency load impedance
- Harmonic load impedances presented to the transistor
- Source impedance presented to the nonlinear input capacitance

In practical devices, nonlinear input capacitances generate harmonic components at the input, modifying the intrinsic input voltage waveform  $V_{1i}(t)$ .

Assuming approximately linear transconductance, the intrinsic output current waveform  $I_{2i}(t)$  follows the shape of the input voltage waveform (rectified and scaled). Changes in input waveform shape are, therefore, directly reflected in the output current, leading to different optimal load conditions.

This work focuses on Second-Harmonic Input Distortion (*H2ID*) and its role in shaping these waveforms.

Rather than defining amplifier operation through fixed harmonic terminations, this atlas adopts a waveform-centric perspective, in which:

- The intrinsic current waveform is defined by the *H2ID* vector
- A complementary voltage waveform is synthesized
- The corresponding harmonic impedances are derived

This approach reveals a rich design space in which:

- Classical Class-B and Class-F behaviour arise naturally
- Additional high-efficiency modes exist beyond classical definitions
- Certain regions require non-physical or impractical impedances
- Some regions inherently limit achievable efficiency

The dataset presented here provides a systematic exploration of this design space, enabling practical waveform-based amplifier design.

## Atlas Contents

Each *H2ID* operating point in this atlas includes:

### Waveform Data

- Normalized intrinsic voltage waveform
- Normalized intrinsic current waveform

### Performance Metrics

- Waveform efficiency
- Conduction angle

### Scaling Parameters

- $V_{dc}, V_{max}$
- $I_{dc}, I_{max}$

### Harmonic Load Requirements

- Fundamental impedance  $Z_{Li1}$
- Second-harmonic impedance  $Z_{Li2}$
- Third-harmonic impedance  $Z_{Li3}$

### Additional Design Information

- Qualitative classification (e.g., Class-F-like, inverse Class-F-like)
- Indicators of practical constraints (e.g., negative intrinsic source resistance requirements)

## Practical Use of This Atlas

The data provided in this document can be used to:

- Pre-select high-efficiency operating regions before designing a power amplifier
- Define target harmonic impedances for load-pull or matching design
- Guide waveform engineering using limited harmonic control
- Identify regions of the design space that should be avoided

The atlas is intended to complement, not replace:

- Circuit simulation
- Load-pull measurements
- Harmonic tuning

Instead, it provides structured insight that significantly reduces design iteration effort.

## Typical Workflow

1. Select some of the operating points based on the performance required, the expected behaviour with increasing second-harmonic input distortion and any constraints on the **H2ID vectors**.
2. **Scale** the voltage and current associated with each selected operating point and then scale the intrinsic load impedances accordingly.
3. Map the intrinsic impedances to the **external reference plane** (insertion point for the load matching network or the harmonic tuners used) .
4. With the required load tuners or load matching network in place, match the input of the transistor at the fundamental frequency (add resistance for stability , if required) and then tune the **external second-harmonic source impedance** to optimize the performance, or to minimize the difference between the *H2ID* vector calculated and the *H2ID* vector targeted.
5. Tune the complete circuit for optimum performance.
6. Establish the variations allowed from the optimum terminations for acceptable performance.

The current waveform should be scaled by the factor

$$I_{scale} = I_{maxT}/I_{max} \quad (1)$$

where  $I_{max}$  is the maximum of the normalized intrinsic current waveform and  $I_{maxT}$  is the current limit for the transistor (a lower value can also be targeted).

The voltage should be scaled by the factor

$$V_{scale} = V_{dc\_actual}/V_{dc} \quad (2)$$

where  $V_{dc}$  is the *dc* voltage associated with the normalized waveform and  $V_{dc\_actual}$  is the actual *dc* voltage. The maximum of the scaled voltage waveform should be within the device limits. (If not, reduce the actual *dc* voltage or select a different operating point.)

