

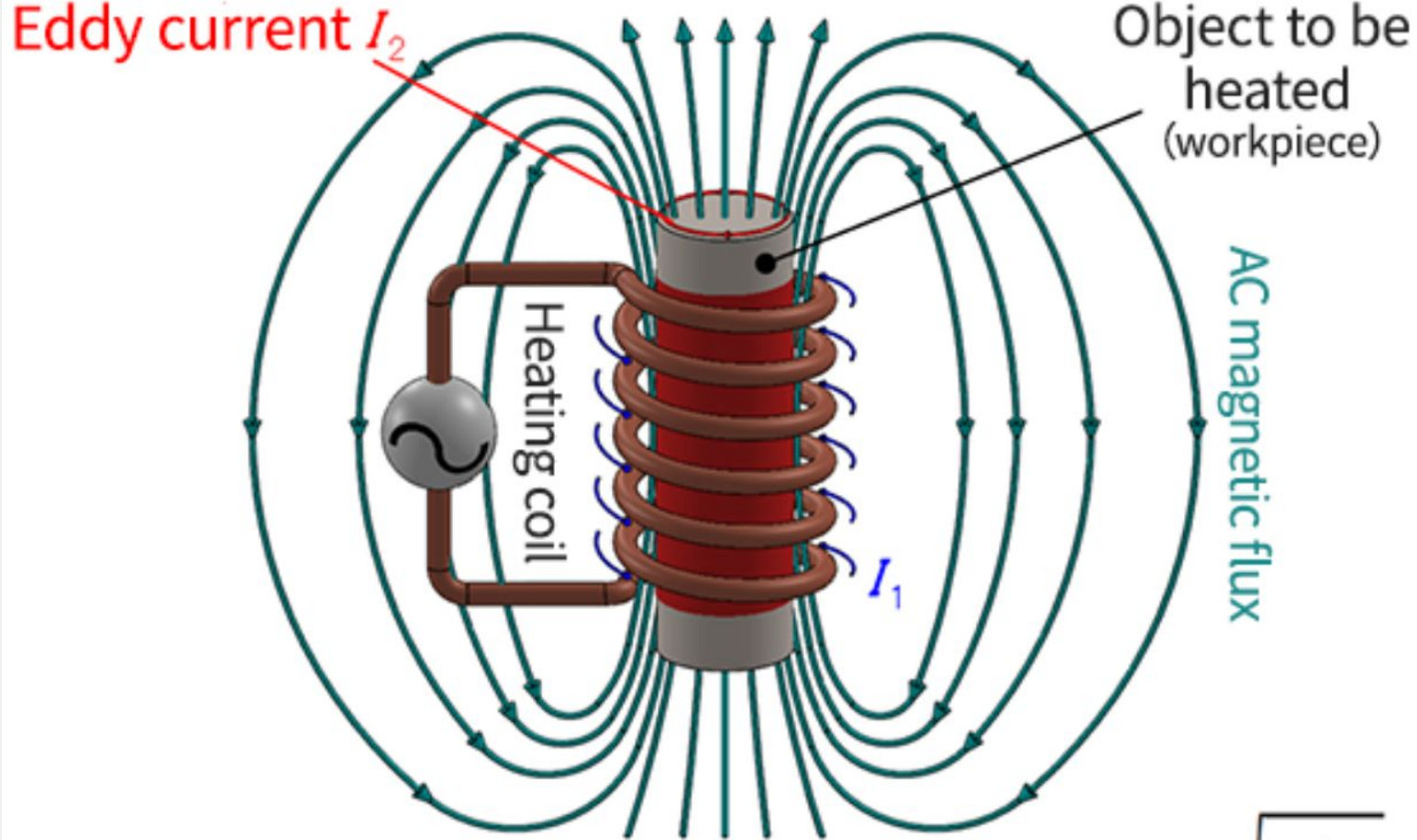
Piec indukcyjny

Szymon Romanowski

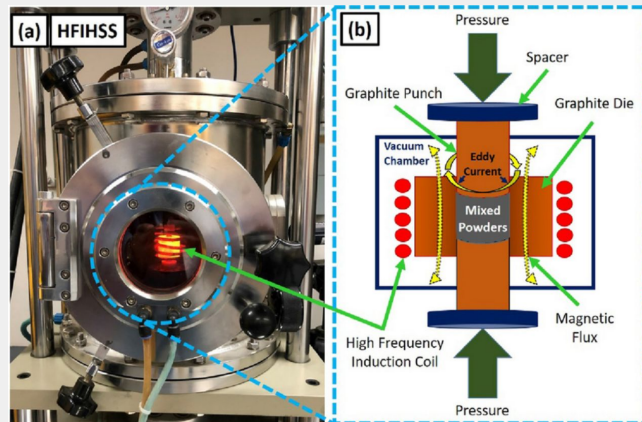
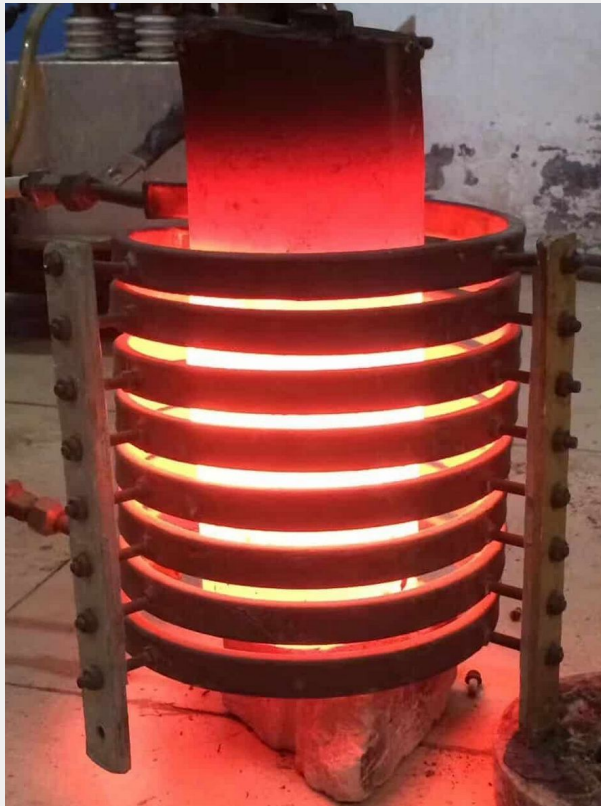
O czym będę opowiadał:

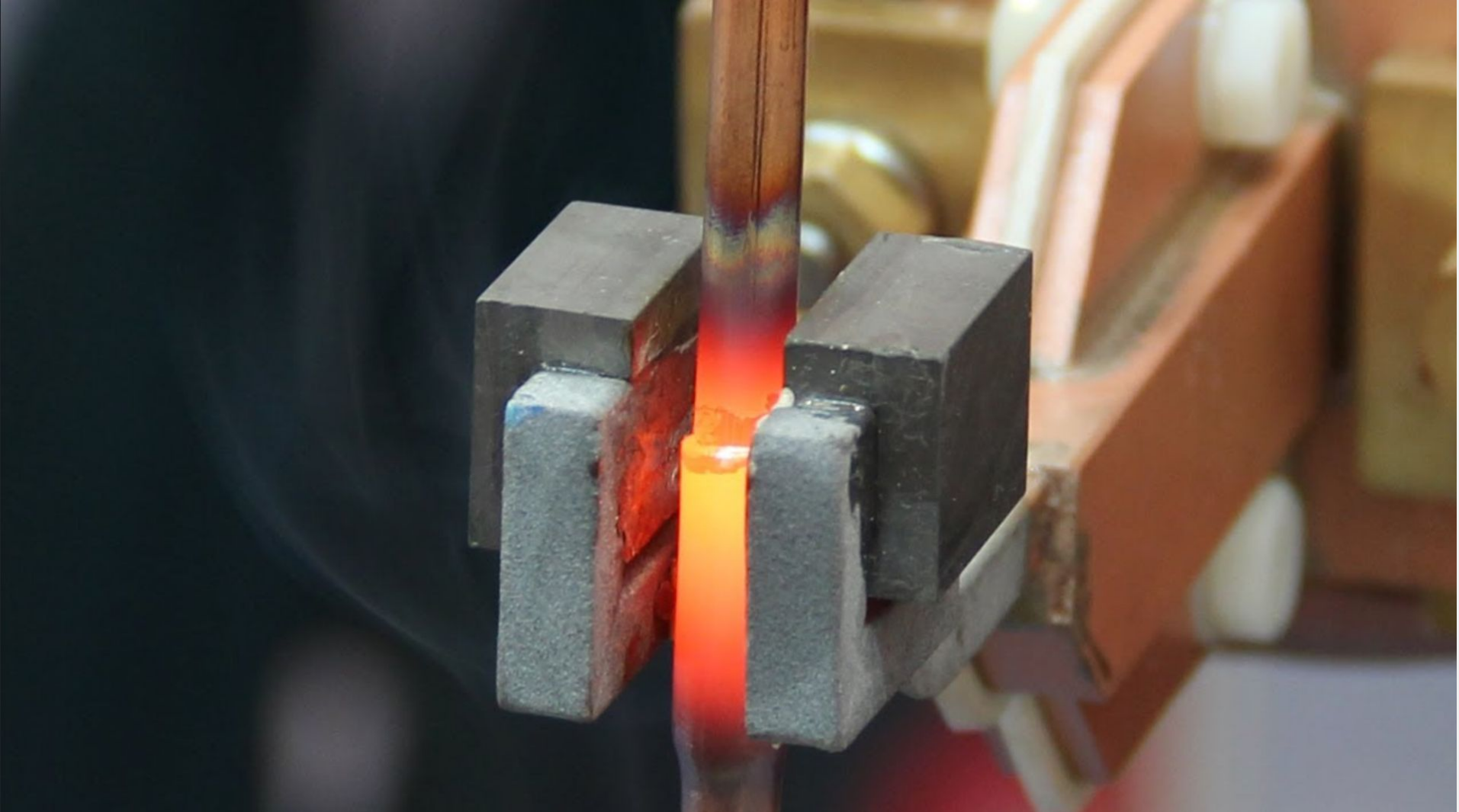
1. Ten slajd ma najwięcej tekstu spośród wszystkich slajdów;
2. Co to znaczy, że indukcyjny?
3. Obrazy wybrane - cechy technologii, zastosowania;
4. Pierwszy kontakt z internetem, czyli zaufaj mi, znam się;
5. A co jeśli wcale nie? Historia porażek;
6. Dygresja RTFM czyli czytaj uważnie noty katalogowe/manuale;
7. Drugi kontakt z internetem - nie ufaj nikomu, wszystko sprawdzaj;
8. Historia zwieńczona sukcesem;
9. Czyli kilka miesięcy pracy i jeszcze więcej czytania;
10. Prezentacja aktualnego stanu mojego projektu;

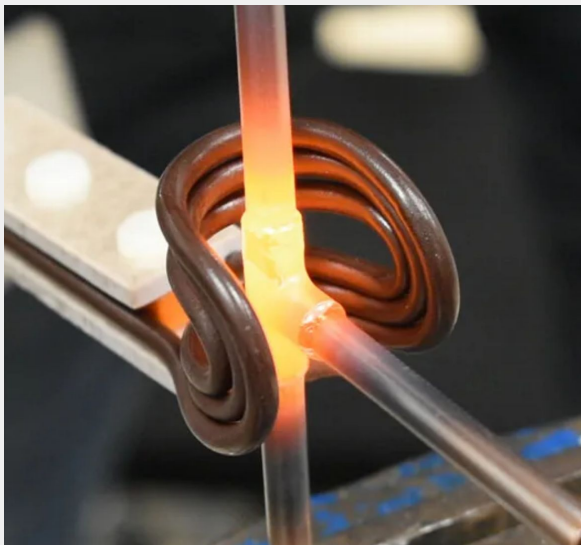
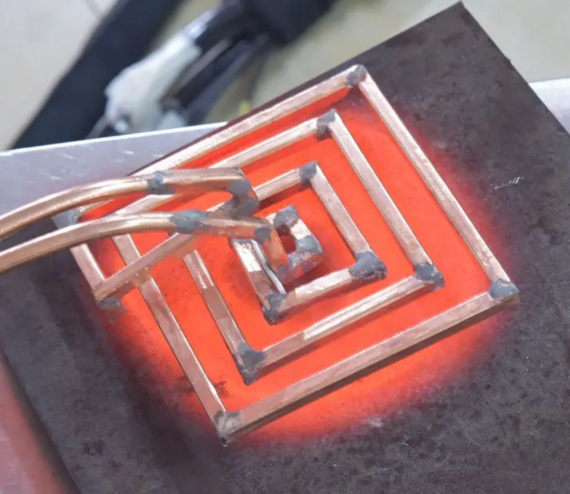




