MICROCHIP
2019 MASTERs
台灣技術精英年會(第八屆)

23104 – PC12

The wireless power transmission of the medium power , three performance indicators and three key technologies

MICROCHIP

SMART | CONNECTED | SECURE

Defined in this article

Wireless charging - power is transmitted to the battery which is built in the receiving end for charging

Wireless power transmission - power is transmitted to the receiving end for direct operational use

Low Power **＜20W**
It is applied to the charging of a handheld smart device. The power source of the transmitter is mostly USB power.

Medium Power **20W~1KW**
It is applied to power tools and lightweight mobile vehicles. The power source is mostly from the dedicated DC power supplies

High Power **＞1KW**
It is applied to large electric vehicles. The power source is mostly directly driven by the AC grid.

Current technical capabilities

The operating input and output DC voltage Vin is 12V-36V.

Practical maximum operating current 10A, limit operation up to 15A.

The practical sensing distance is 1/4 of the outer diameter of the coil

Mass production module up to 500W, sensing distance 40mm (coil outer diameter 160mm)

C-L-C resonant circuit & Full-bridge driving architecture

Maximum output power is (Vin ^2)/2

When the voltage is 12V, the maximum output power is (12^2)/2 = 72 W

When the voltage is 24V, the maximum output power is (24^2)/2 = 288 W

When the voltage is 36V, the maximum output power is (36^2)/2 = 648 W

The measurement accuracy of voltage and current is +/- 2%

In the power transmission stage, the operating frequency is 110 kHz-140 kHz,

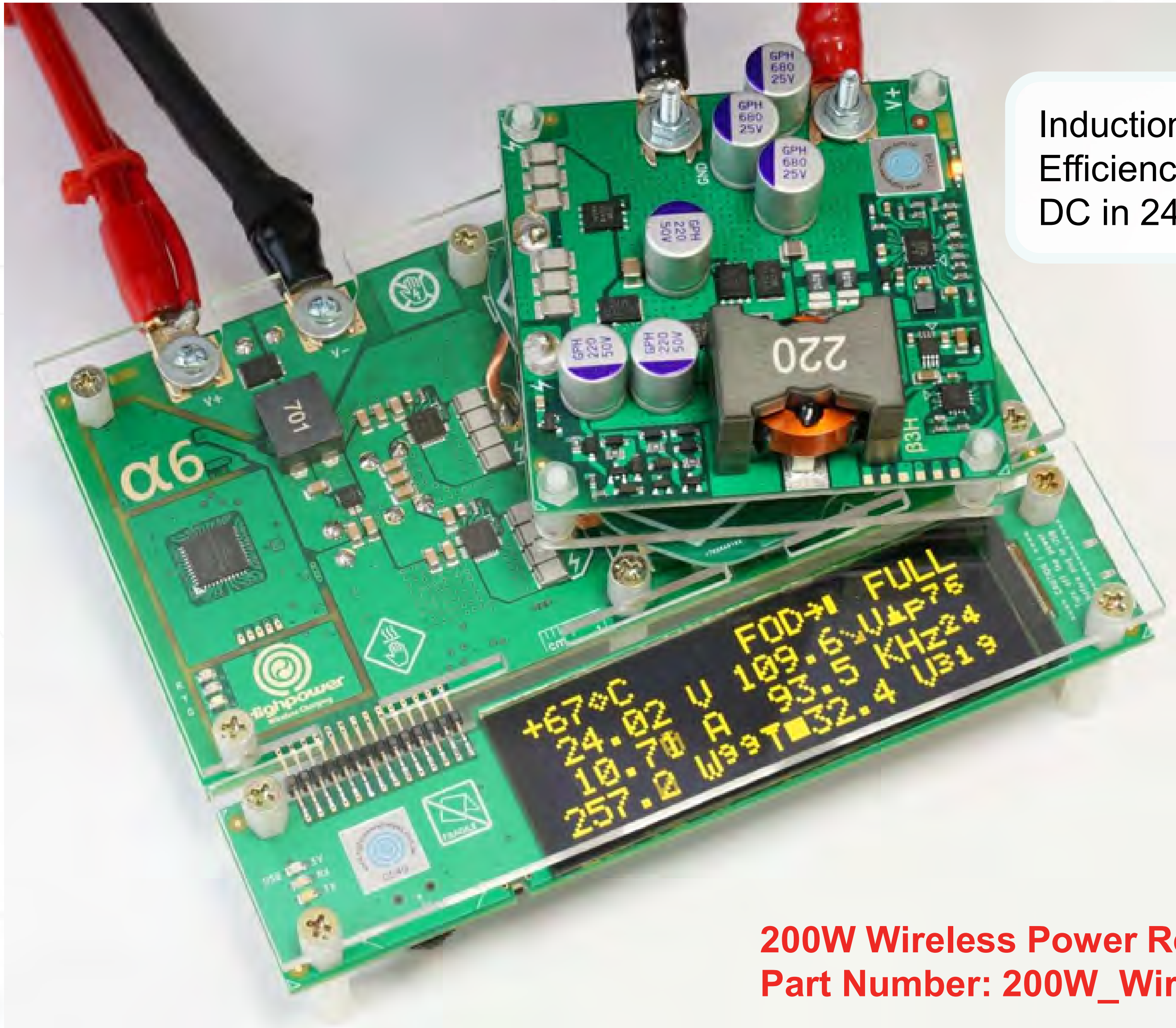
Resonant frequency is set to 80 kHz-100 kHz

The maximum operating voltage of coil is 200V-ac

*FCC requires the operating frequency must be higher than 110KHz

**CE requires the operating frequency must be lower than 140KHz

200W Wireless Power Transmitting Module and Power Receiving Module



Induction distance 5-10 mm
Efficiency > 90% @200W
DC in 24V out 24V-10A MAX

200W Wireless Power Reference Design
Part Number: 200W_Wireless_Power

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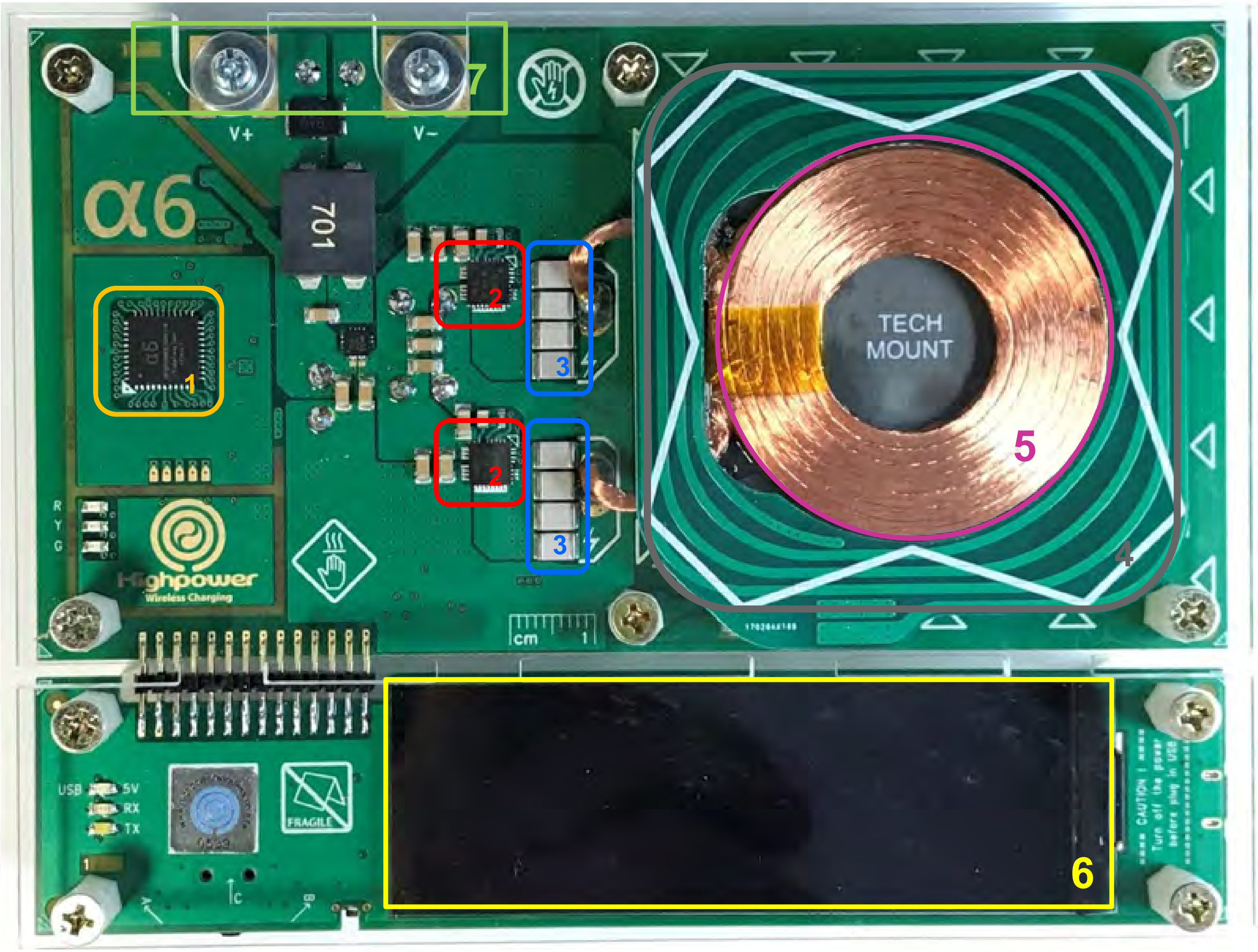
Parts Layout of Power Transmitting Module - Top



1 Main controller

2 Driver

3 Resonant capacitor

4 NFC detection coil

5 Power transmission coil

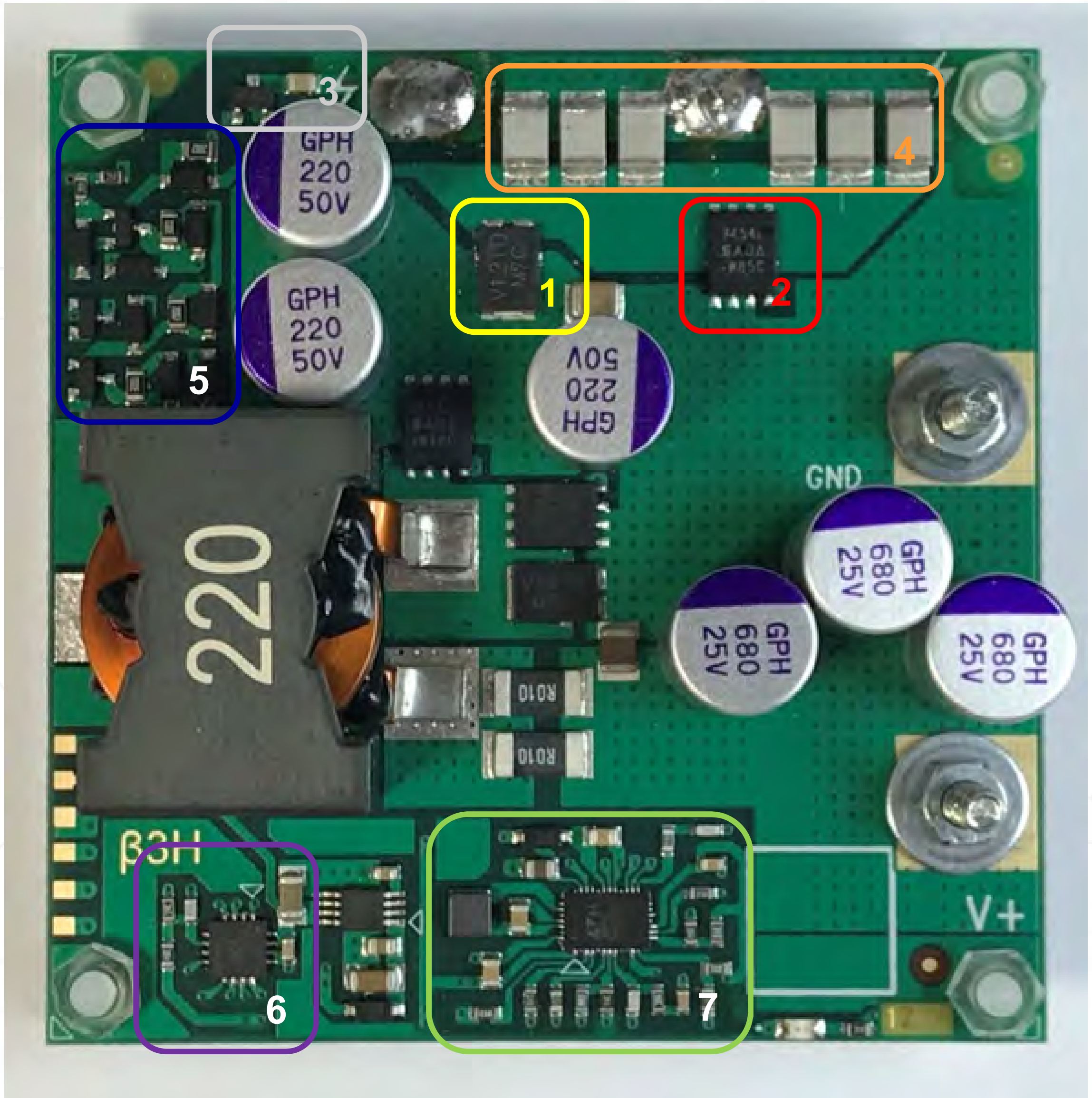
6 OLED display panel

7 DC power input

Parts Layout of Power Transmitting Module - Bottom

1 Signal processing area
2 Buck circuit
3 Buzzer
4 Coil temperature sensor
5 Pcb temperature sensor
6 Function switch 1
7 Function switch 2