The intrinsic impedances should be scaled by

$$Z_{scale} = V_{scale}/I_{scale} \quad (3)$$

Note that *H2ID* is directly dependent on the intrinsic source impedance ( $Z_{Si}$ ) presented to the nonlinear input capacitor (Thevenin impedance).  $Z_{Si}$  depends on the external source impedance, as well as the intrinsic second-harmonic load impedance and internal feedback and loading in the transistor. The mapping of the external source

impedance to the intrinsic source impedance limits the useable *H2ID* operating points (harmonic injection could be considered to solve this).

A model of the transistor (or at least the parasitic components on the outside side of the transistor) is required to map the intrinsic load impedances to the external reference plane. In the Ampsa Amplifier Design Wizard (Ampsa ADW), a small-signal model is fitted to a set of wideband S-parameters, after which the power parameters are calculated and used for the mapping. Assuming linearity, the mapping is exact (feedback and loading included) - In practice, the correlation with harmonic-balance results is usually excellent.

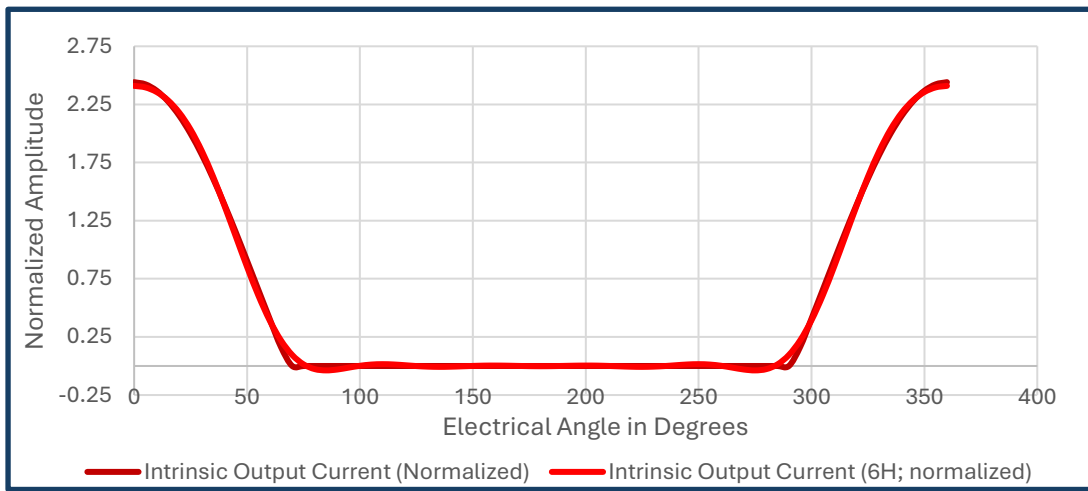
## Advanced Workflow

1. Select some of the operating points based on the performance required, the expected behaviour with increasing second-harmonic input distortion and any constraints on the **H2ID vectors**.
2. **Scale** the associated voltage and current waveform data provided in the *H2ID* dataset (Excel® files) as describe above.
3. Use the scaled data to plot the **intrinsic dynamic load line** on a rectangular plot with the *I/V*-plane boundaries (boundary lines) associated with the transistor of interest. Apply a scale factor to the voltage and current waveforms and adjust this factor until the dynamic load line is inside the constrained area.
4. The ratio of the effective voltage swing from *dc* at the point where the knee is touched by the dynamic load line and the actual *dc* voltage can be used to calculate the efficiency with the knee considered (hard clipping assumed). The waveform efficiency should be scaled by this factor.
5. Use the scale factors applied to calculate the associated intrinsic load impedances.
6. Map the intrinsic impedances to the **external reference plane**.
7. With the required load tuners or load matching network in place, match the input of the transistor at the fundamental frequency (add resistance for stability, if required) and then tune the external second-harmonic source impedance to optimize the performance, or to minimize the difference between the *H2ID* vector calculated and the *H2ID* vector targeted.
8. Tune the circuit for optimum performance.
9. Establish the variations allowed from the optimum terminations for acceptable performance.