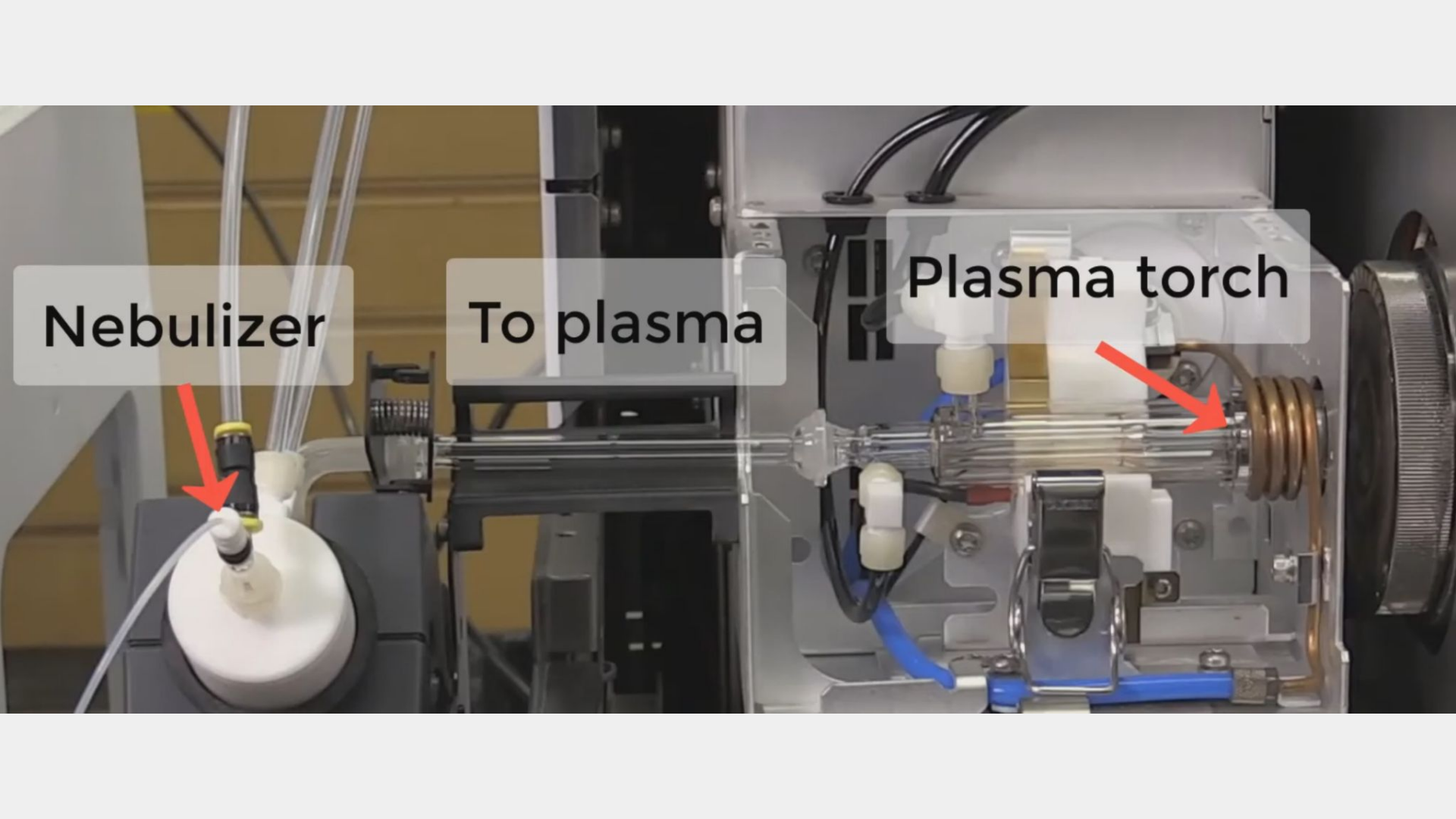
Skin effect: Current penetration depth $\delta = \sqrt{\frac{1}{\pi f \mu \sigma}}$









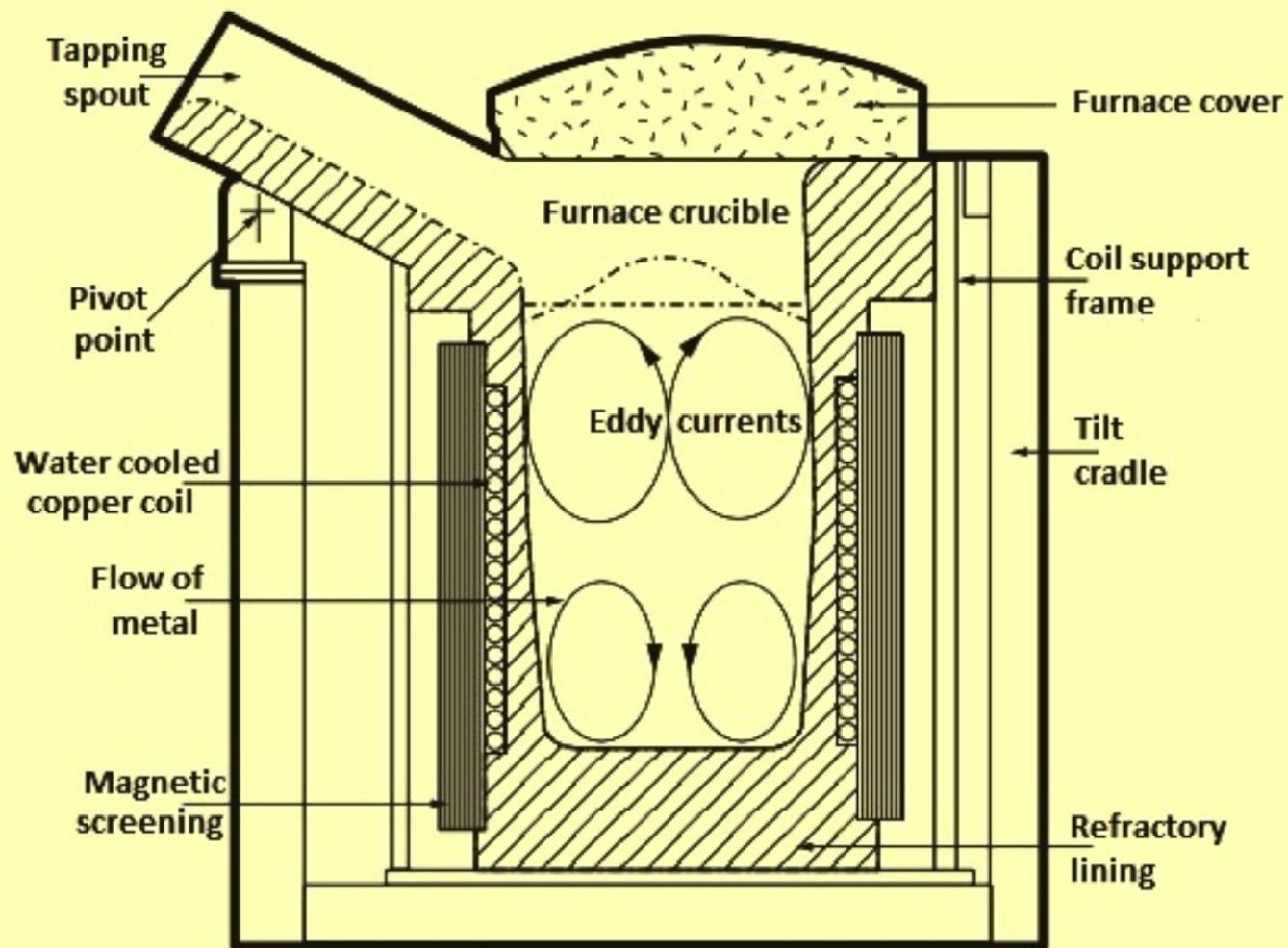


Nebulizer

To plasma

Plasma torch

Schematic diagram of a coreless induction furnace



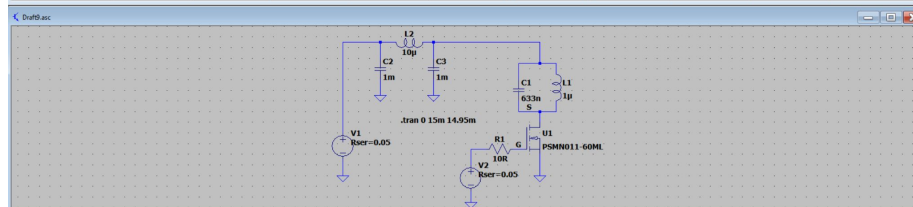
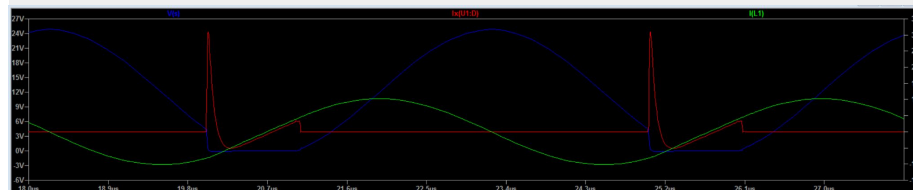
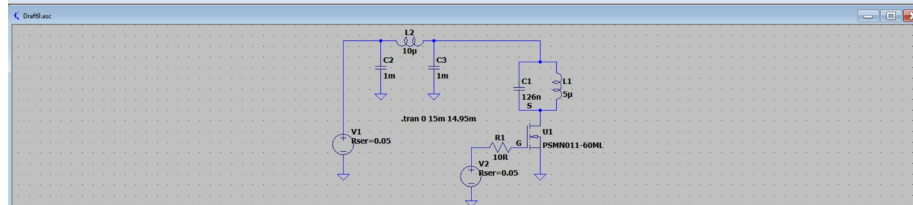
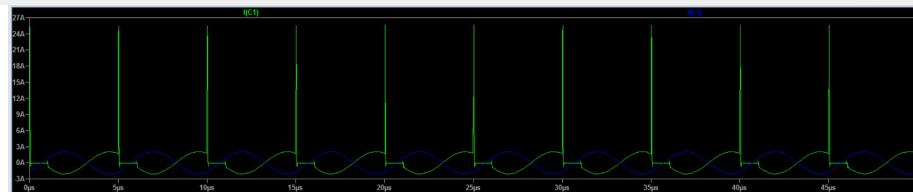
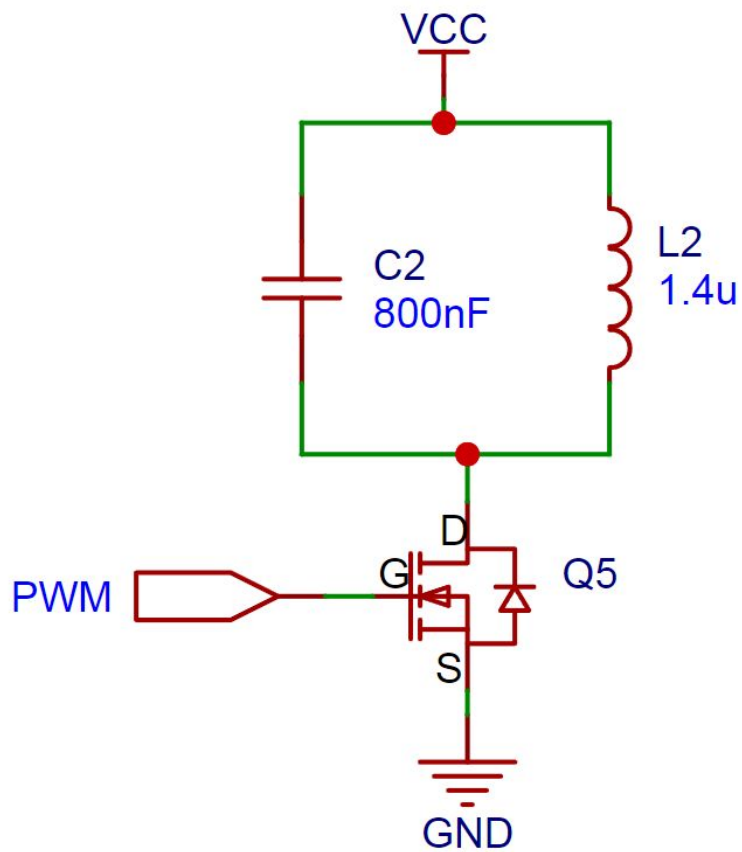