Parts Layout of Power Receiving Module



1 Upper side of rectification: diode

2 Lower side of rectification : MOSFET

3 Signal modulation capacitor

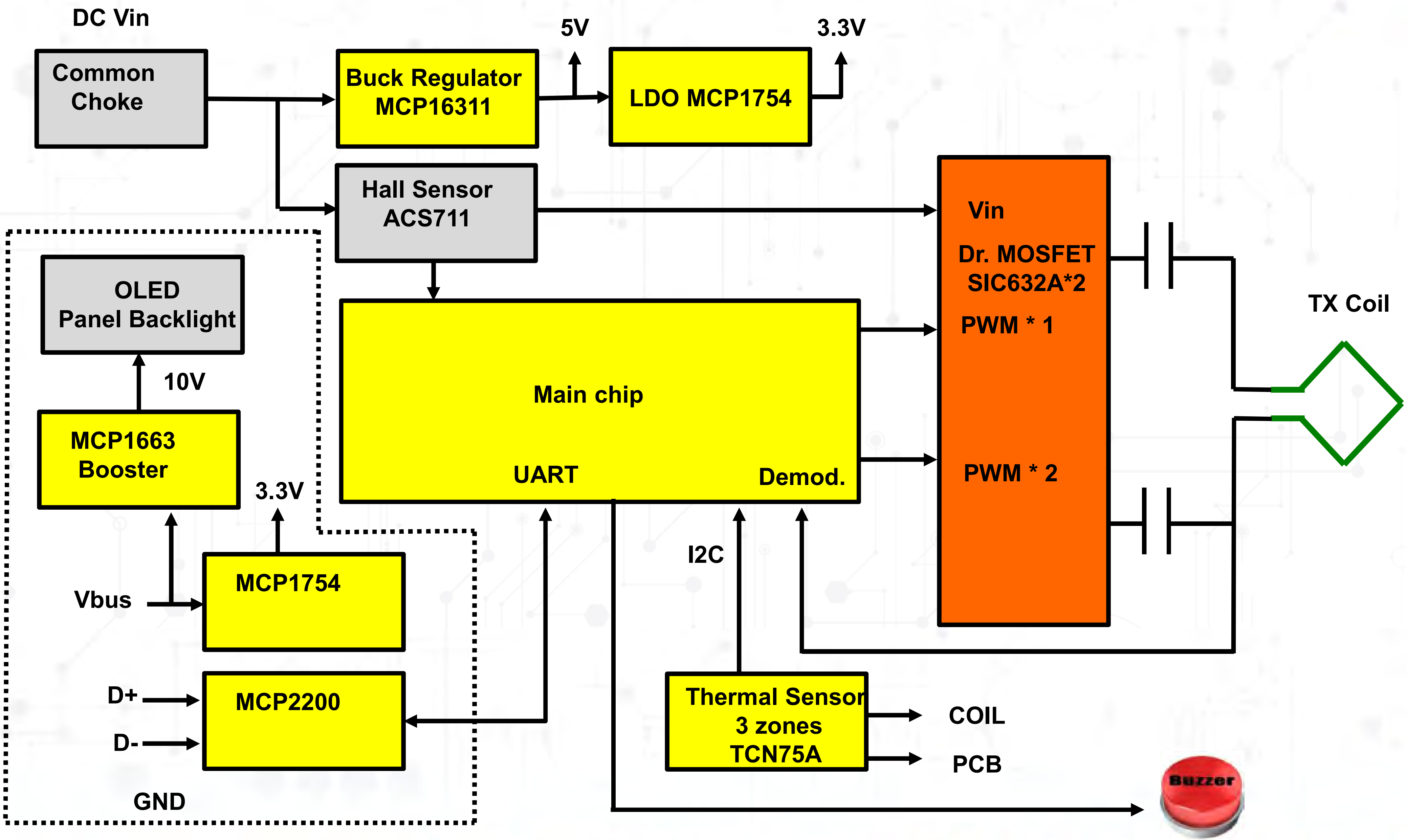
4 Resonant capacitor

5 Rectification control circuit

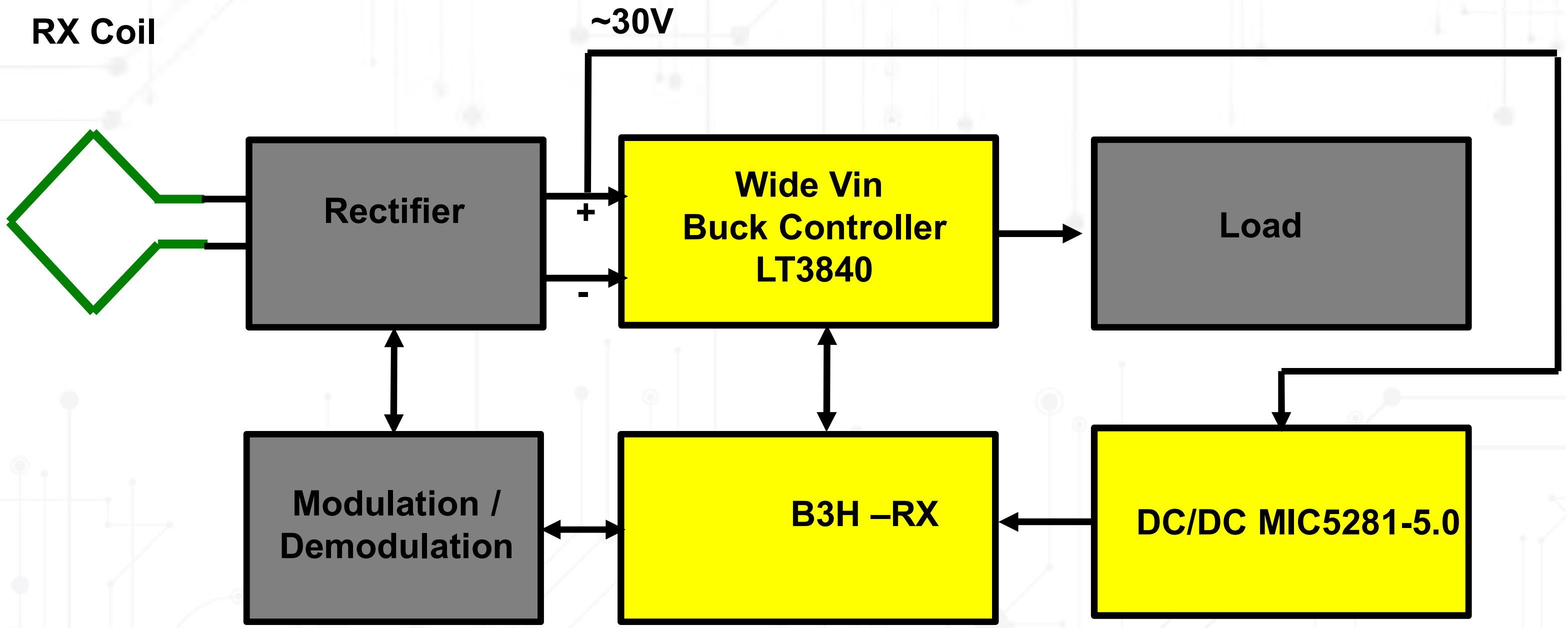
6 Main controller

7 DC/DC controller

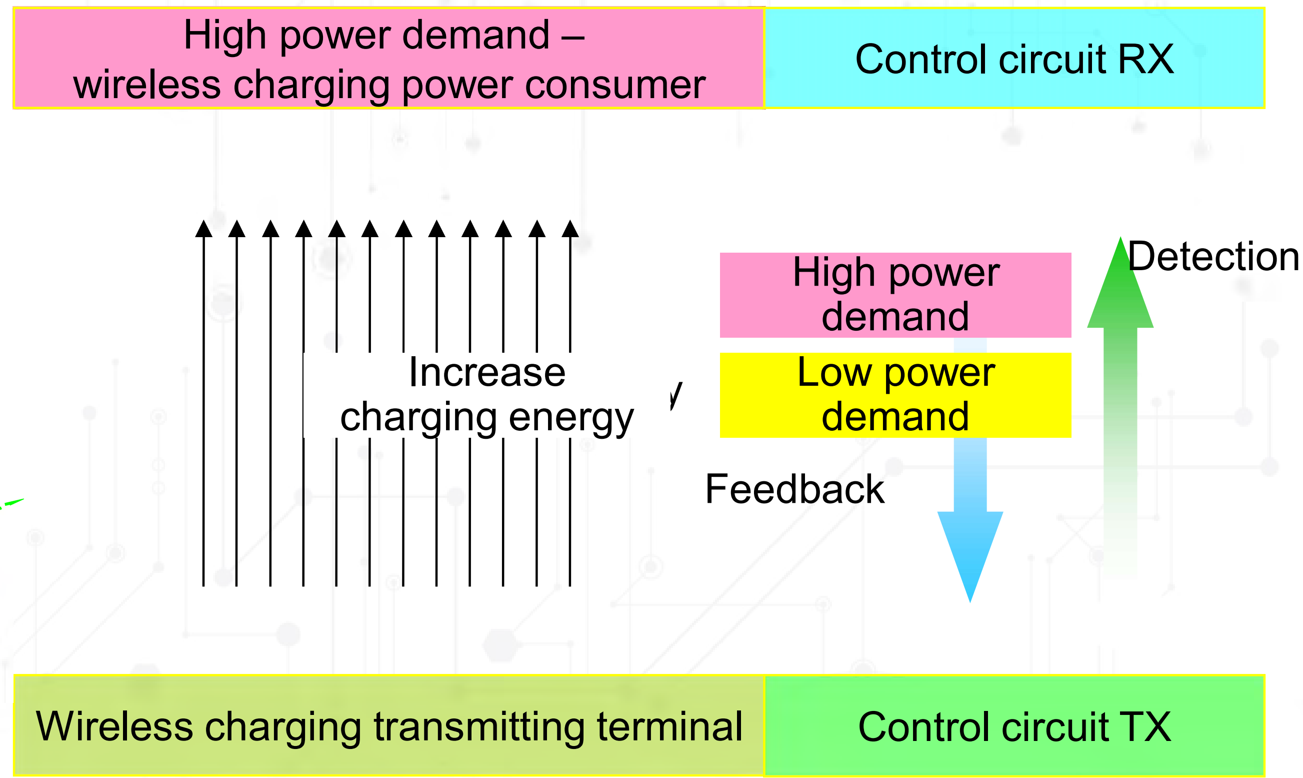
Transmitter Block Diagram



Receiver Block Diagram



Message transmission function for power supplier and power consumer

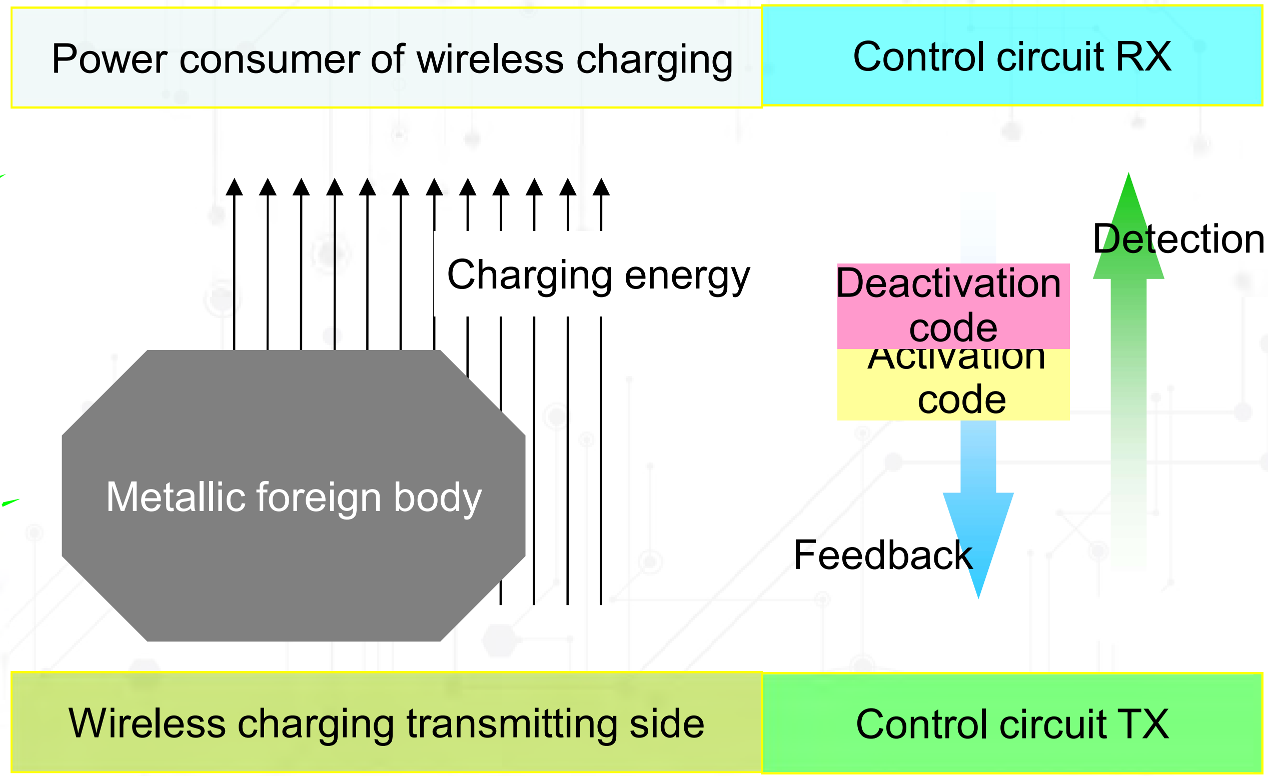


Power control can be achieved using the code content.

Data code transmission is the core technology of wireless power system

If the data code of "existing foreign body" is activated, then the energy transmission will not start.

Safety control can be achieved using the code content.