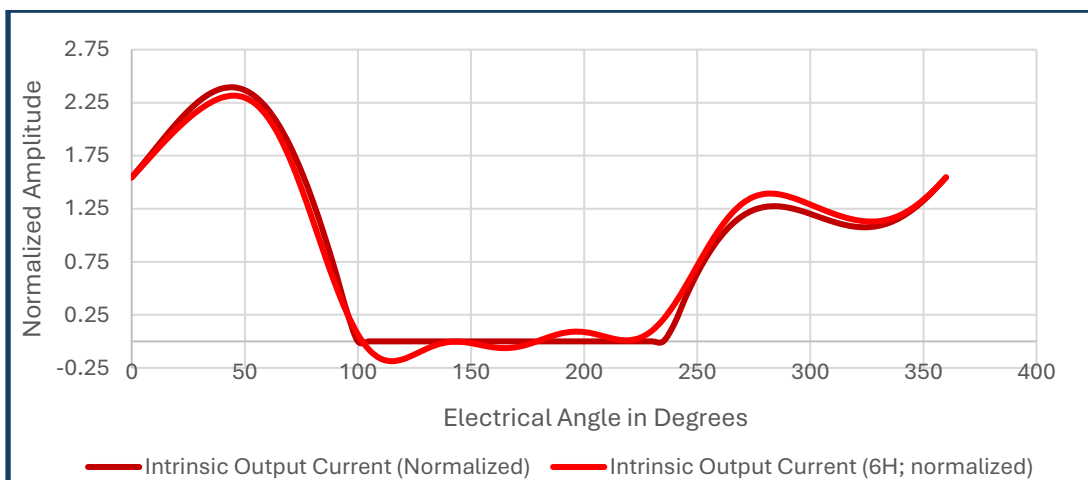
## Harmonic Content of H2ID Current Waveforms

The number of harmonics in the complementary voltage waveforms were limited to three. Intrinsic shorts are required at the higher harmonics to prevent degradation of the performance. The matching networks designed are, however, unlikely to provide exact shorts at these harmonics and the number of significant harmonics in the H2ID current waveform and the actual terminations presented at these harmonics are, therefore, important.

Up to 18 harmonics may be required at some operating points for a tight fit to the actual current waveform. Examples at two different operating points are provided below. The actual current waveforms were compared to the waveforms limited to six harmonics here. This comparison is done at several operating points in the H2ID dataset.



**Figure 1.** Comparison of the H2ID current waveform associated with  $H2ID=(0.5; 360^\circ)$  and the waveform limited to the first six harmonics.



**Figure 2.** Comparison of the H2ID current waveform associated with  $H2ID=(0.5; 210^\circ)$  and the waveform limited to the first six harmonics.

## Ampsa H2ID Atlas – Volume 1

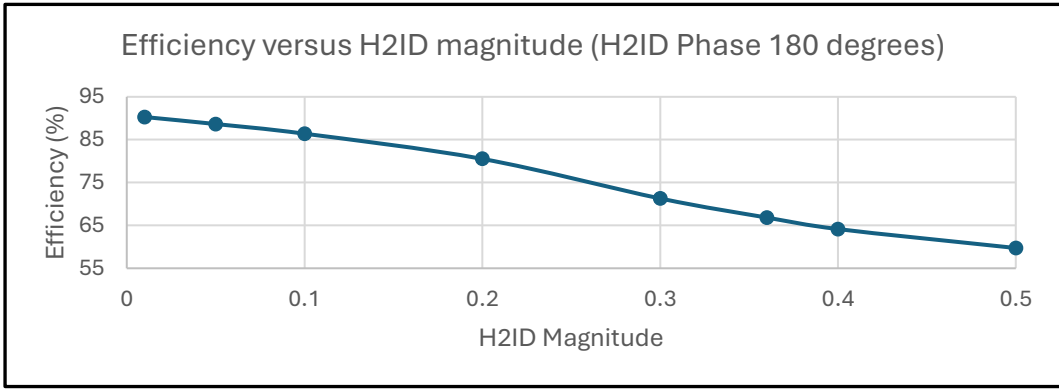
The maximum waveform efficiency obtainable (%) and the current waveform conduction angle (degrees) as a function of the *H2ID* magnitude and phase.