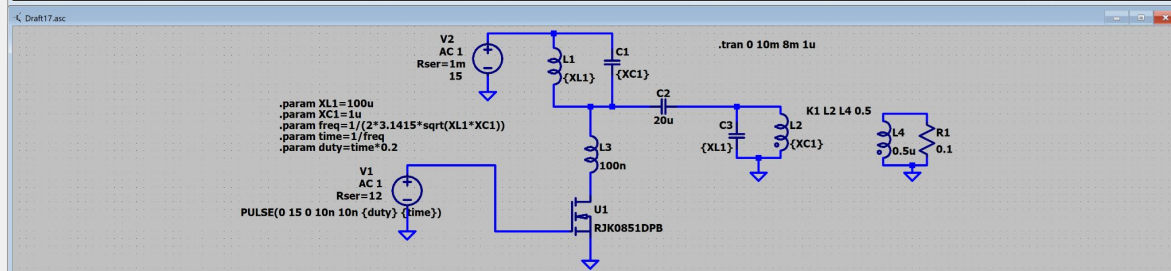
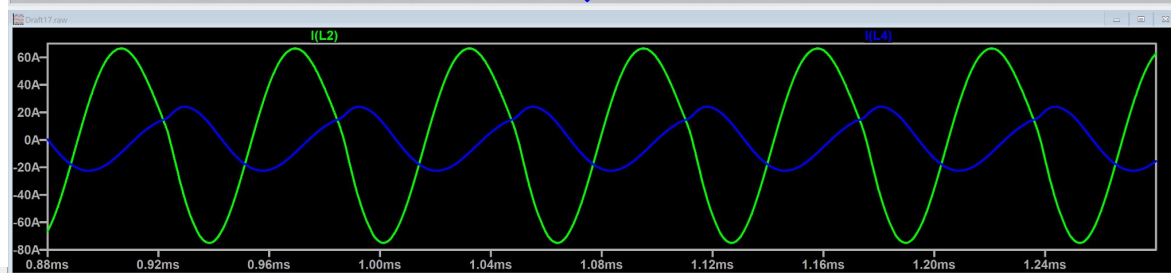
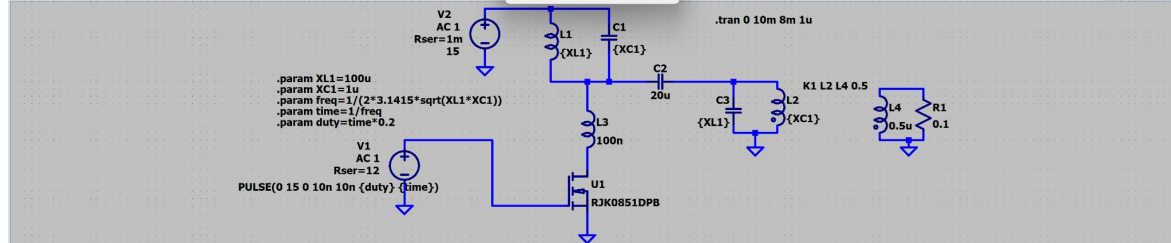
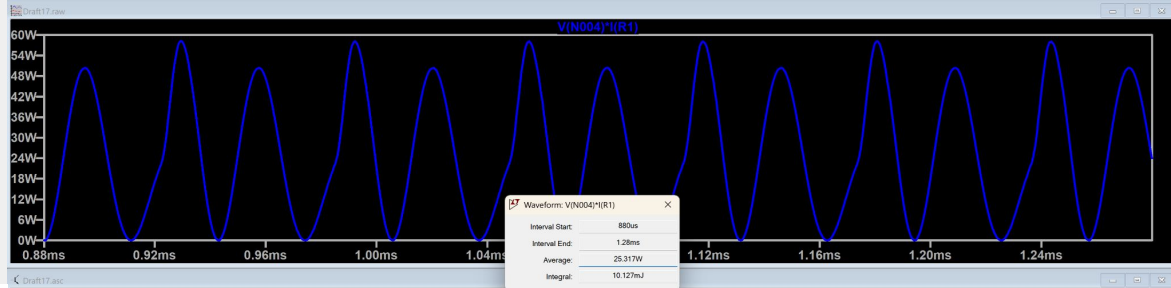
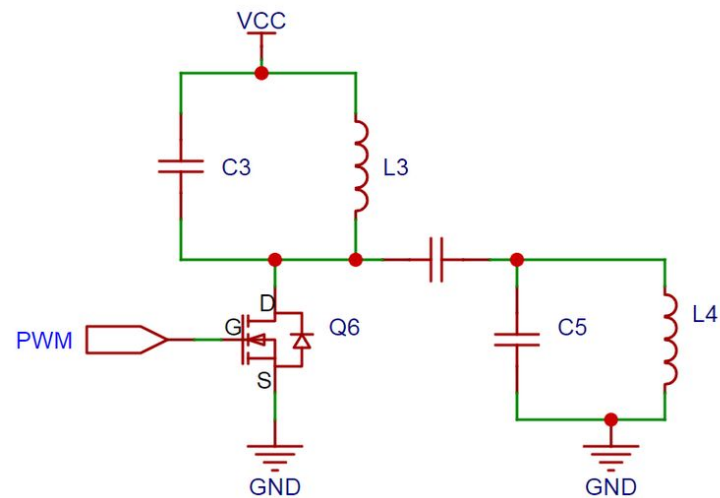


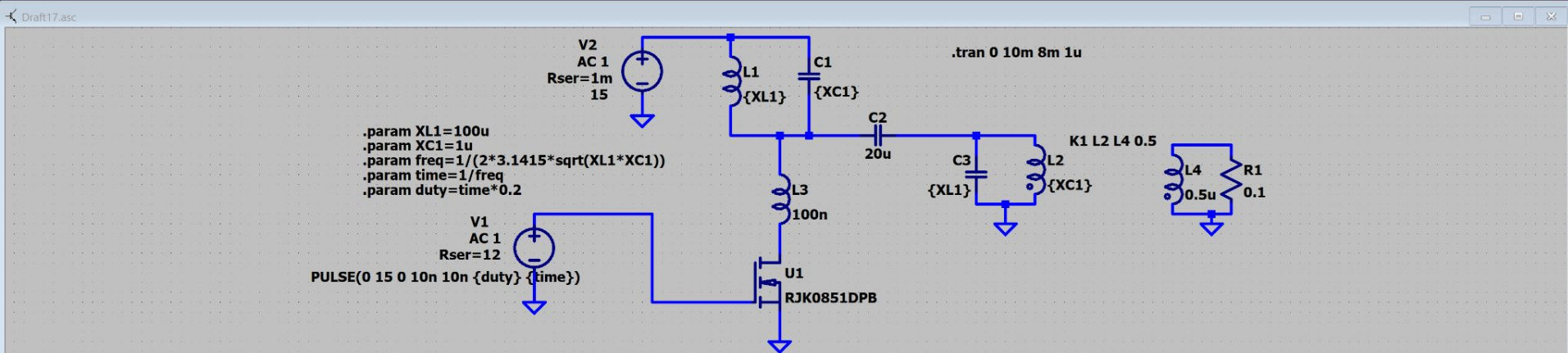
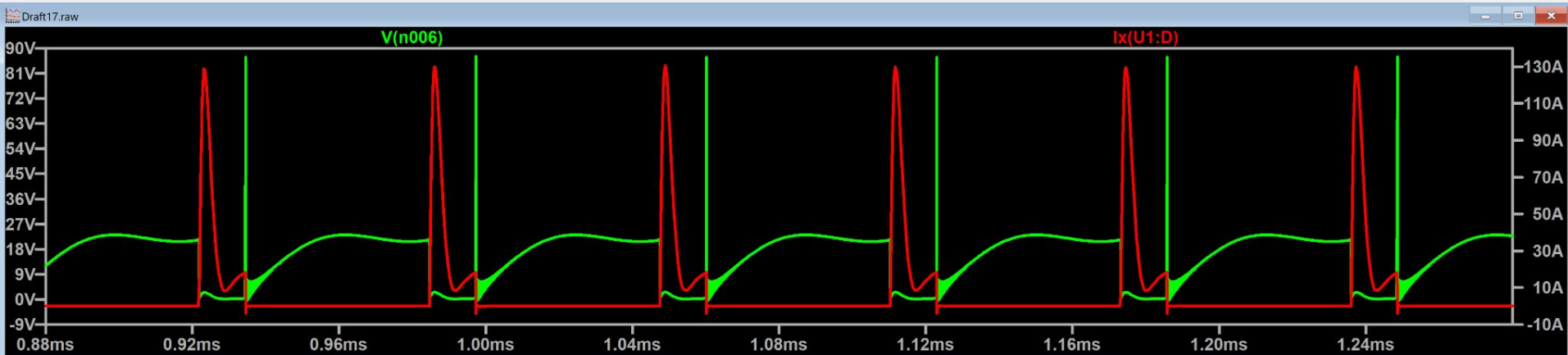


Po co pytać, trzeba robić

Przygoda numer 1.