Medium-power wireless power transmission technologies

Three Performance Indicators

A. Transmission distance

B. Transmission power and efficiency

C. Dynamic output load

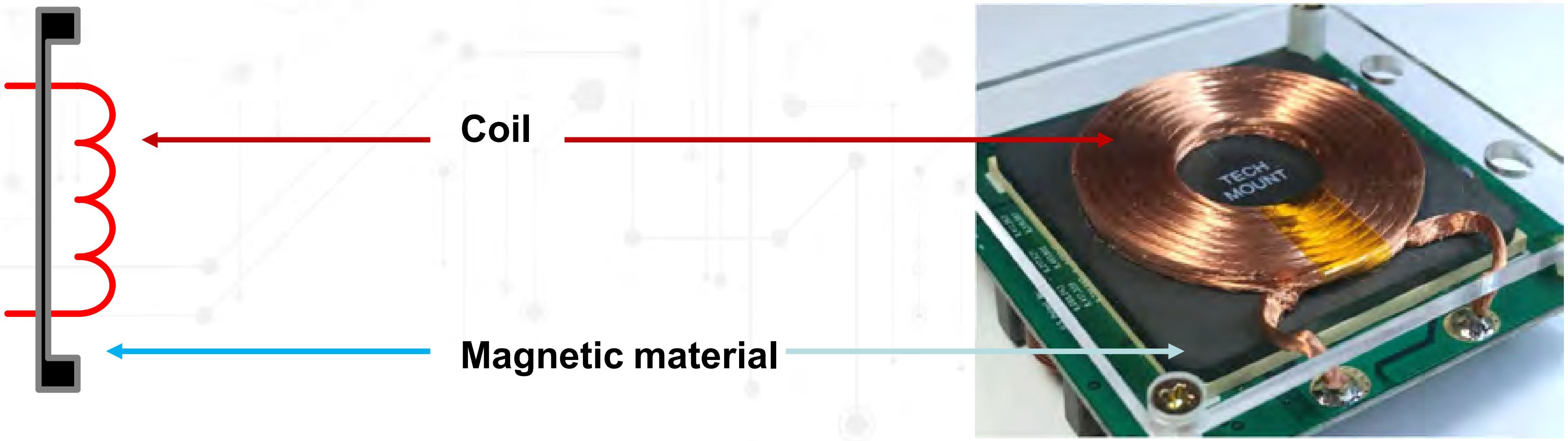
Three Key Technologies

X. Output power regulatoin

Y. Communicate on power transmission coil

Z. Metallic foreign body detection

A01. Basic Structure of Induction Coil



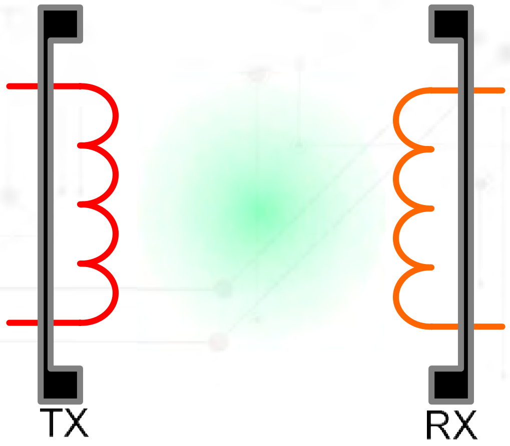
Use of Magnetic Material

Limit electromagnetic energy to the sensing direction at the transmission end

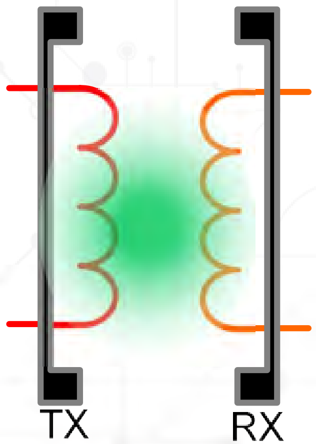
Block electromagnetic energy at the receiving end to prevent it from hitting the rear component

The inductance value will increase when the coil gets close to the magnetic materials

A02. Coil and Mutual Inductance of Coils

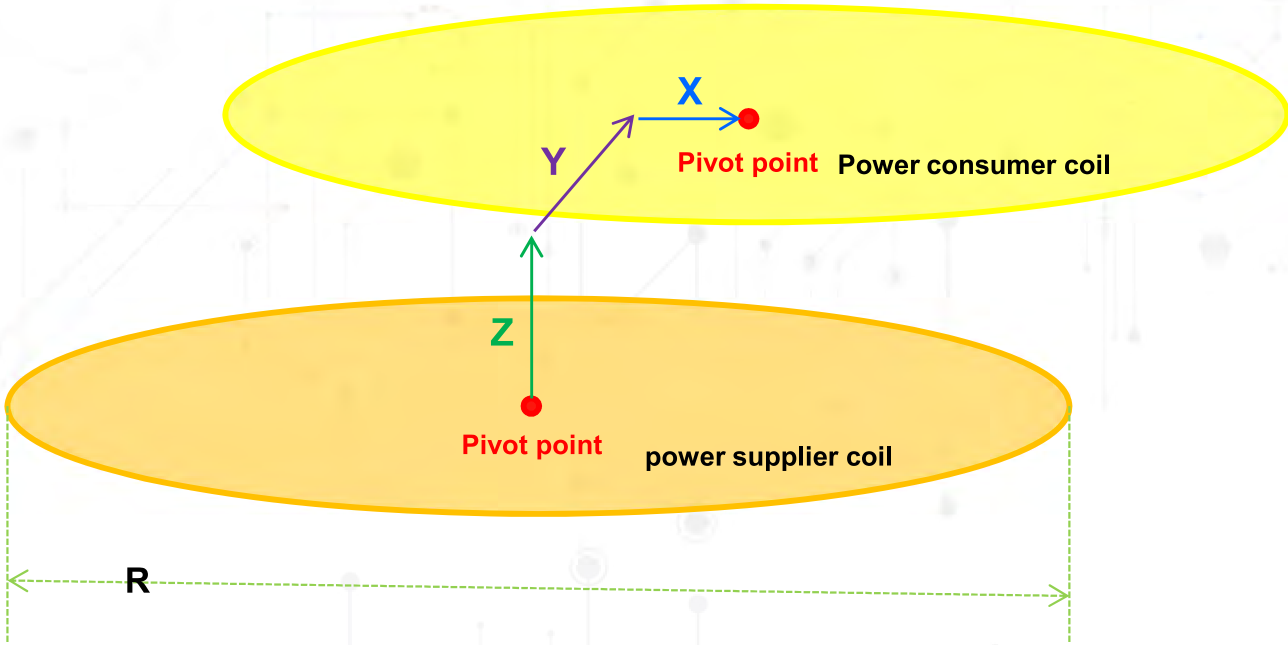


The inductance value will increase when the coil gets close to the magnetic materials
In addition to this case, when another coil gets close to that coil, the inductance value will also increase because of the magnetic materials in the rear of the coil. This phenomenon is called mutual inductance.



The closer the two coils are, the more the coil inductance increases.
This change in inductance affects the operation of wireless power transmission.

A03. Coil size and induction distance

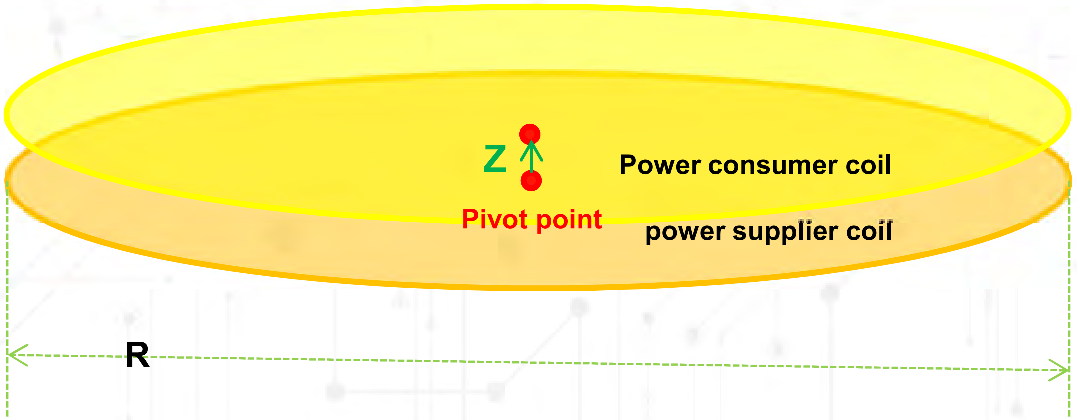


X - horizontal axis of plane offset Y - horizontal axis of plane offset Z - vertical height
R - coil diameter.
When the two coils are of different sizes, take the smaller diameter for calculation.

For 90% efficiency X + Y + Z < 1/8 R
For 85% efficiency X + Y + Z < 1/4 R
For 70% efficiency X + Y + Z < 1/2 R

The induction distance affects the efficiency and is limited by the coil size.
The available induction distance is determined by the minimum acceptable efficiency.

A04. Excessive Coupling of Coil Induction



X - horizontal axis of plane offset	Approximate zero
Y - horizontal axis of plane offset	Approximate zero
Z - vertical height	the distance is extremely short
R - coil diameter.	

Conditions of the Occurrence

1. Two coils have similar specifications.
2. The distance between these two coils are excessively short.

Alpha Winding X + Y + Z < 1/16 R

Spiral Forward Winding X + Y + Z < 1/8 R

Excessive Coupling

The power at the power supply is completely transmitted to the power receiving device, causing the received power (usually referred to as voltage) on the power receiving end to be excessively large.The power exceeds the power regulation capability range, so the circuit may not operate normally or be damaged.

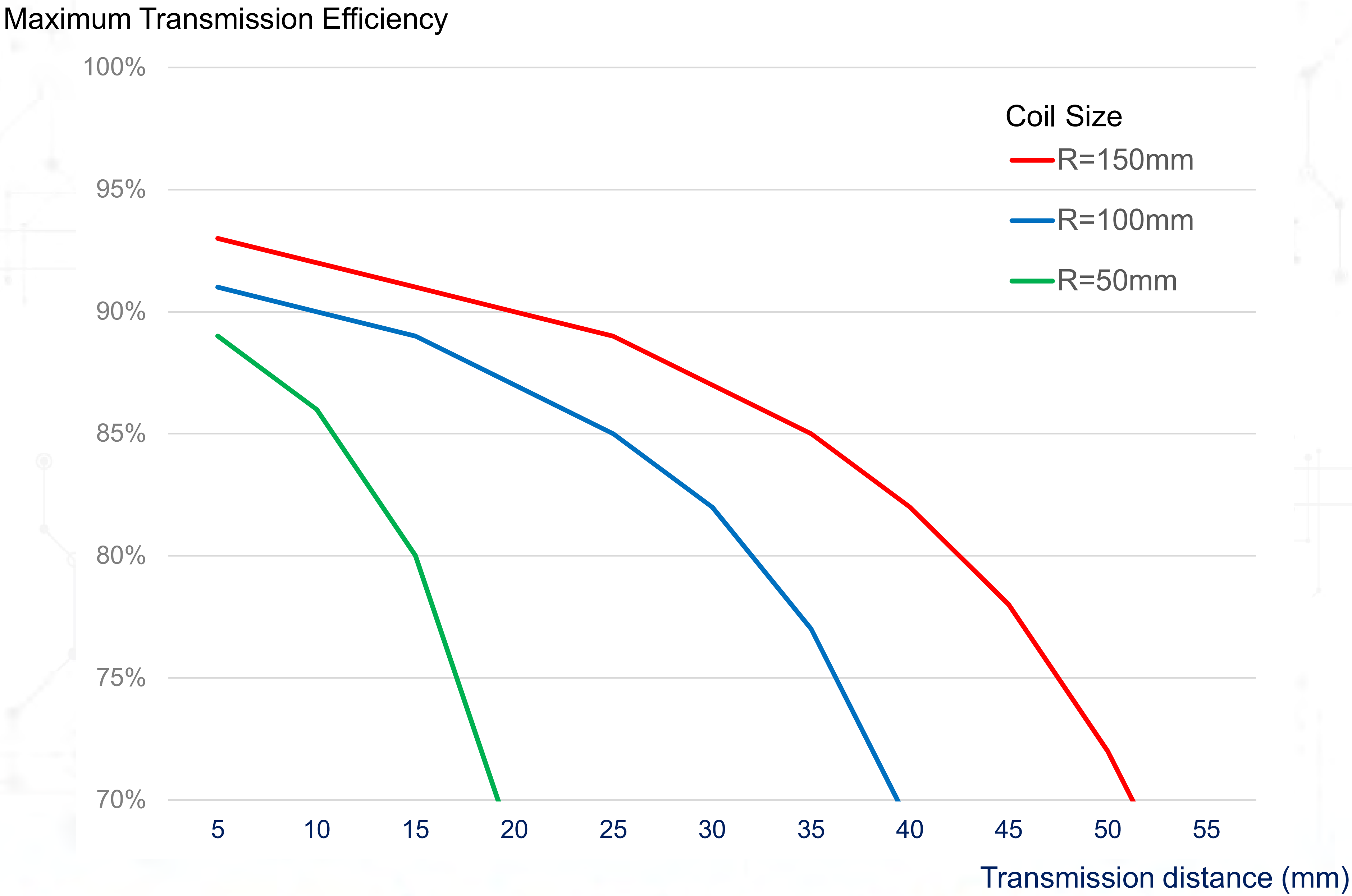
A05. Structure of Traditional Coils

	Alpha Winding	Spiral Forward Winding
Inductance Value	Double layered wire with small diameter can cause large inductance	Single-layered wire is not suitable for making small-diameter coils because the inductance it causes cannot meet the requirements
Lead Ends	Both ends are led out by the outermost ring and easy to assemble	The leads are led out from the innermost ring and the outermost ring, and the innermost lead wire crosses the surface of the coil to affect the efficiency.
Power Distribution	Power is concentrated on the outermost side	Power is concentrated on the outermost and innermost sides
Mutual Inductance	Little change in inductance value	Great change in inductance value
Reponse Characteristics	The efficiency declines after the coil is shifted horizontally	The excessive coupling is easy to occur

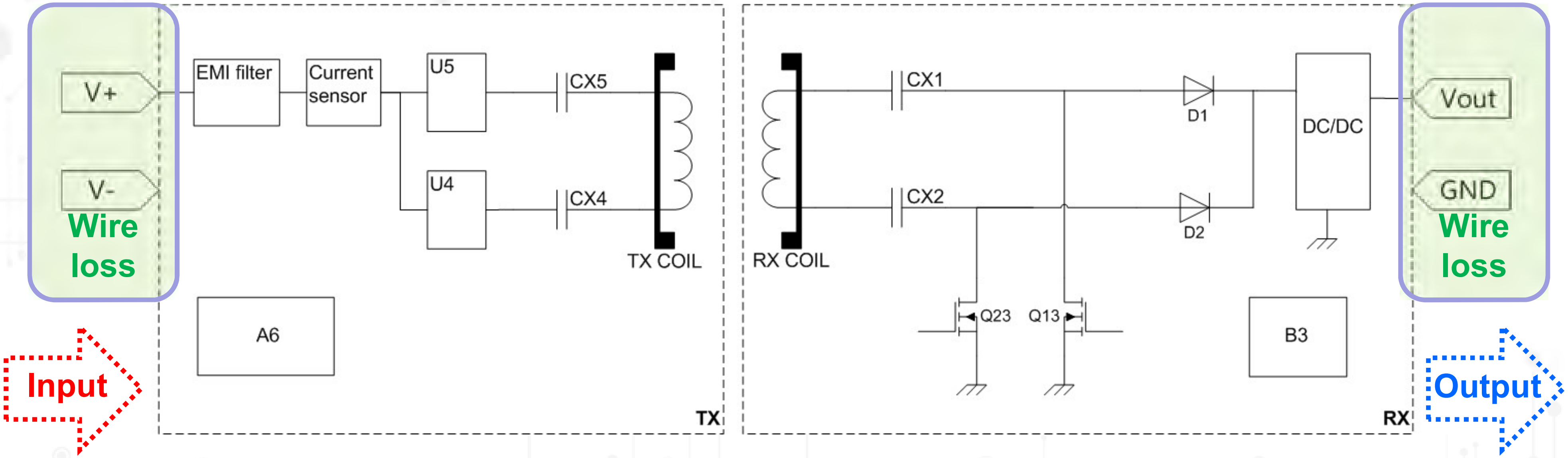
A06. Structure of Modified Coils

	TX	RX
Inductance Value	Less inductance, lower impedance and loss is reduced	More windings and larger inductance
Lead Ends	The outermost ring and the innermost ring have the strongest power, and the middle part has the weakest power. Increasing the winding pitch, shortens the length of the weak-power zone can reduce the impedance of the entire coil to improve efficiency.	
Power Distribution	TX and RX adopt asymmetrically varying pitch winding, which can alleviate excessive coupling even when the distance between the two coils is very short.	
Mutual Inductance	The power is evenly distributed over the entire sensing surface, and the performance degradation is gentler under the condition of coil displacement. From this perspective, it is superior to the traditional coil.	