	H2ID Angle	180°	180°	190°	190°	200°	200°	210°	210°	225°	225°	240°	240°
<b>H2ID Magnitude</b>													
0.01													
0.05													
0.1													
0.2													
0.3													
0.36													
0.4													
0.5													

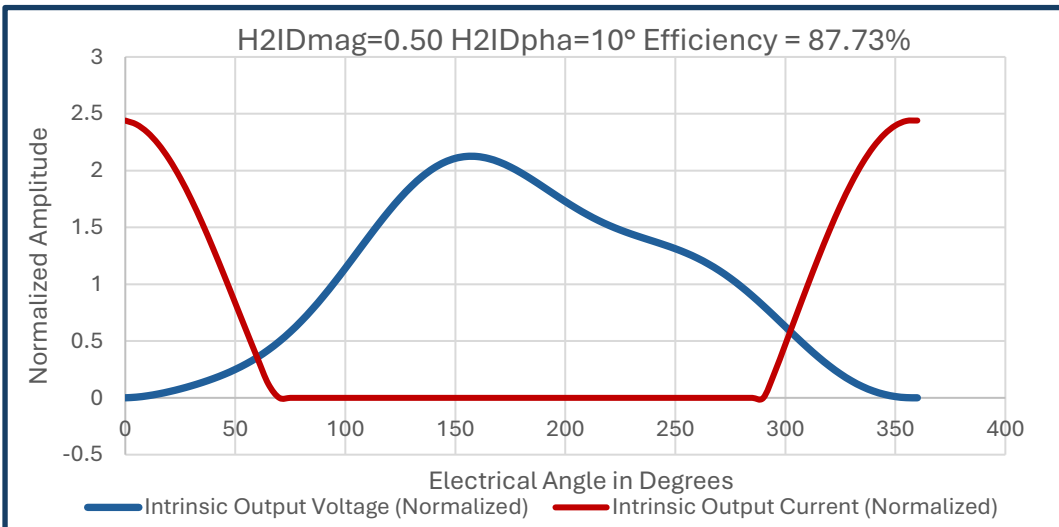
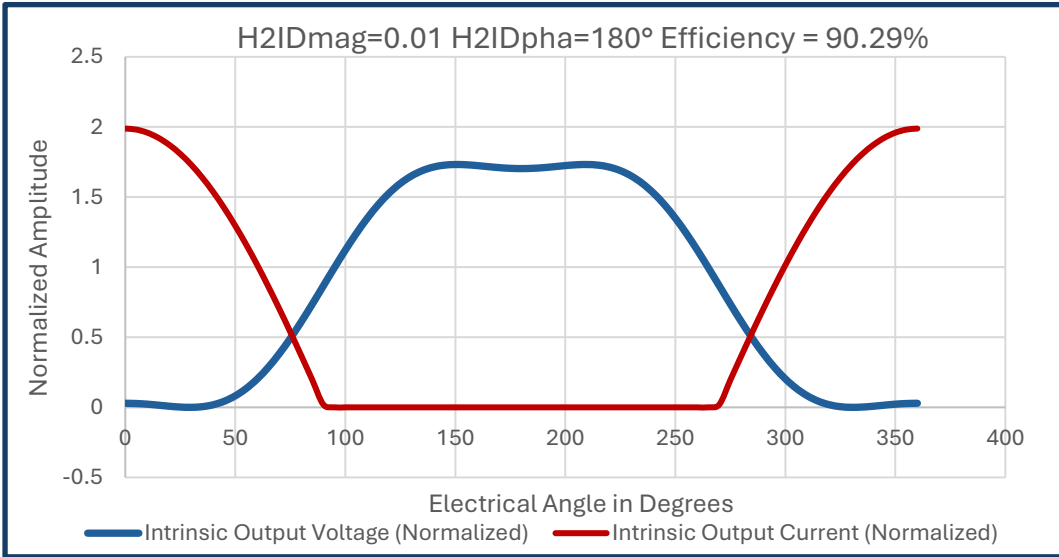
	H2ID Angle	255°	255°	262°	262°	270°	270°	278°	278°	285°	285°	300°	300°
<b>H2ID Magnitude</b>													
0.01		90.49				90.58							179.4
0.05		90.24				90.56							177.1
0.1		89.98				90.69							174.1
0.2		89.45				82.77							167.4
0.3		88.56				84.51							159.3
0.36		83.27				85.46							154.1
0.4		82.88				86.07							150.6
0.5		80.57				87.67							142.5