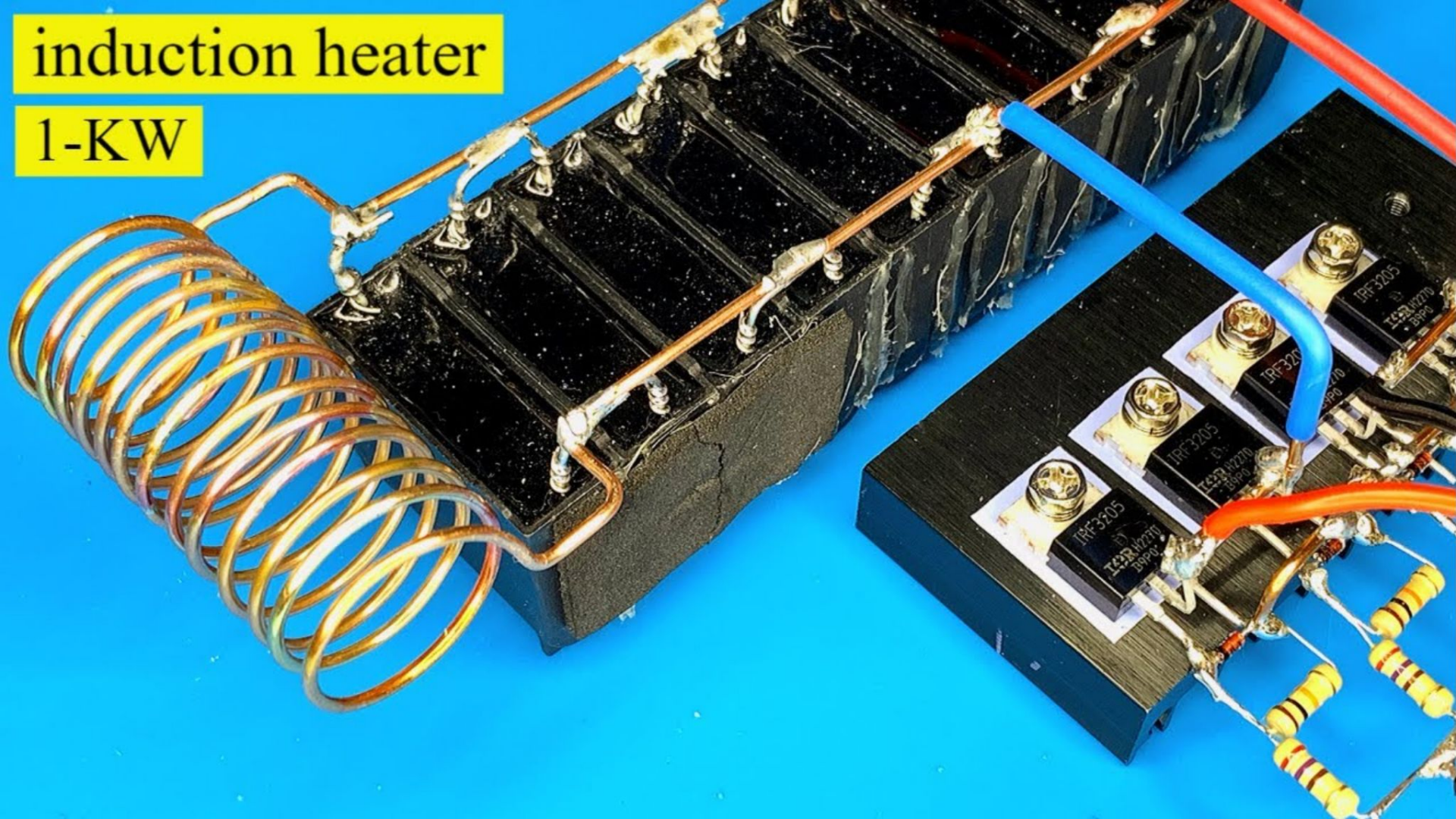


Może jednak zapytam

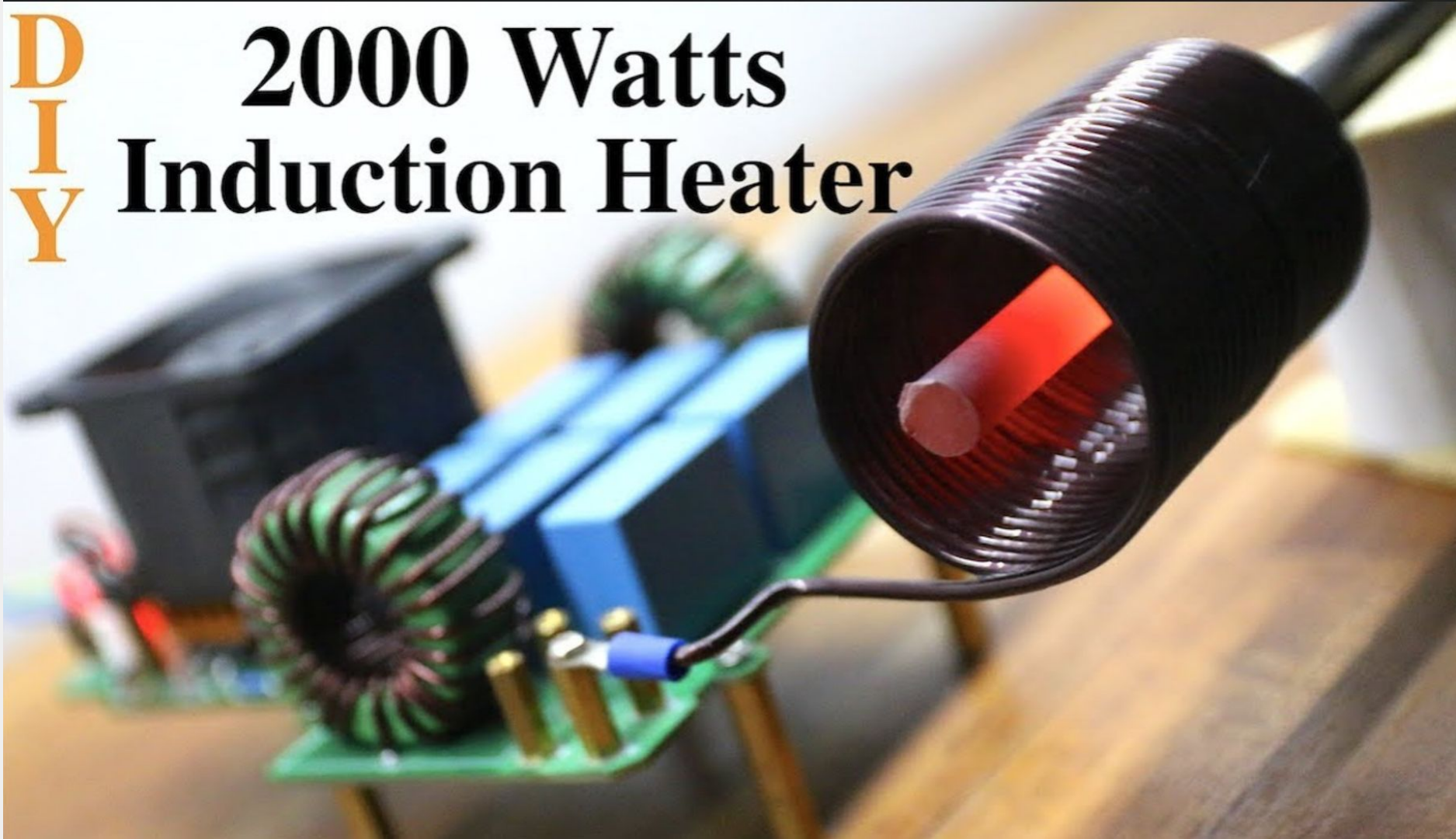
Przygoda numer 2.

induction heater

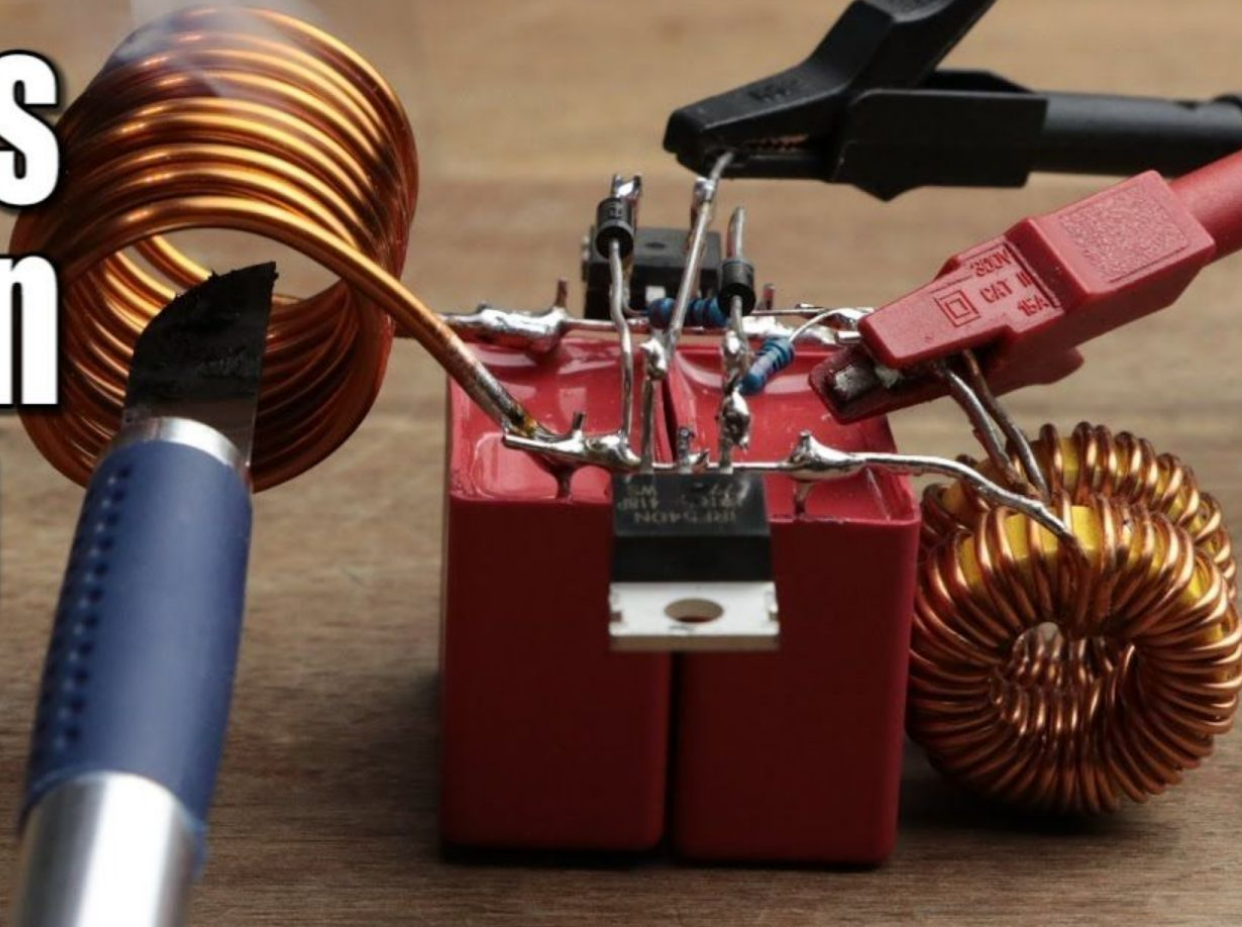
1-KW



DIY 2000 Watts Induction Heater



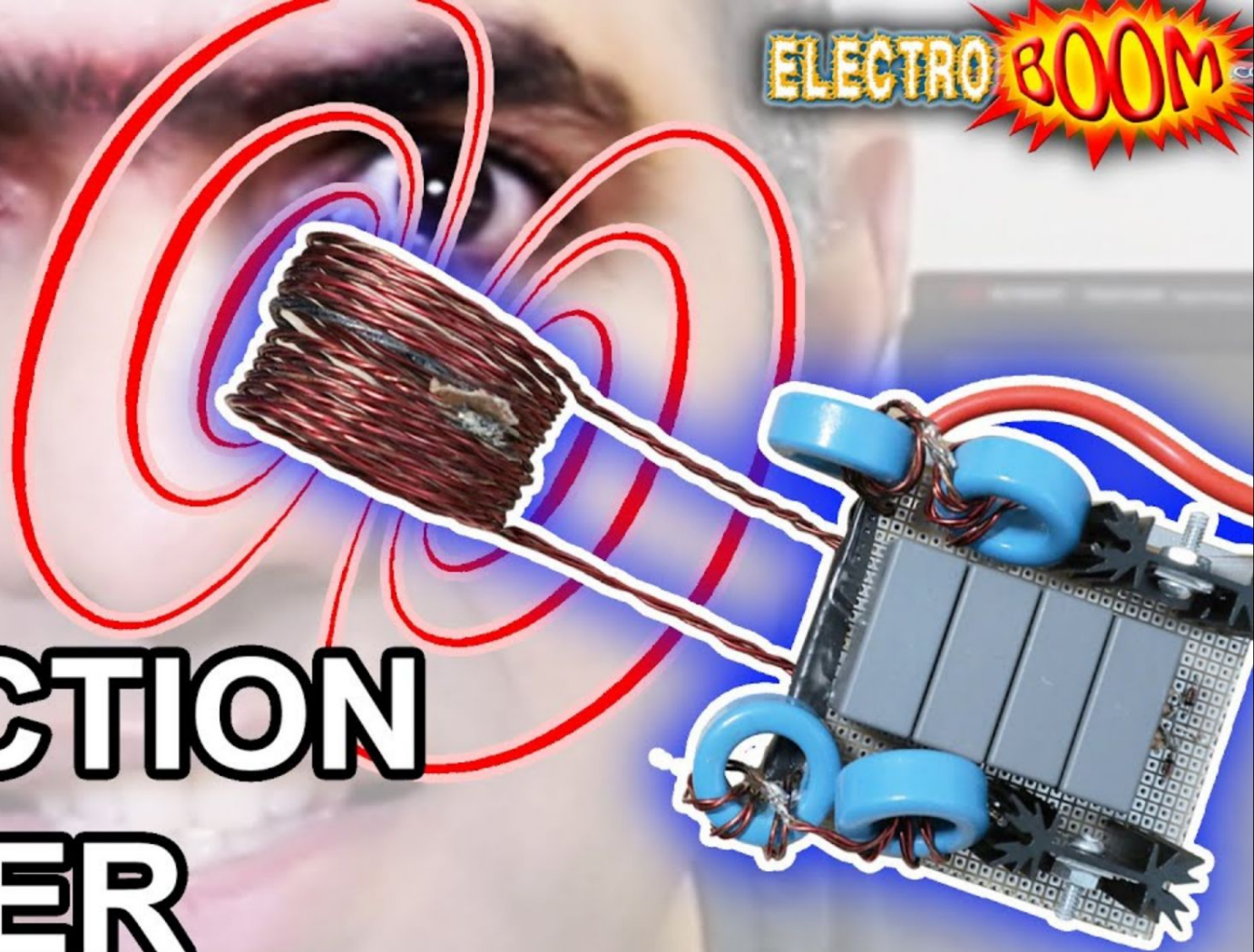
How Does Induction Heating Work?