A07. Coil Size and Maximum Transmission Efficiency



B01. Efficiency definition

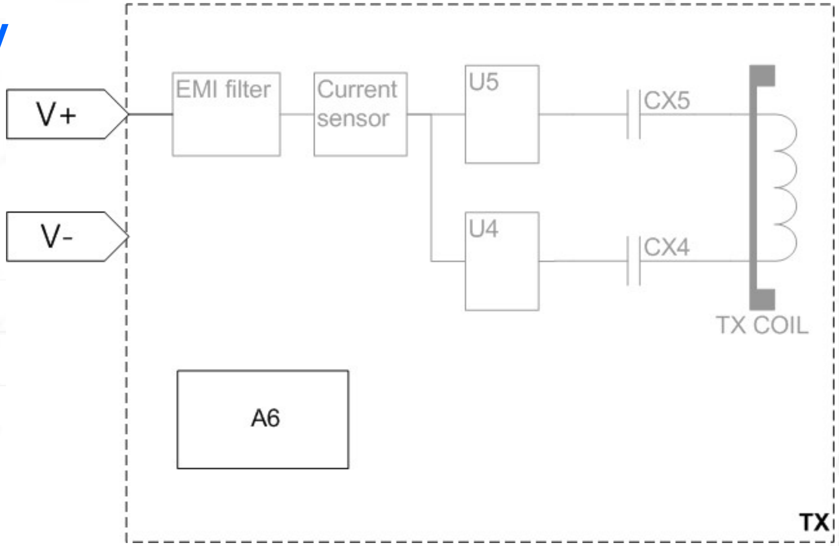


Efficiency is defined as (Output/Input) %.
Both the input and the output are DC.

In actual operation, the efficiency can be improved by adjusting the circuit and the settings. But the wire loss of the output and the input is often neglected, which will result in efficiency measurement errors. This system can operate smoothly only under stable DC. The design basis is an architecture of low voltage and large current. Under large current, the voltage drop caused by the loss will obviously affect the operation. A power supply monitoring mechanism is provided in the software to stop the operation when the voltage changes greatly within a short time.

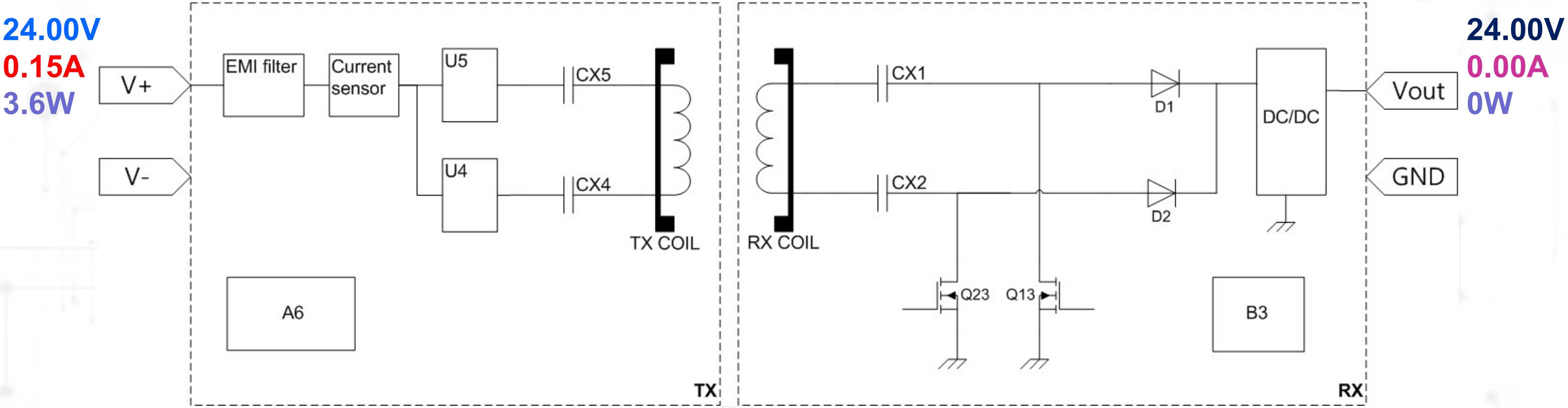
B02. Power consumption when the TX end is in standby

24.00V
0.04A
1.0W



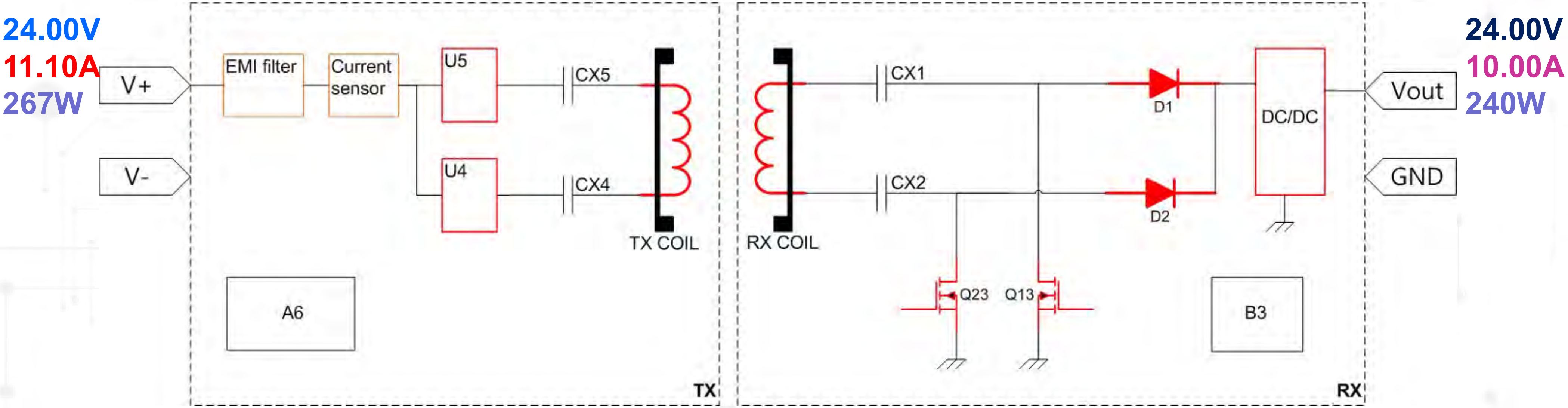
When RX is not induced, the power input on TX needs to maintain the basic operation of A6. Monitor power supply and scan the signal on the coil to see whether RX approaches or not. As A6 operates under the voltage of 3.3 V, the input voltage of 24 V needs to be decreased, which will cause basic loss. The power consumption is about 1 W in the standby state.

B03. Loss analysis with no-load on the output of RX under 0 A



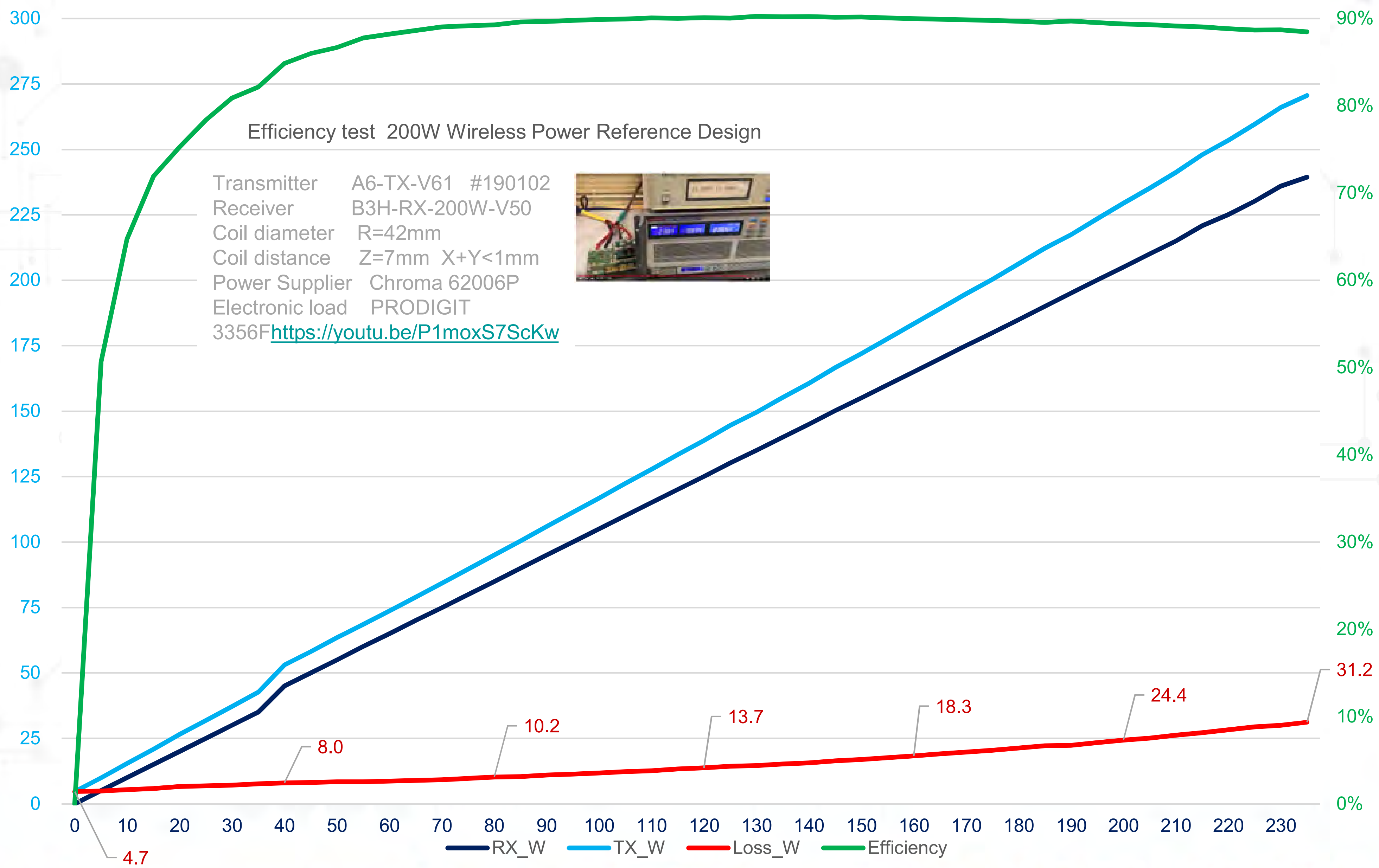
Position	Component used by EVB	Loss form	Impedance loss	Description
EMI filter	ICM4743ER701V	≈ 6 mΩ	< 1 mW	Low loss because of low current
Current sensor	ACS711	≈ 1 mΩ	< 1 mW	Low loss because of low current
U4, U5	SIC632A	≈ 20 mΩ	< 1 mW	The main reason is that the switching loss is not included in the calculation.
TX & RX COIL	Custom	≈ 22 mΩ	< 1 W	Under no load, the energy is mainly consumed on the coil
Q13, Q23	SI7454DDP	≈ 33 mΩ	< 1 mW	The main reason is that the switching loss is not included in the calculation.
D1, D2	V12P10	VF = 0.4V	< 1 mW	Low loss because of low current
DC/DC	LT3840	EF = 97%	< 1 mW	The loss under no load of DC/DC is determined by the controller performance.