	H2ID Angle	315°	315°	330°	330°	340°	340°	350°	350°	360°	360°
<b>H2ID Magnitude</b>											
0.01											
0.05											
0.1											
0.2											
0.3											
0.36											
0.4											
0.5											

## Maximum Efficiency Obtainable versus H2ID Magnitude for different H2ID Phase Angles



### Selected High Efficiency H2ID Complementary Waveforms



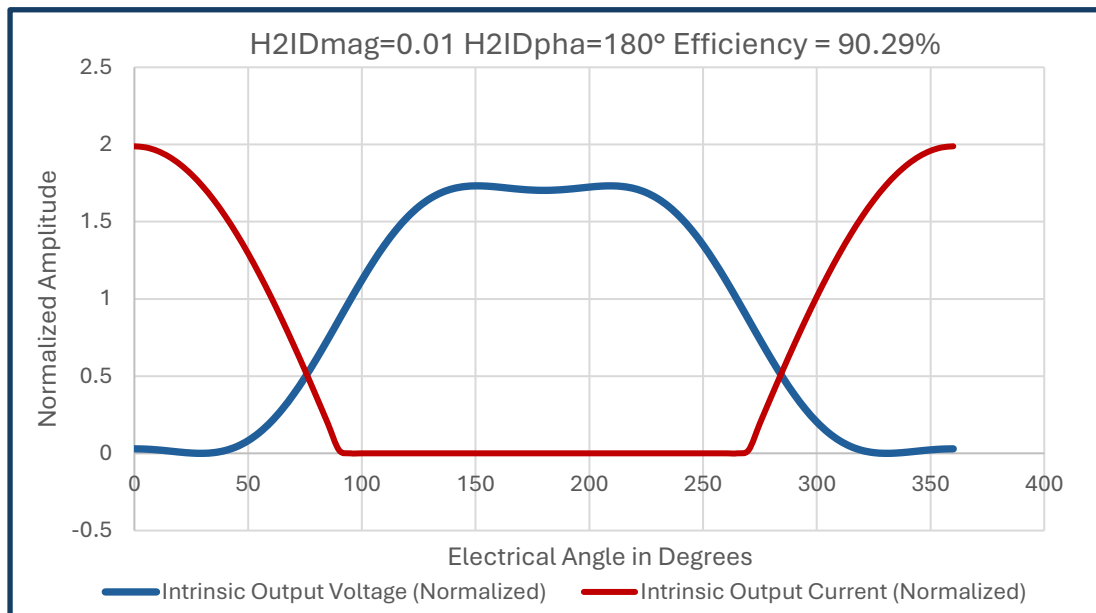
## H2ID Operating Point (0.01; 180°; 90.29%)

Magnitude: 0.01

Phase: 180°

Efficiency: 90.29%

### Intrinsic Waveforms



### Design Classification

High efficiency. High third-harmonic impedance. Class-F-like waveforms. Conduction angle 181.1°.