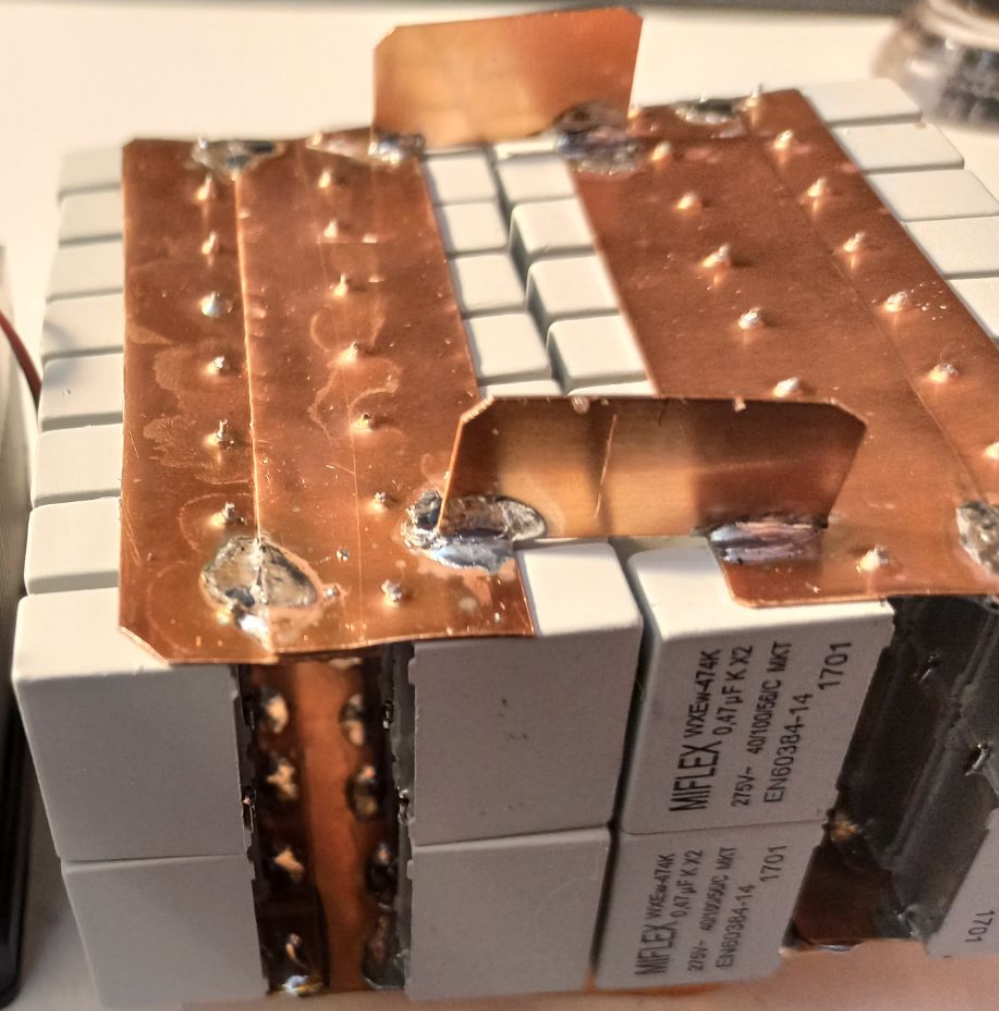
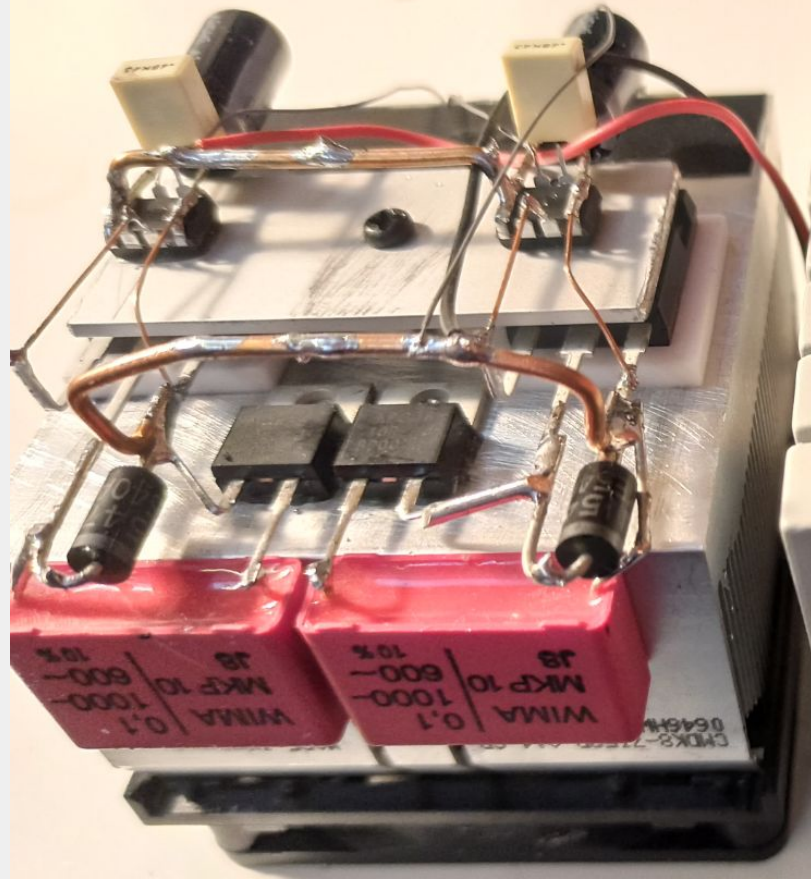