B04. Loss analysis with full-load on the output of RX under 10 A

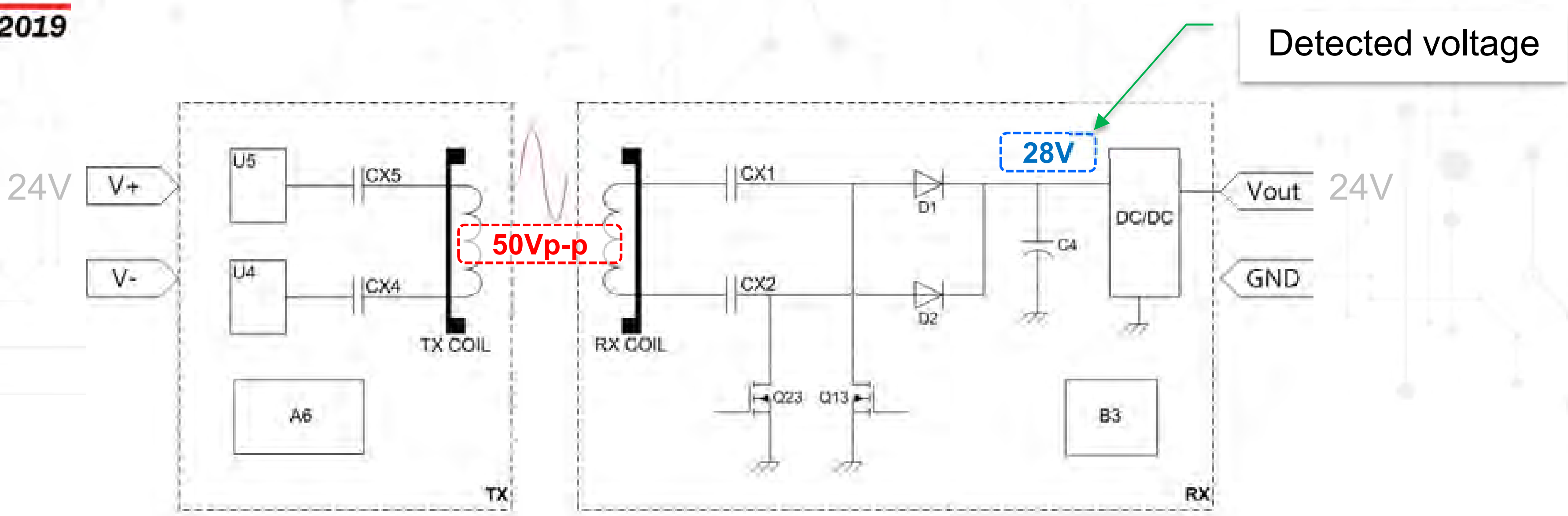


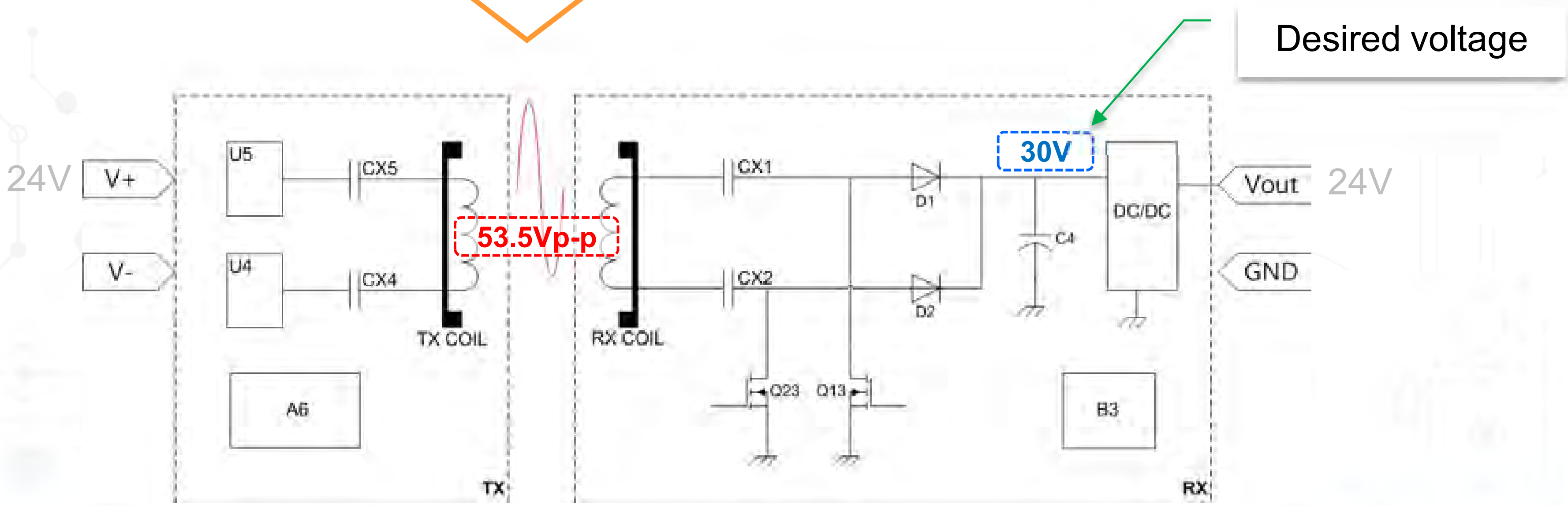
Position	Component used by EVB	Loss form	Impedance loss	Description
EMI filter	ICM4743ER701V	≈ 6 mΩ	0.6 W	Loss increases with higher current
Current sensor	ACS711	≈ 1 mΩ	0.1 W	Loss increases with higher current
U4, U5	SIC632A	≈ 20 mΩ	2 W + 2 W	Main heating components of TX
TX & RX COIL	Custom	≈ 22 mΩ	2 W + 2 W	The coil temperature will rise after the power consumption is accumulated.
Q13, Q23	SI7454DDP	≈ 33 mΩ	3 W + 3 W	High temperature parts of RX
D1, D2	V12P10	VF = 0.4V	4 W + 4 W	High temperature parts of RX
DC/DC	LT3840	EF = 97%	< 7 W	The peripheral parts configured for the main controller determine the performance.

B05. Maximum Transmission Efficiency and Loss



C01. Adjust coil voltage to maintain power output





C02. How to regulate power

1. Pre-set the desired voltage of the power consumer

For example: The desired voltage is set to 30 V

2. The power consumer encodes the detected voltage and feeds it back

For example: A voltage of 28 V is detected

3. The power supplier decodes the voltage data obtained from the power consumer

Data string decoding is completed. The decoding result of the data string indicates the current voltage of the power consumer is 28 V. For example, the current coil voltage is 50 V

4. Calculate the new desired coil voltage

(Desired voltage/Detected voltage) = (New desired coil voltage/Current coil voltage)
(30 V/28 V) = (?/50 V) In order to increase the new coil voltage to 53.5 V, the desired voltage shall be compensated.
The voltage of the power consumer is inducted by the amplitude of the power supplier coil , and will be proportional with other conditions remaining constant.

5. Reduce frequency to increase the coil amplitude, or increase frequency to decrease the coil amplitude

The relationship between the coil amplitude and frequency depends on multiple factors. It is impossible to predict the frequency required to reach the desired coil voltage. Therefore, successive minor adjustments shall be performed.

6. Re-measure the coil voltage

Traditional AC voltage measurement methods measure the average value through rectification. The measurement usually takes hundreds of AC cycles. The new technology directly measures AC peak values and is able to obtain the result in a single cycle.

7. Check if the desired voltage has been achieved

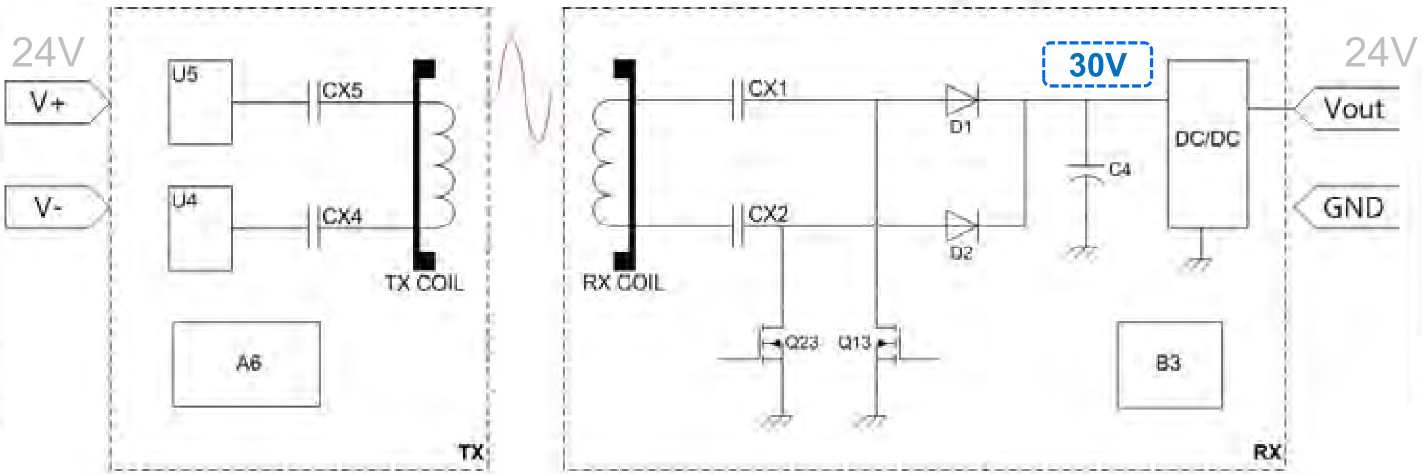
Measure the coil voltage and check if the desired voltage has been achieved. If not, return to Step 5 and make another round of regulation.

8. Power regulation is completed

Return to Step 1 and preform the next round of regulation. This provides a fast power regulation. Step 4 to Step 8 are usually done in 2 ms.

C03. Exemplify A Quick Increase in Load Conditions

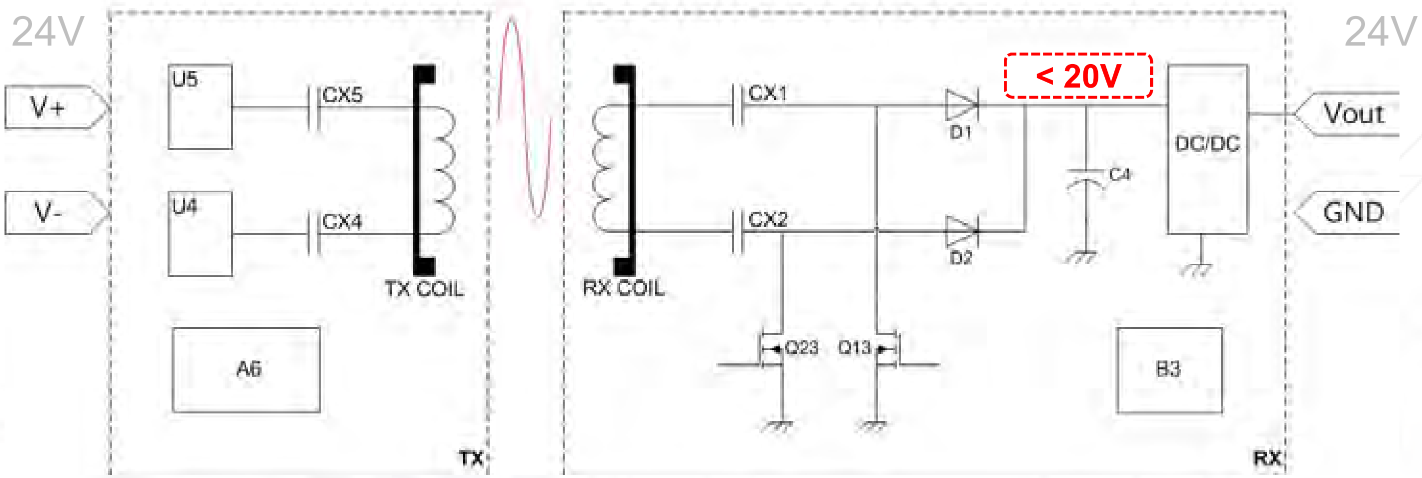
Load 0A



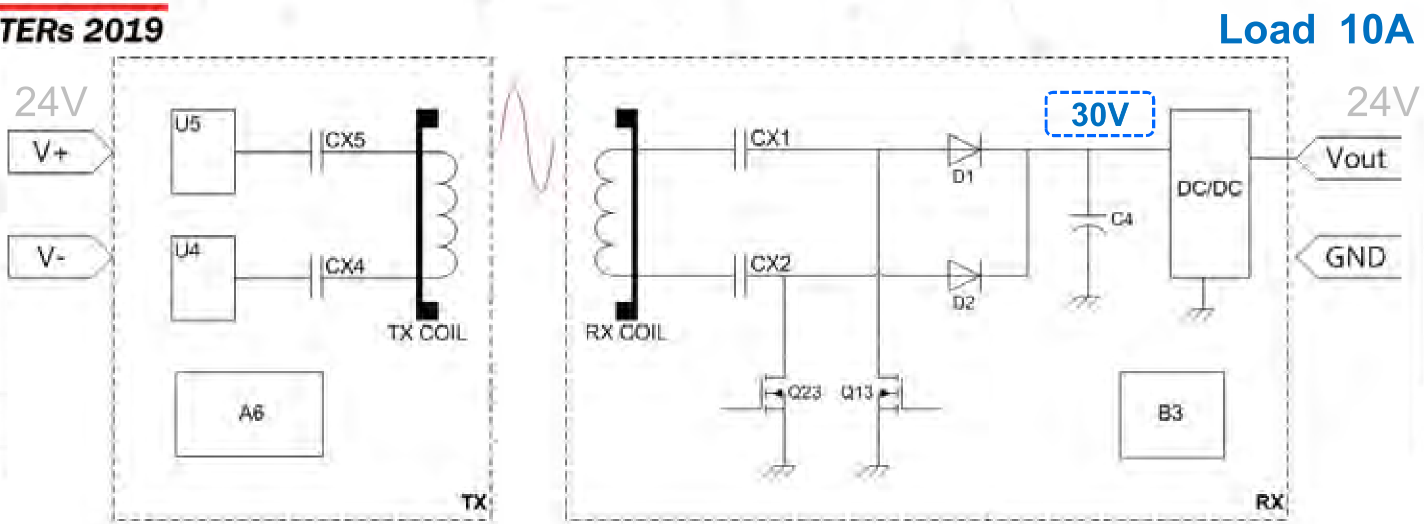
When the TX driver output condition is not changed after the load is increased.
The voltage after the rectifying of the RX rectifier will drop due to the increased load
The more the load increases, the greater the voltage decreases.
Finally the Vout output voltage cannot meet the design requirements.