### Scaling Parameters

Parameter	Value	Parameter	Value
$V_{dc}$	0.8661	$I_{dc}$	0.6394
$V_{max}$	1.7322	$I_{max}$	1.9884

### Harmonic Load Requirements

Harmonic	Impedance
Fundamental ( $Z_{Li1}$ )	1.0000 + j0.0000
2 <sup>nd</sup> Harmonic ( $Z_{Li2}$ )	0.0000 + j0.0000
3 <sup>rd</sup> Harmonic ( $Z_{Li3}$ )	21.2539 + j0.0000

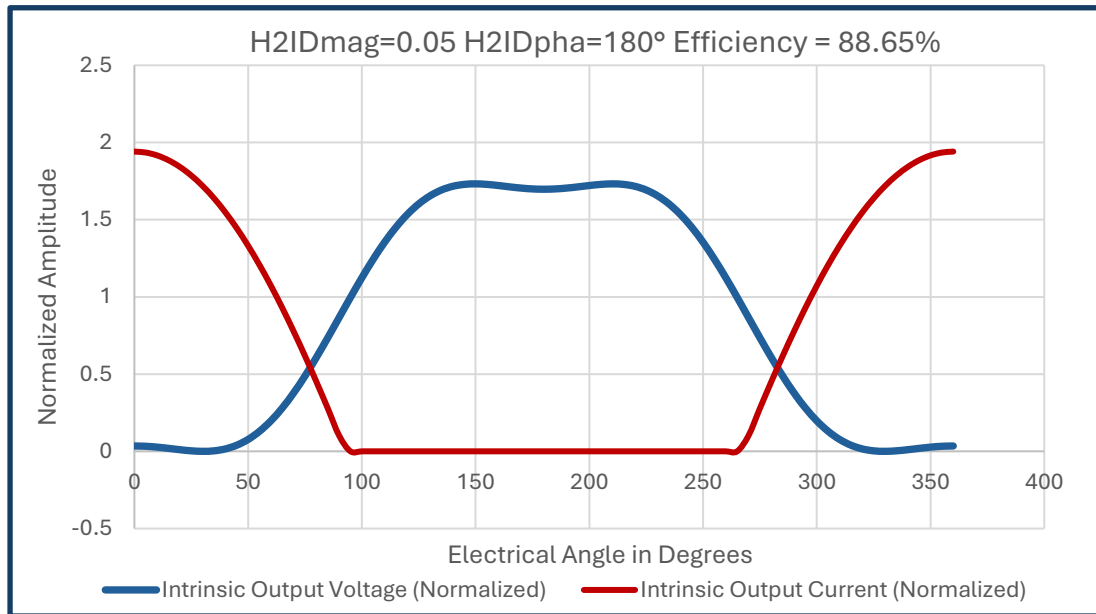
## H2ID Operating Point (0.05; 180°; 88.65%)

Magnitude: 0.05

Phase: 180°

Efficiency: 88.65%

### Intrinsic Waveforms



### Design Classification

High efficiency. High third-harmonic impedance. Class-F-like waveforms. Conduction angle 185.7°.

### Scaling Parameters

Parameter	Value	Parameter	Value
$V_{dc}$	0.8660	$I_{dc}$	0.6513
$V_{max}$	1.7321	$I_{max}$	1.9412

### Harmonic Load Requirements

Harmonic	Impedance
Fundamental ( $Z_{Li1}$ )	1.0000 + j0.0000
2 <sup>nd</sup> Harmonic ( $Z_{Li2}$ )	0.0000 + j0.0000
3 <sup>rd</sup> Harmonic ( $Z_{Li3}$ )	4.3293 + j0.0000

## Appendix A

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