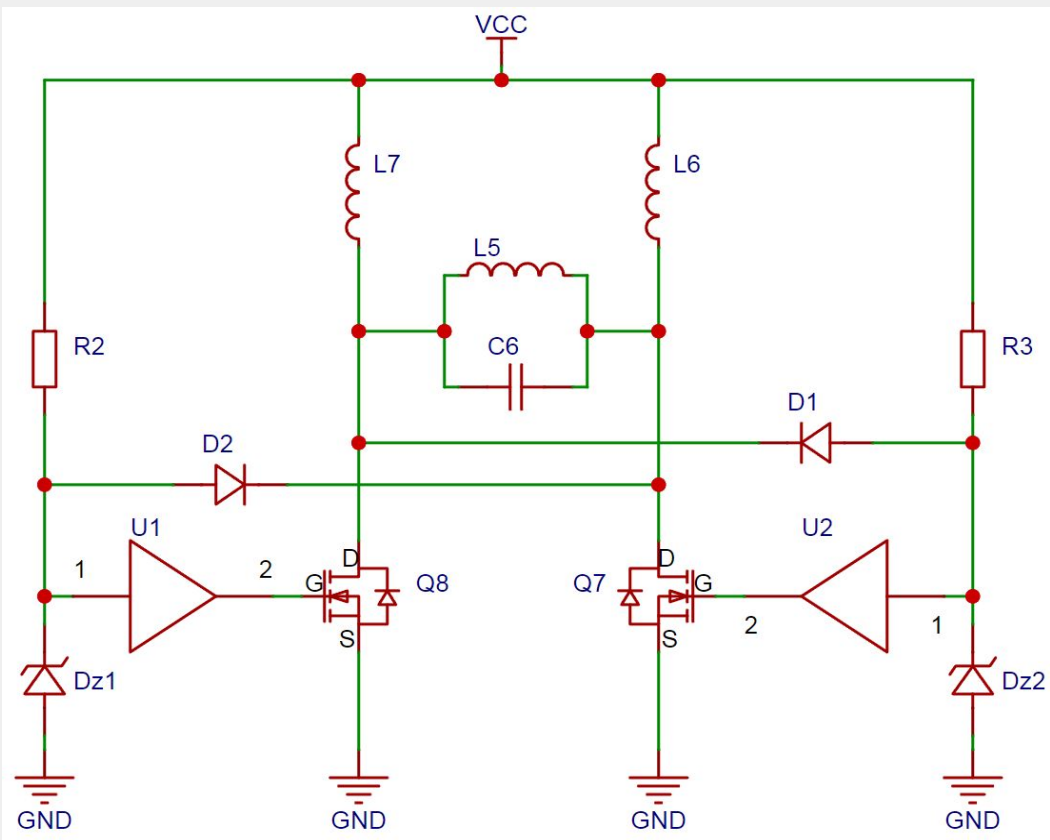


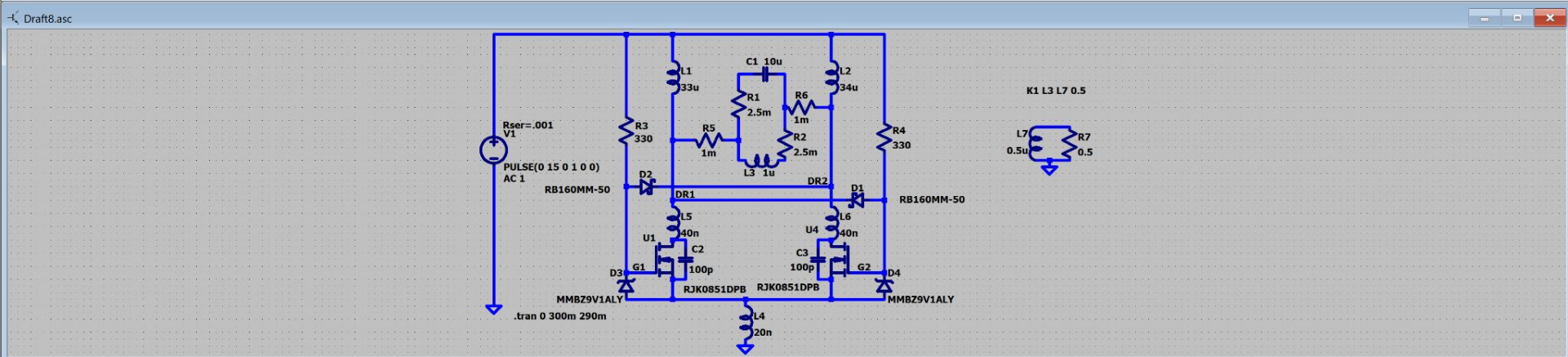
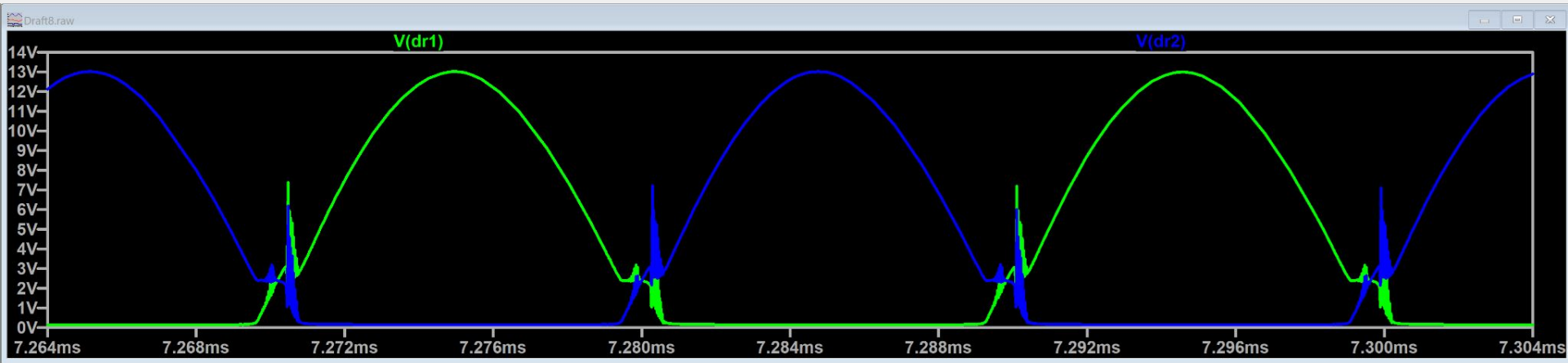
ELECTRO BOOM

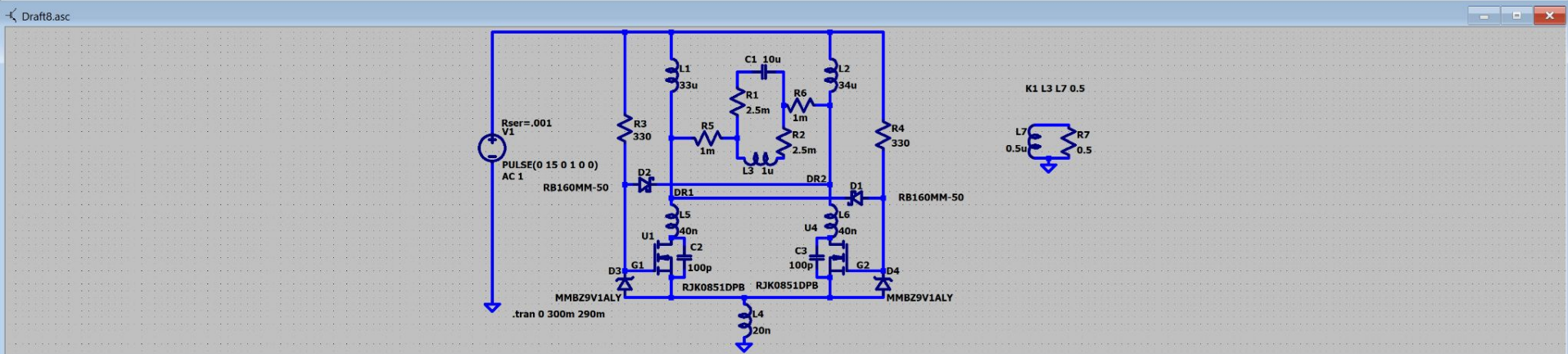
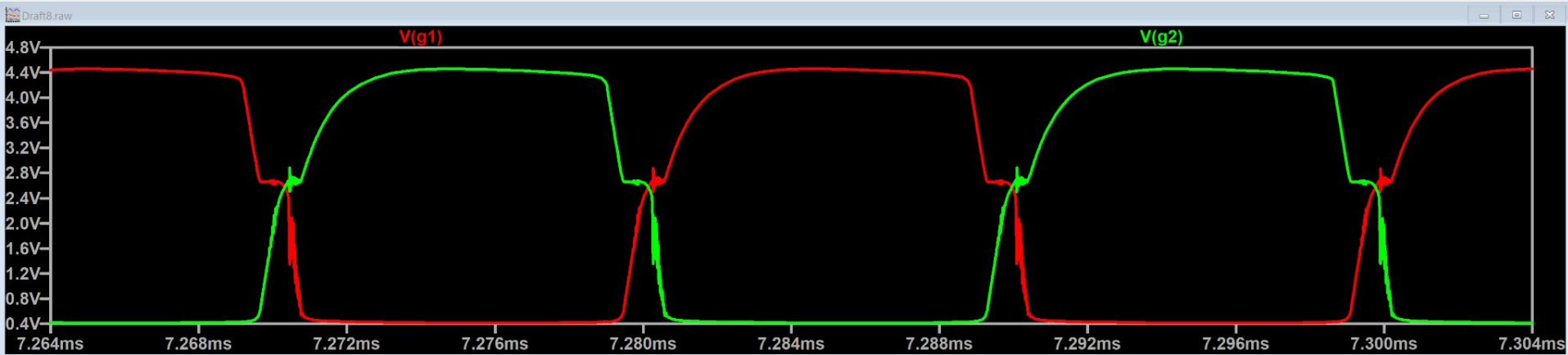
INDUCTION HEATER

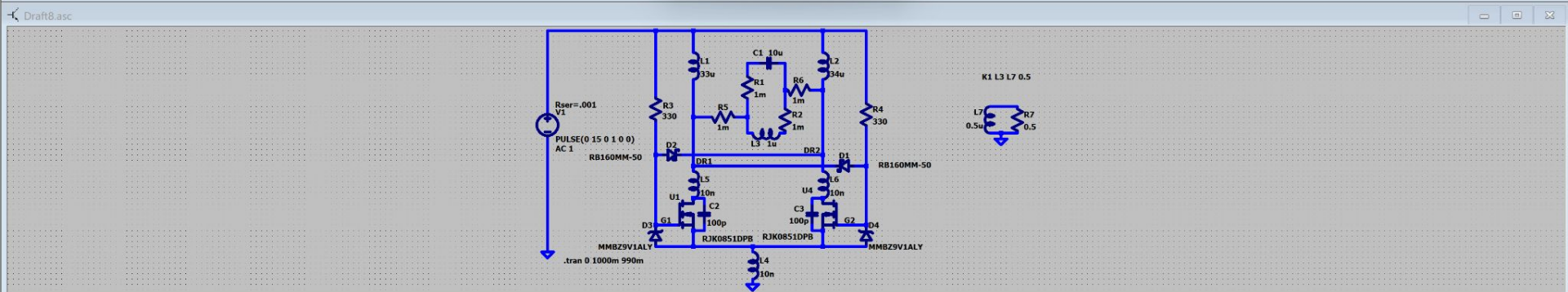
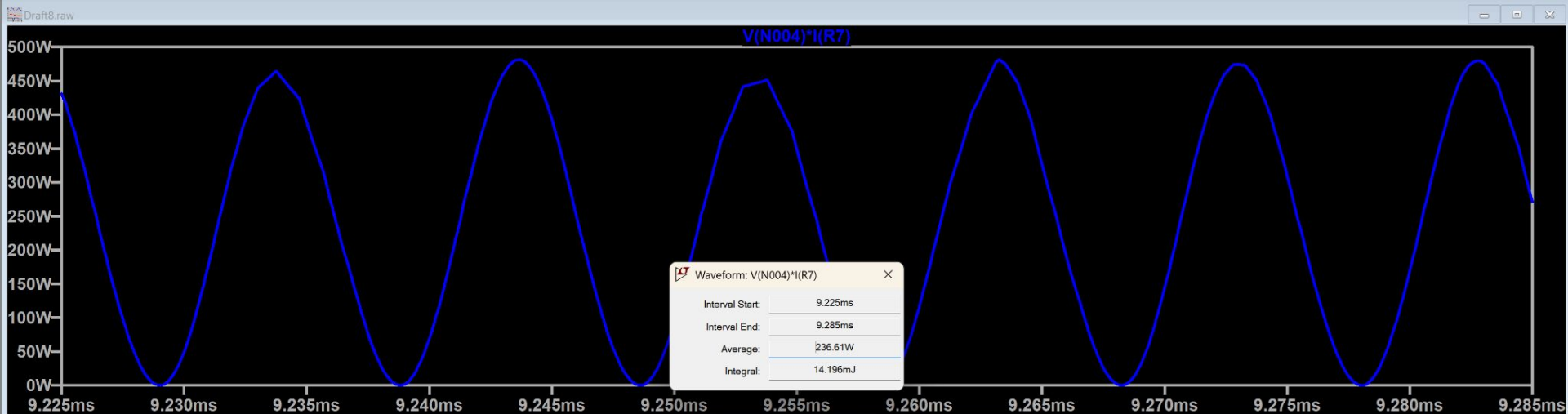


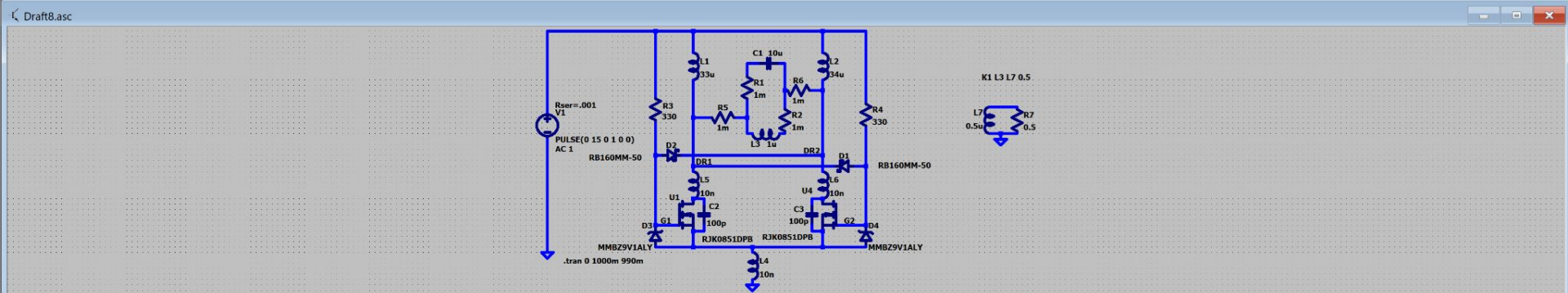
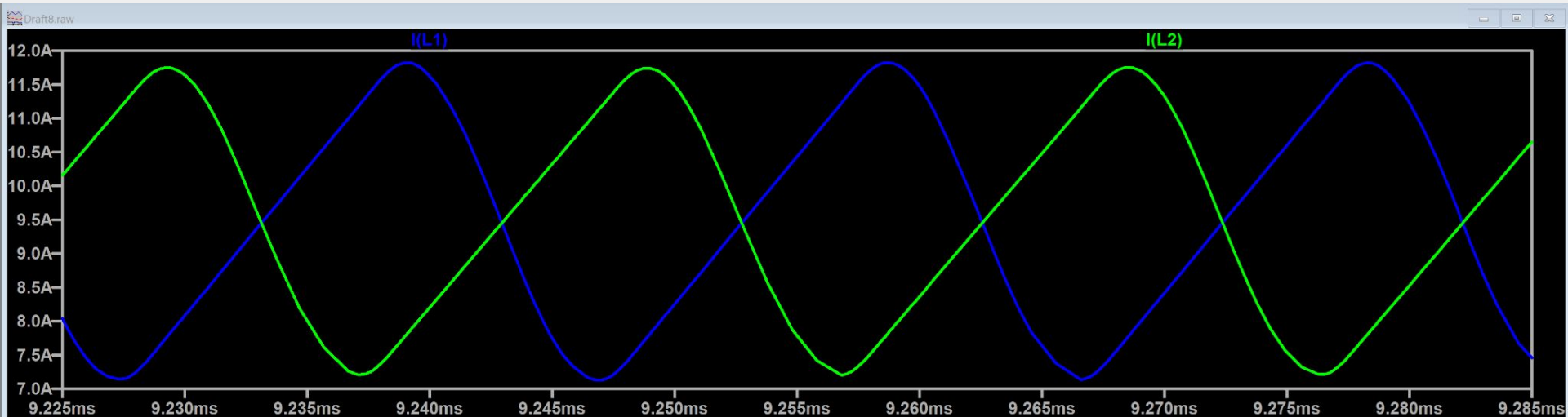