Do not adjust the drive output status
After increasing the load

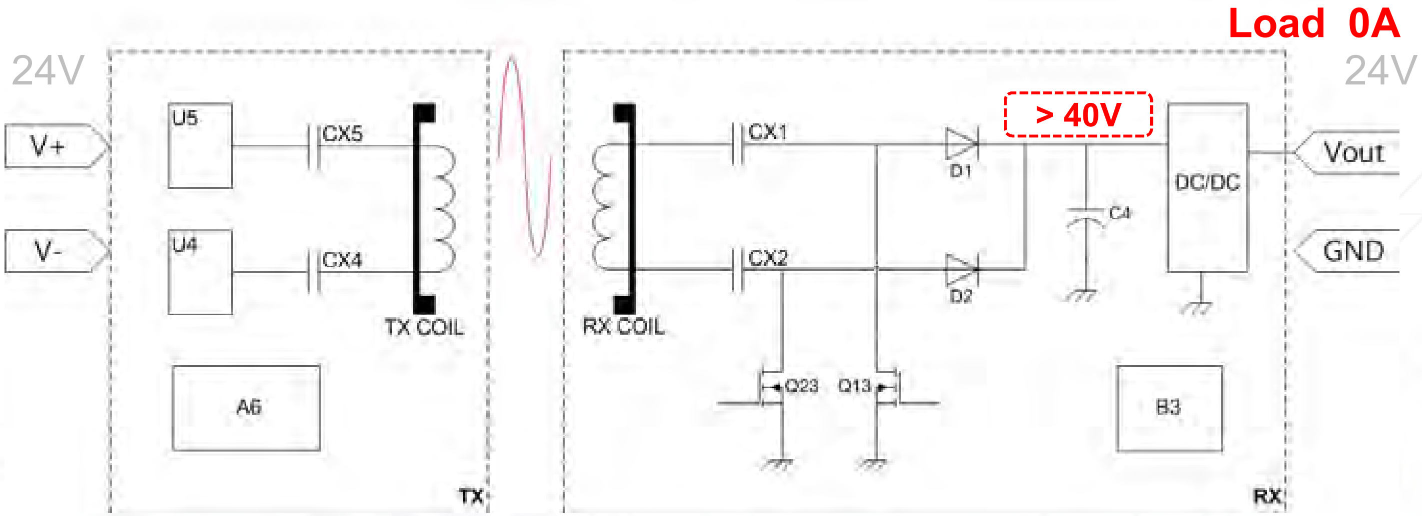
Load 10A



C04. Exemplify A Quick Decrease in Load Conditions



Do not adjust the drive output status
After reducing the load



It originally transmits with high load ; the TX driver will provide more power to transmit power through the coil.
When the load on the RX side is rapidly reduced, if the power provided by the driver on the TX side is not adjusted, the RX rectifier voltage will rise. If the TX provides too much power, the voltage regulated by the RX rectifier will be too large to exceed the component limit, it will cause the damage of RX hardware .

Three Performance Indicators Are Considered in Practice

A. Transmission Distance

The maximum transmission distance is determined by the size of the coil, and the larger the coil, the farther the transmission distance.

However, when the coil is enlarged, the over coupling is prone to occur. The ideal performance is that the set output efficiency can be achieved for any distance. The cost will increase when the coil is enlarged, and the coil size will be limited during production. The coil design requires a lot of trial samples to find the best match.

B. Transmission Power and Efficiency

The maximum output power is limited by the efficiency. When the power is increased, the increased loss will be partly converted into heat which will be dissipated. Some of thepower will be scattered into the space to cause EMI. To determine the maximum power to be designed depends on whether the heat caused by the entire power loss can be absorbed by the system. The performance is evaluated on the performance of the system temperature control under operation.

C. Dynamic Output Load

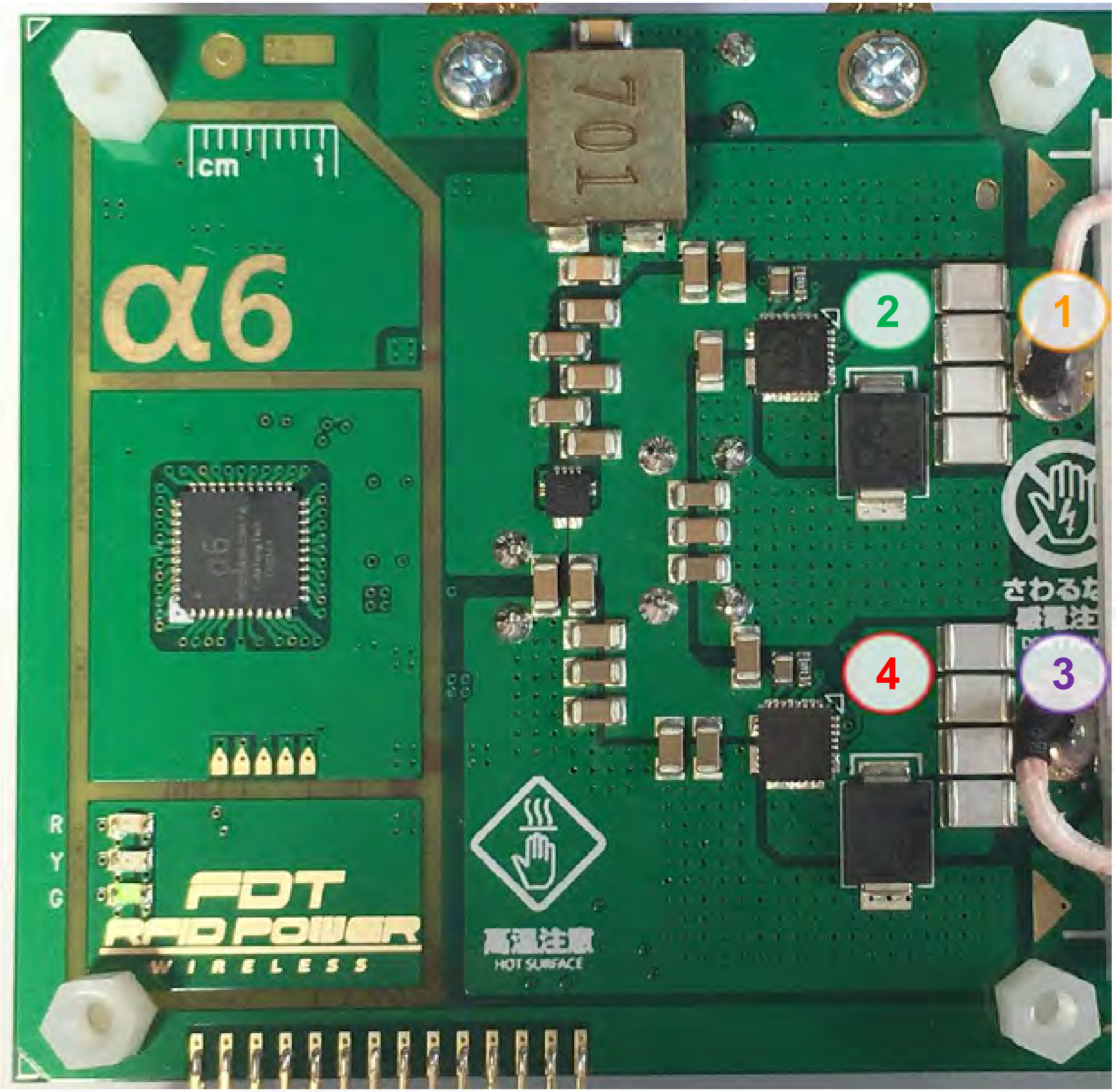
This performance indicator is very difficult to implement. Combining the first two conditions under the design transmission distance and maximum power condition, it can satisfy the requirements of quick switch between no-load to full load and full load to no-load, and the output voltage must be stable.

For example, in the 200w reference design, the sensing range is set from 5mm to 10mm. It can be pulled directly from no-load to 200w, or directly from full load of 200w to no-load. The output voltage can be stably maintained at 24V.

X01. Output Power Adjustment

Adjustment Method	Advantages	Disadvantages
A. Adjust PWM output frequency (Applicable to full bridge/half bridge circuits)	In the coil and capacitor resonance, changing the frequency can have the widest range of control power. It is the most common way. No extra parts, low cost, High efficiency	The amplitude and voltage changes will be delayed after changing the frequency in the resonator system. It takes more than 100 resonant periods for the TX to regulate the voltage received by the RX device. Frequency control is easily out of control at high power output, causing voltage damage
B. Adjust PWM phase difference (Only applicable to full bridge circuits)	The reaction adjustment is quick It takes only 10 resonance cycles for the TX to regulate the voltage received by the RX device. No extra parts, low cost, high efficiency	The adjustment range is small, and the output power cannot be greatly changed.
C. Change driver input voltage	Changing the voltage regulation power of the driver is not affected by the change of the resonant frequency of the coil, and the stable working circuit is less likely to be damaged. Fixed frequency operation can be used in specific applications, which is beneficial for EMC detection.	The adjustment range is small, and the output power cannot be greatly changed. Extra parts, high cost, low efficiency

X02. Measurement points of transmitter circuit



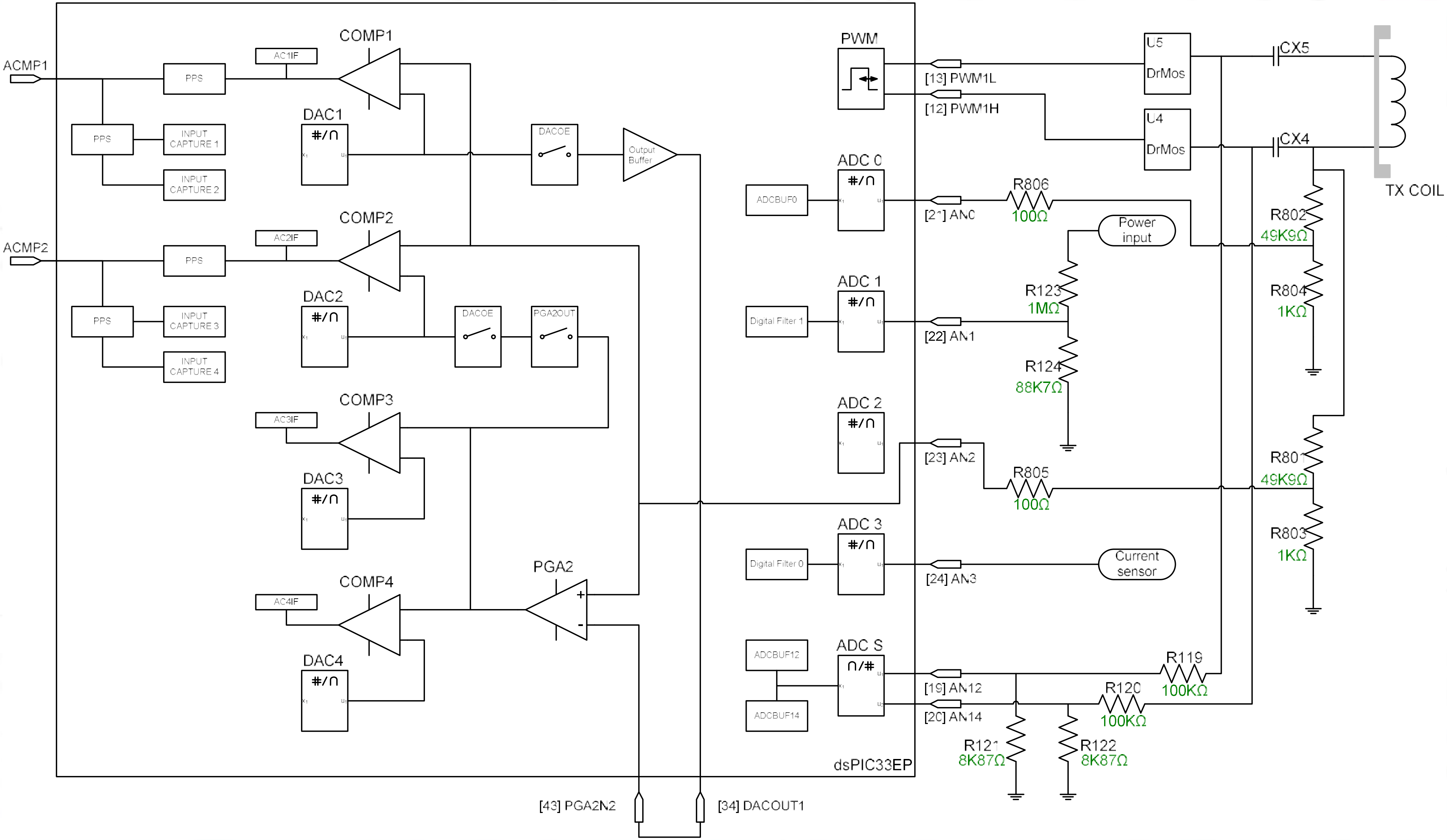
1 Coil terminal A
L-C oscillation point

2 Drive terminal A
Switch device output terminal

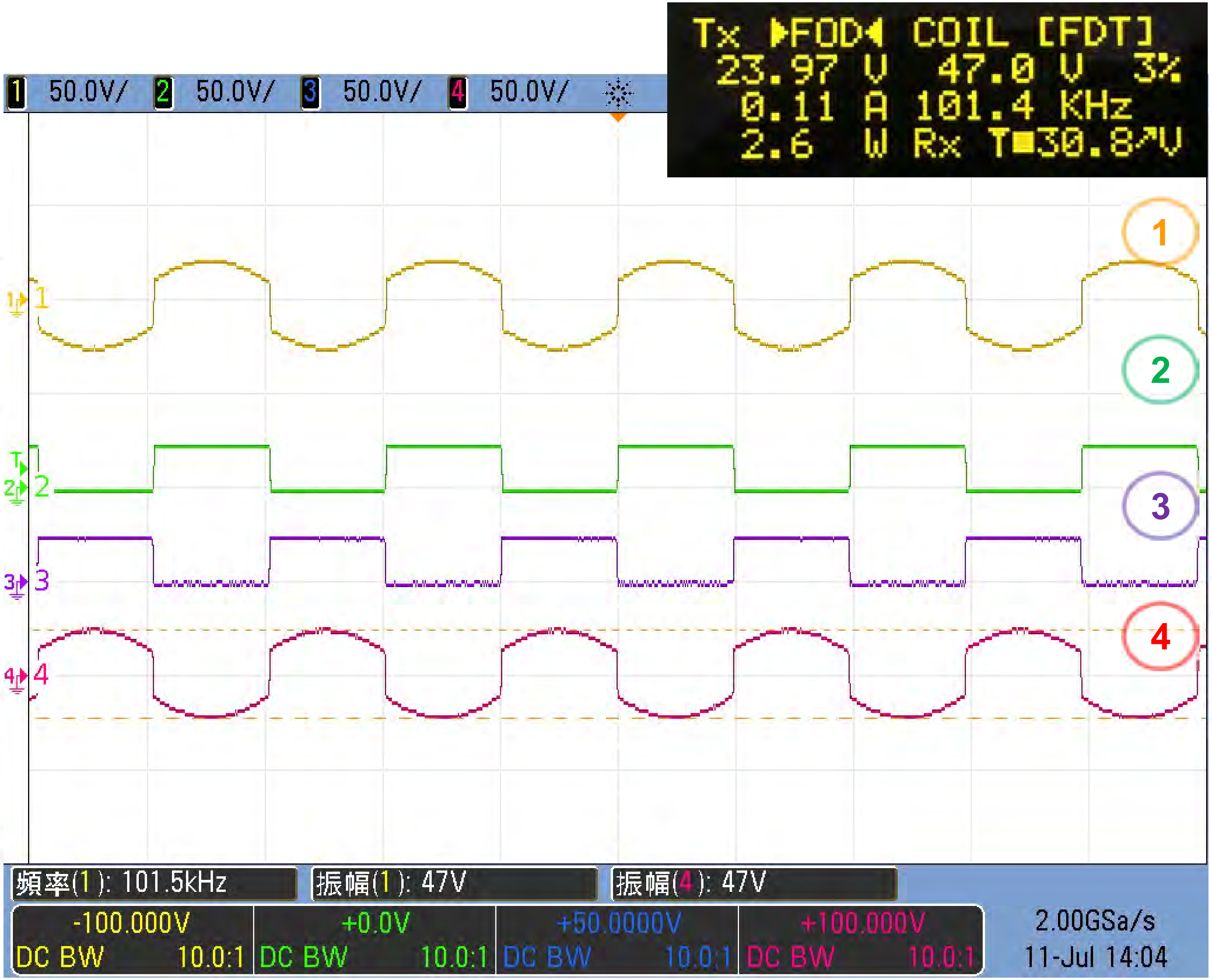
3 Drive terminal B
Switch device output terminal
(inverting)

4 Coil terminal B
L-C oscillation point
(inverting)

Complete analog configuration schematic



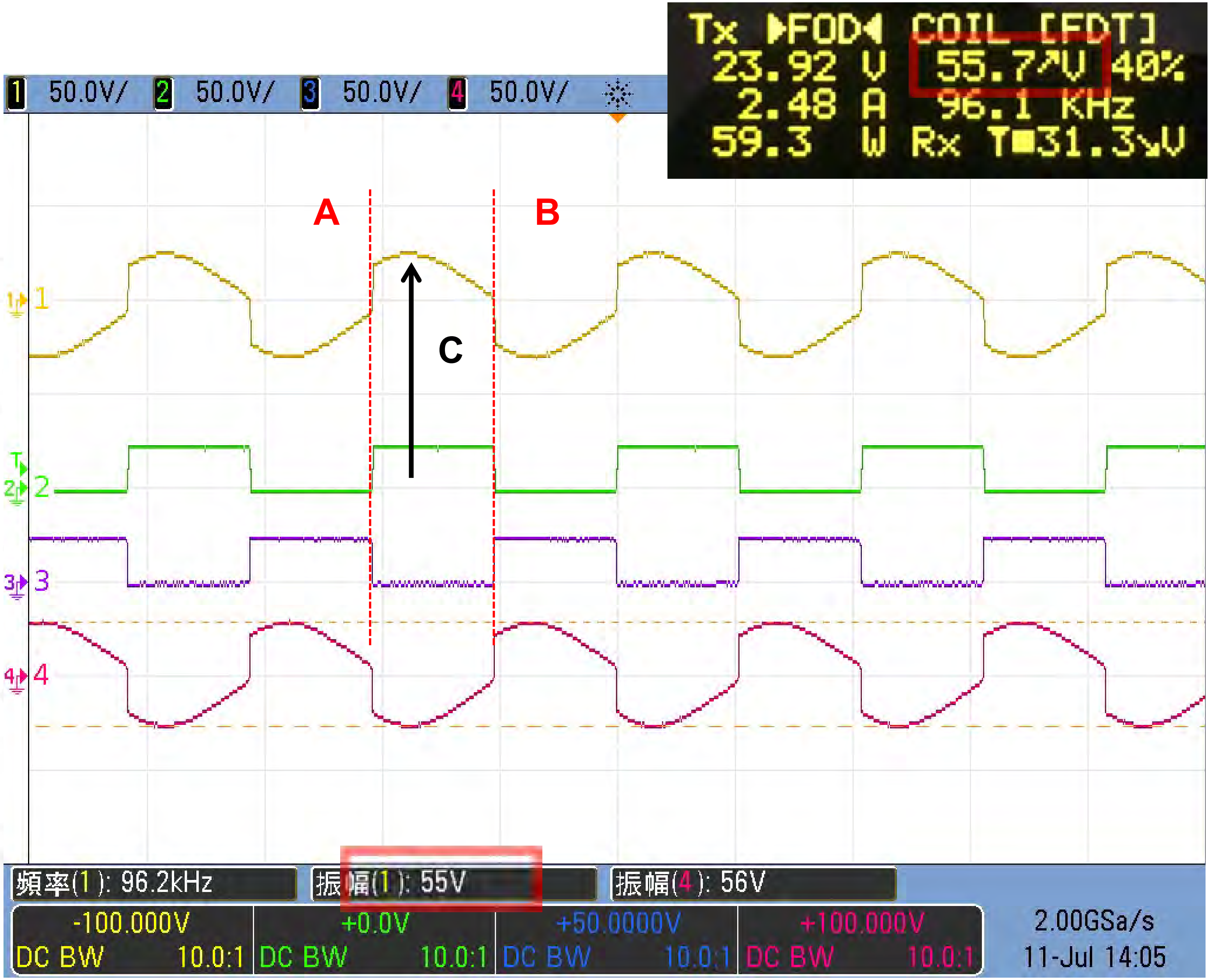
X03. Driver output and coil resonance C-L-C



In a C-L-C circuit with a α-winding coil, the voltage decreases progressively from the highest voltage at the coil lead to zero at the center point of the coil wire.

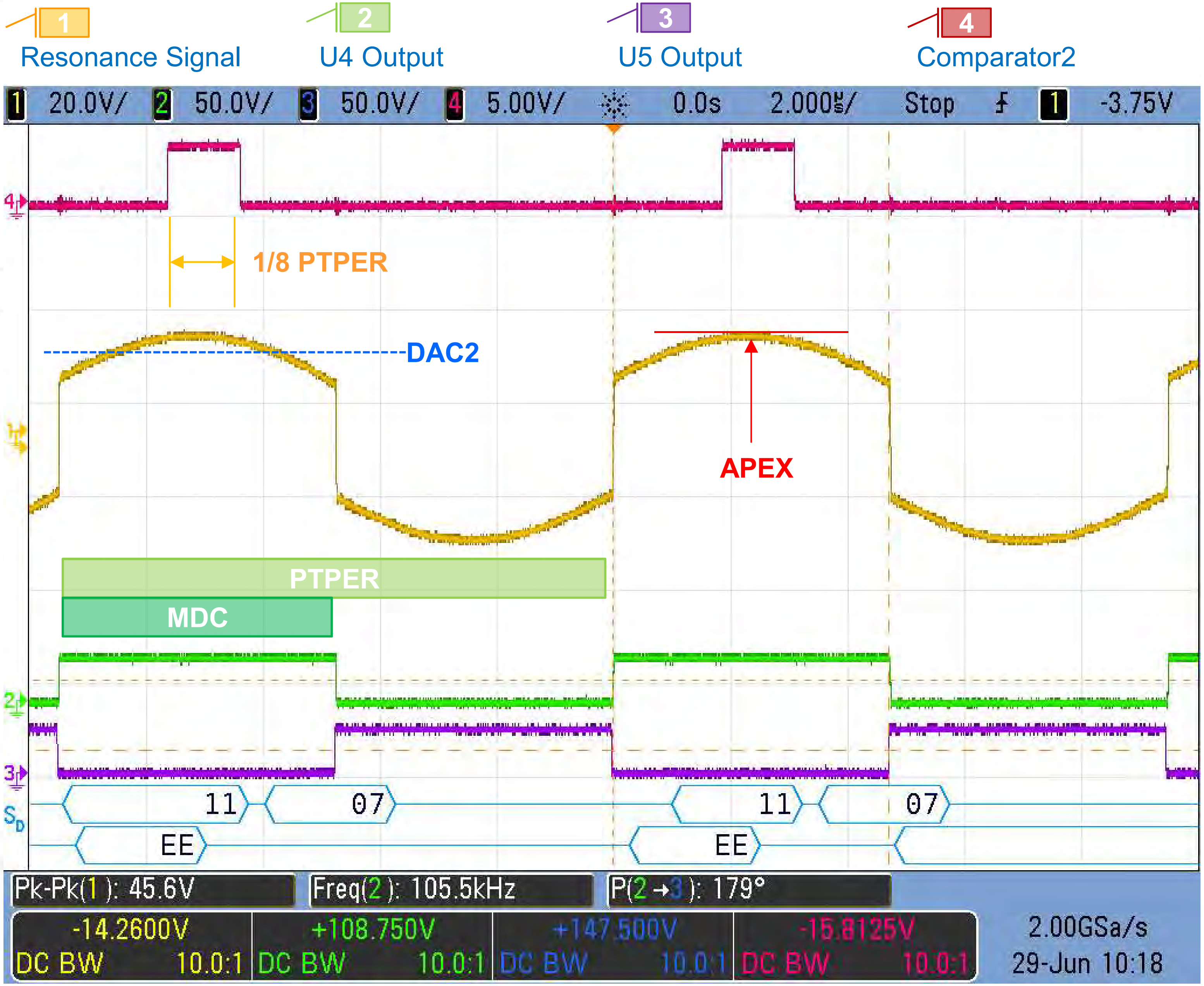
On the coil, the voltage is the highest on the outermost circle and is the lowest near the center, creating the ideal distribution of electromagnetic field strength for wireless charging.

X04. Drive load - force changes



The graph on the left shows the waveform measured with an oscilloscope, and at the bottom of the graph the built-in automatic measurement values are shown. The picture right below these values is the plug-in display module of power supplier module for debugging. The readings are measured by the main controller. It takes complex technologies to achieve accurate measurement of 100 kHz AC peak-to-peak value on a single board circuit. Power regulation requires precise control of the coil voltage. The drive cycle increases and decreases between A and B. C at the peak position is the determination point for the force usage. When there is no force (0%), C is at the center of A and B. After overload, C will move towards A. When C overlaps with A, the force usage reaches 100%.
In the graph, the force usage is 40%.

X05. PWM Period and Coil Resonance Signal



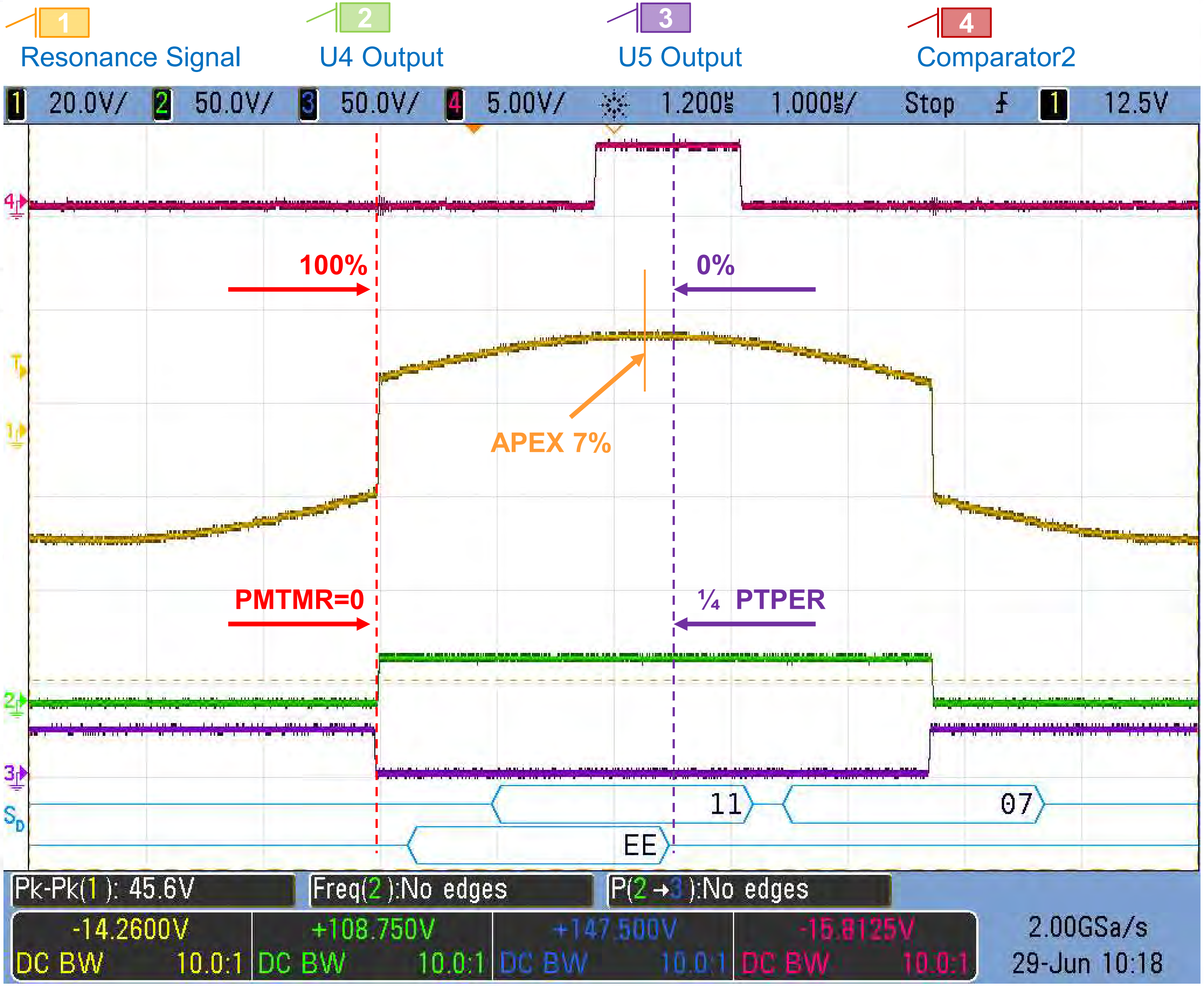
The PWM output has a fixed odds ratio of 50%, and the main period is PTPER. Half of the fixed values is set to MDC. The DAC2 voltage is determined by the comparator 2 output triggering at the high level width.