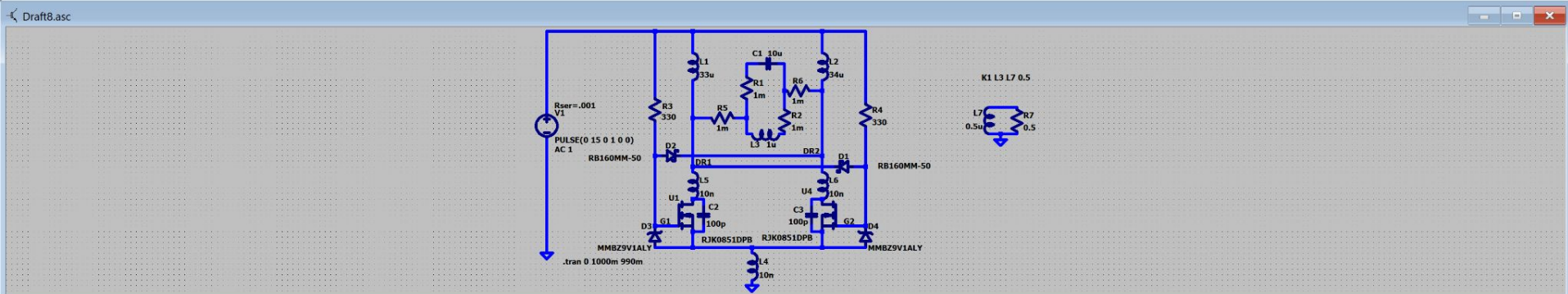


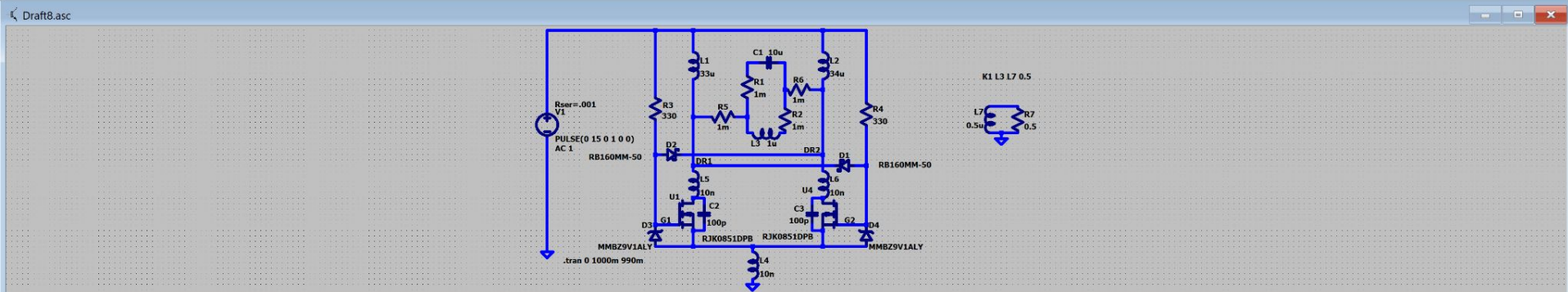
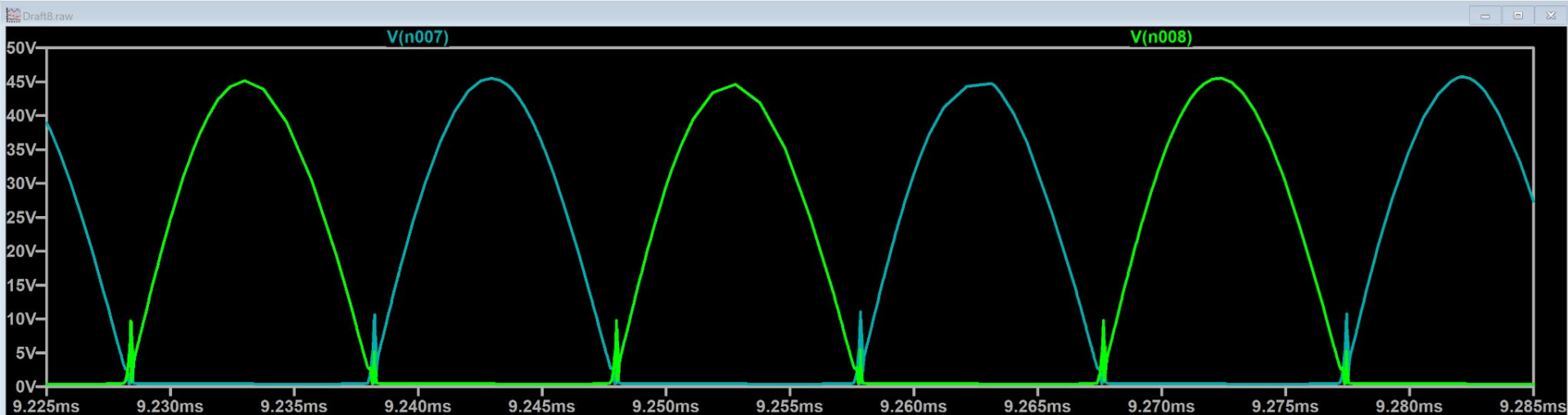


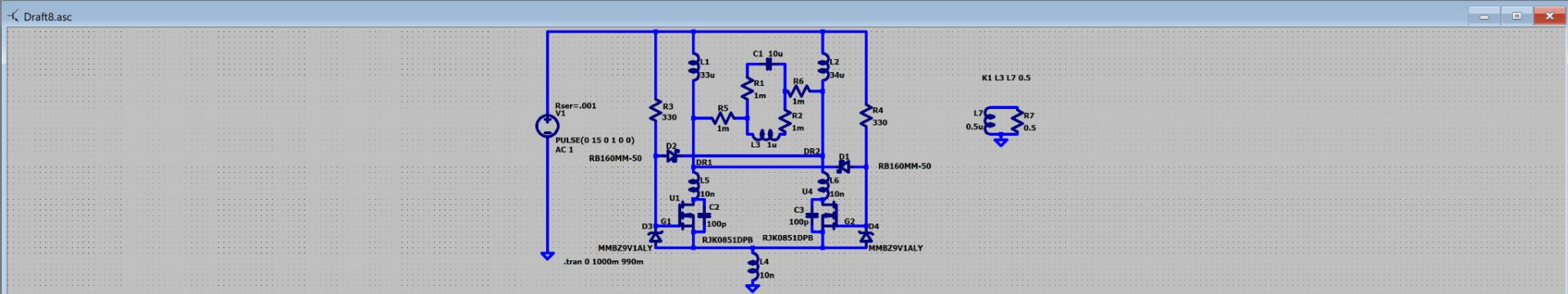
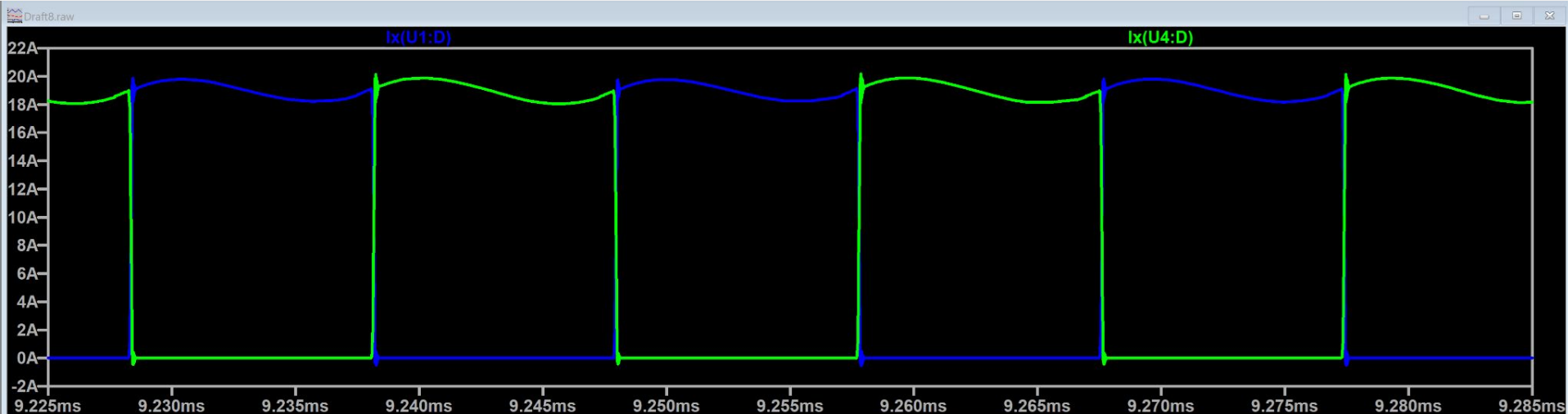


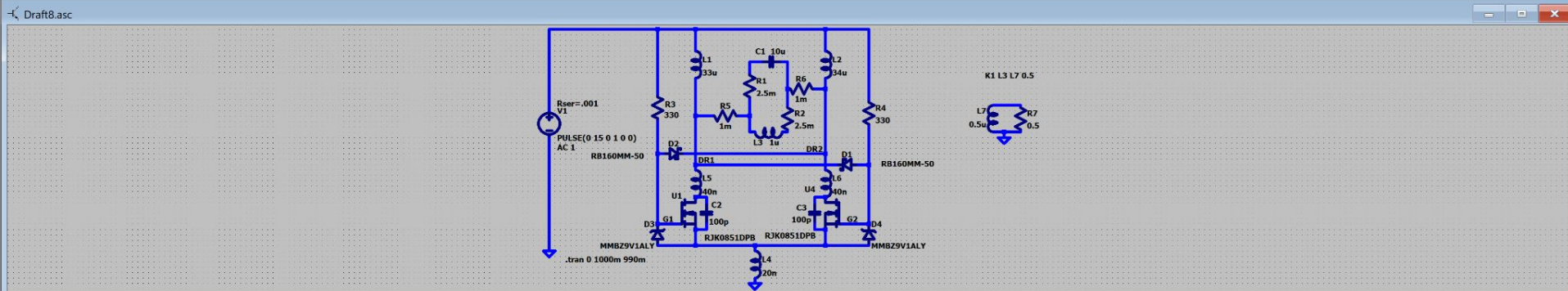
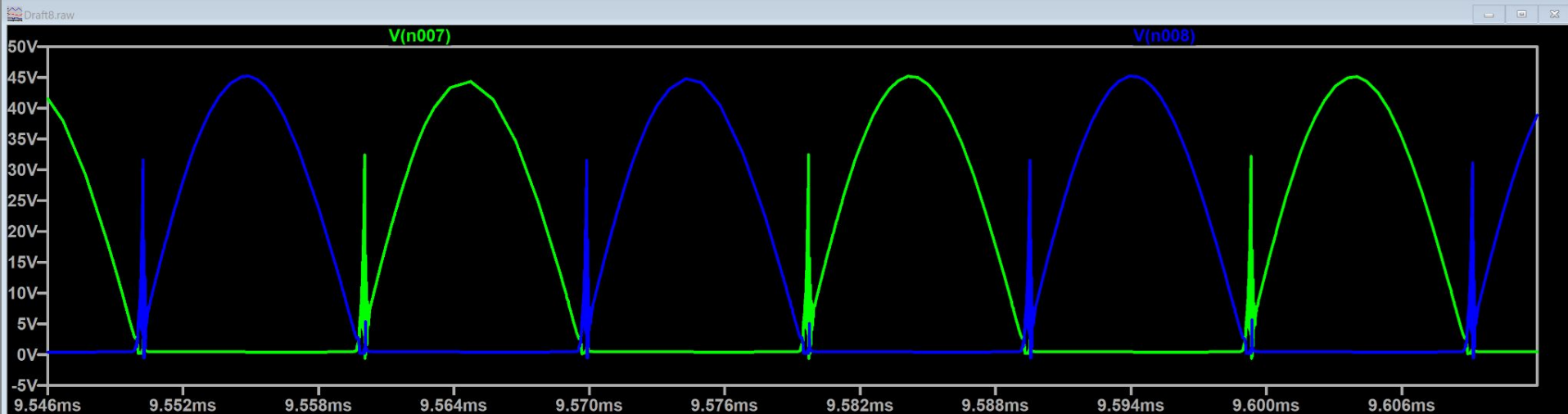