When the high level width is lower than 1/8 PTPER, it indicates that the DAC2 voltage is too high, the trigger time is short, and the DAC2 voltage should be lowered. On the contrary, if the trigger time is too long, the DAC2 voltage should be increased.

The technical goal is to measure the time for the peak of the coil resonance signal peak APEX.

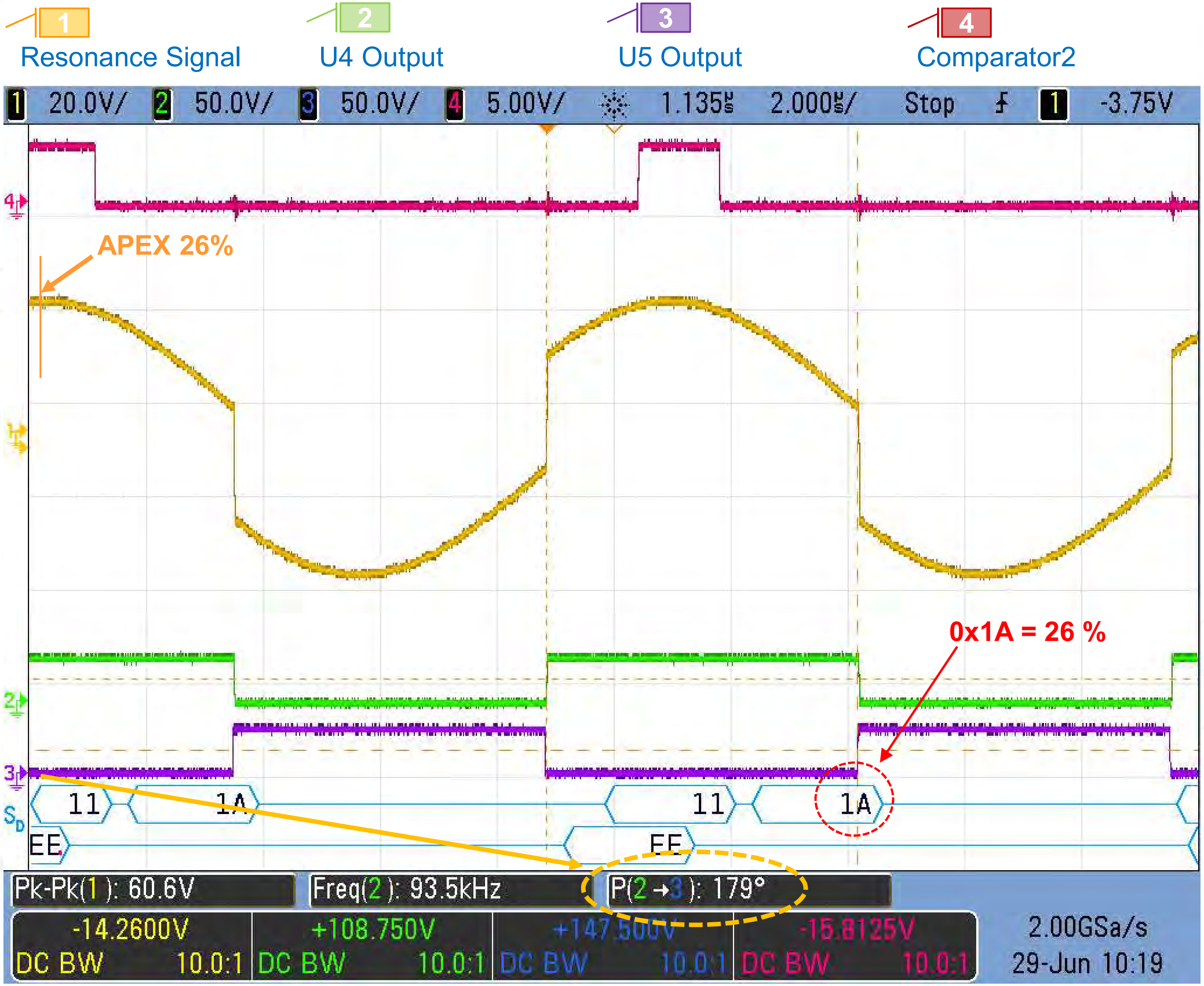
This point will move with the coil resonance configuration and load conditions.

X06. Thrust usage definition



Measure coil resonance signal between CX4 and the coil. The signal will be linked with DrMOS U4 which is connected to PWM1H.
Reset starting point of the main clock PWM1. When PMTER=0, the output of U4 turns from Low to Hi, the voltage of the coil will also start to rise.
When there is resonance on the coil and there is no load and other resistance at all, the APEX will fall in the position of one quarter of the main cycle.
When there is a load on the coil, the fixed point will start to move towards the PWM starting point. When the apex reaches the PWM starting point, it indicates that the maximum thrust usage has been reached. This defines that when the apex is at 1/4 cycle, 0% of the thrust is used . When the apex reaches the position of the PWM start point, 100% of the thrust has been used.

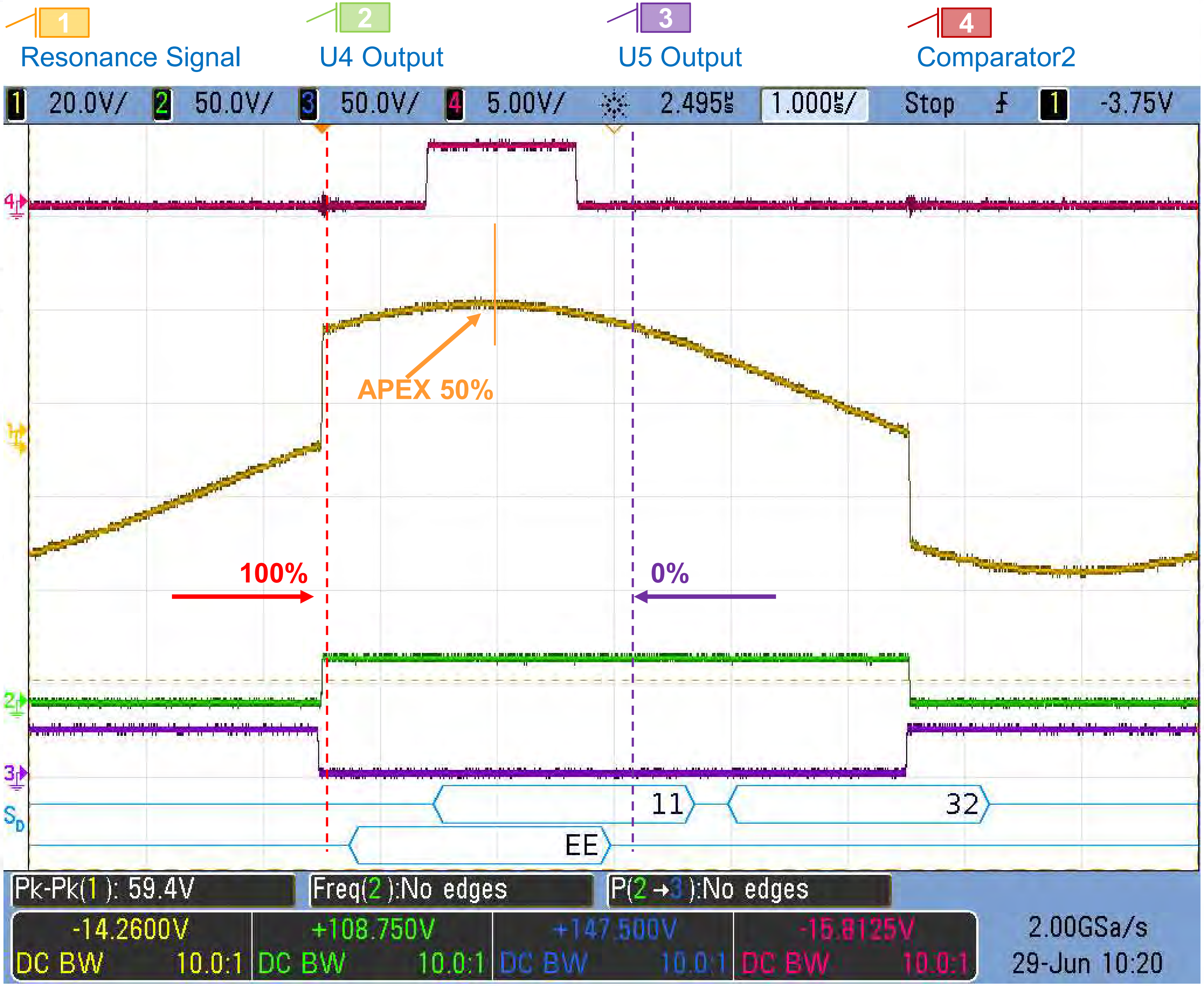
X07. Full-thrust / 26% thrust Output



Signals 2 and 3 are respectively output at both ends of the DrMOS output. When the signals at both ends are 180 degrees out of phase, the full thrust output is carried out.

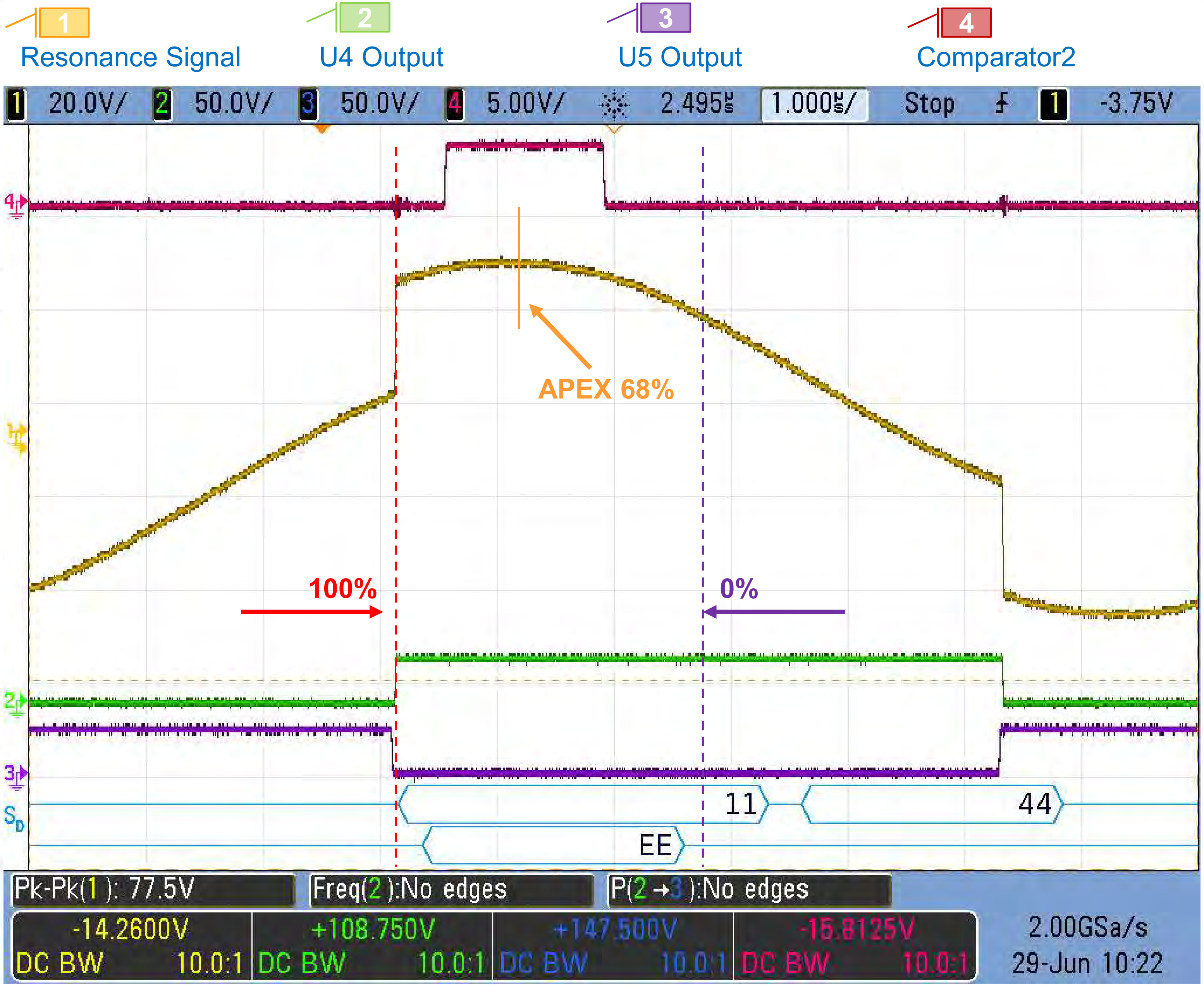
In order to facilitate the description, the amount of thrust used in the IC is transmitted in tandem to the display. The result of the calculation is 26%. The result of this calculation is the signal analysis result of the previous cycle.

X08. Full-thrust / 50%thrust Output



When the load increases, the peak will move to the PWM starting point.
PWM is the non-fixed frequency of the frequency conversion system
Therefore 0% of the position is 1/4 PTPER which will change with frequency.
Note that the comparator 2 trigger result that occurs in this cycle will not be processed until the PWM1 interrupt of the next cycle.

X09. Full-thrust / 68%thrust Output



After the load is increased, the calculated thrust usage will increase, but there are many influencing factors.
List a few factors:

Under the same output power
The coil distance becomes far
→ the efficiency is deteriorated
→ the thrust usage is reduced

Under the same coil distance
RX terminal resonance capacitance increases → thrust usage decreases

Under the same coil distance and output power
driving voltage at the TX terminal increases → thrust usage reduces

Design to maintain the amount of thrust used below 70%. If the used thrust is more than 80%, the insufficient power supply is prone to occur.

X10. Thrust Control 78° Phase Shift / 50% Thrust Output

This is an example of low load output
The position of the apex can be changed by the PWM phase shift. That is, the peak can be moved to a position where the thrust usage is calculated by 50% under no load conditions.

The way of reducing thrust through the phase shift can reduce the thrust to the maximum by 90 ° phase-shaift. And the full thrust can be achieved when the phase shift reaches 90° .

The thrust control here is to reduce the thrust usage by 50% through the PWM phase shift.