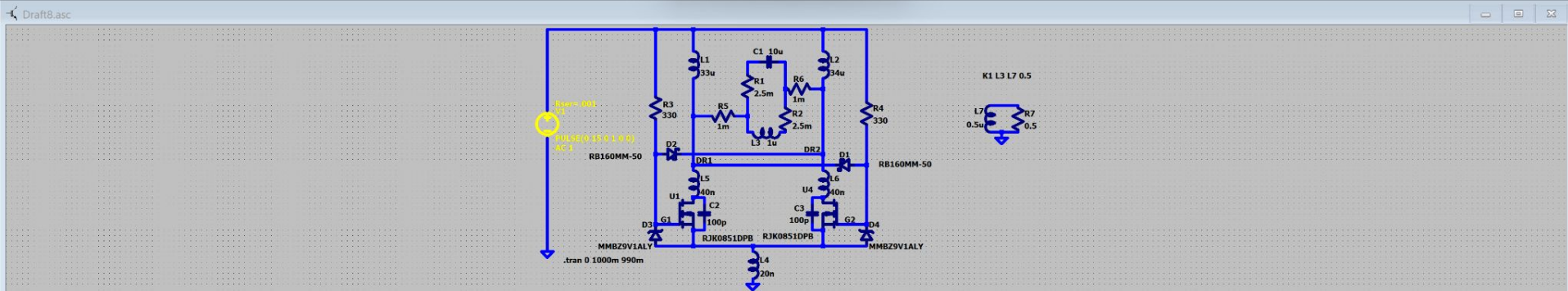
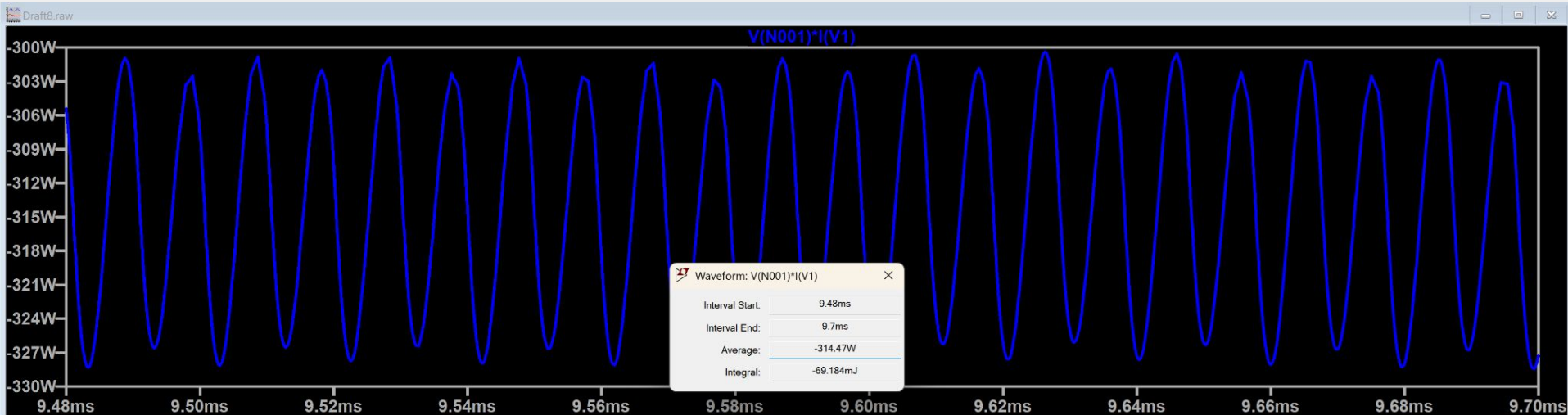


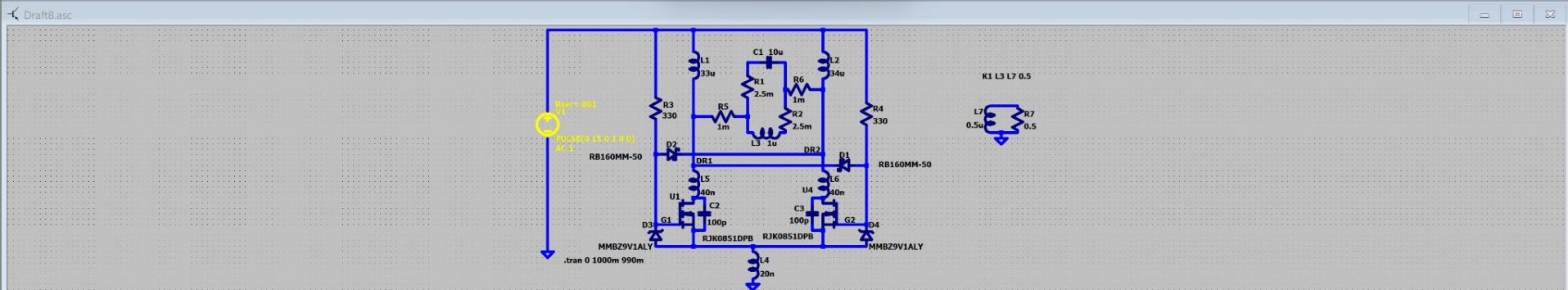
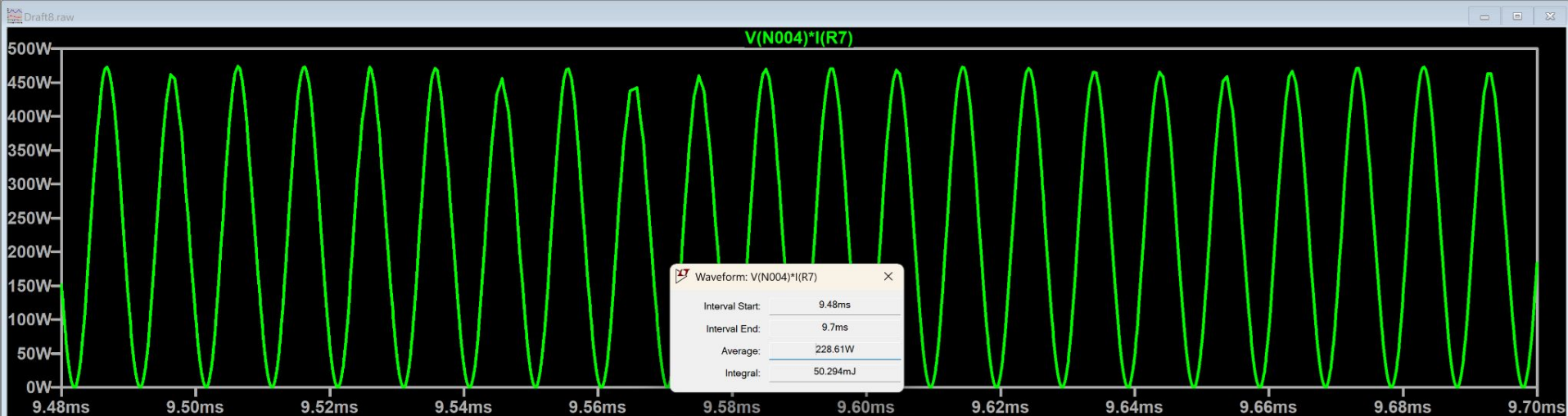




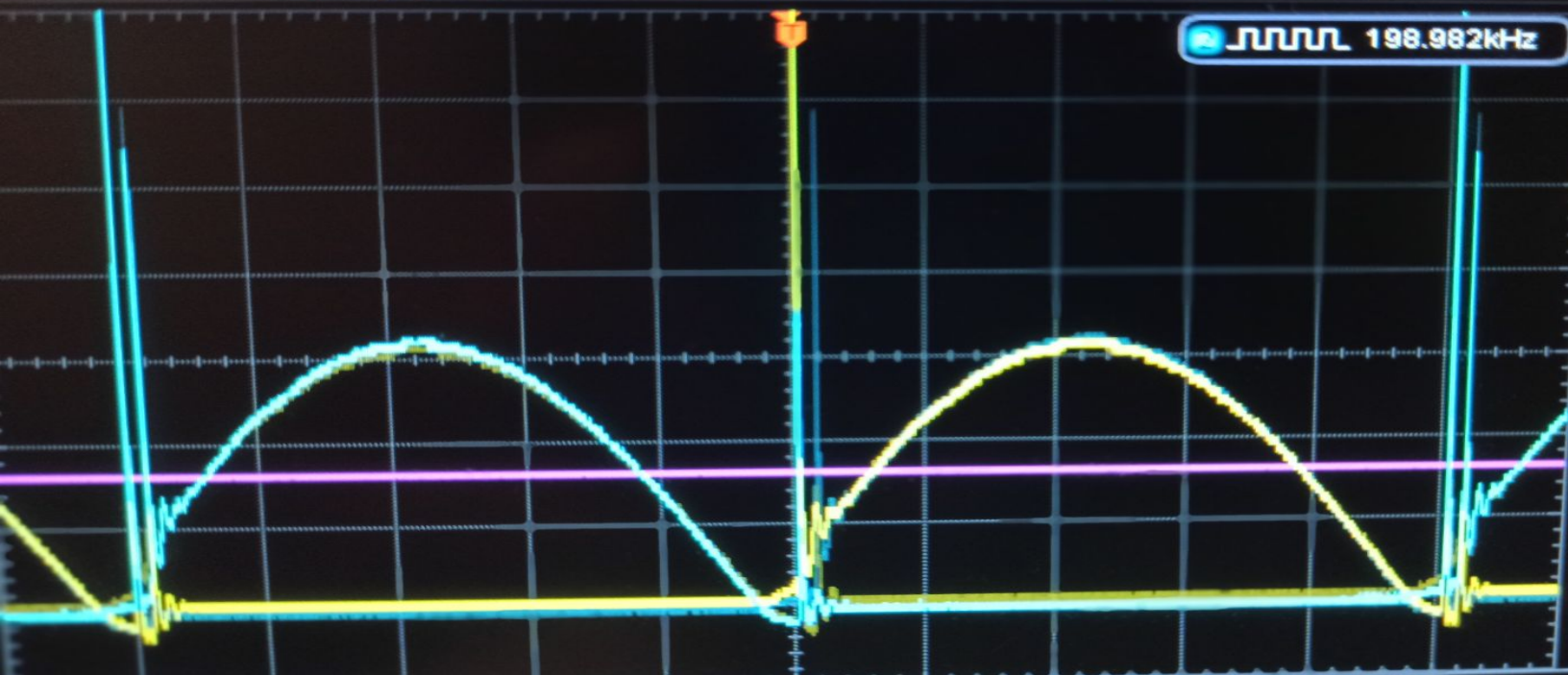








M 2.00us 250MS/s 6.00M pts D -100.000000ns T f 4.88 V



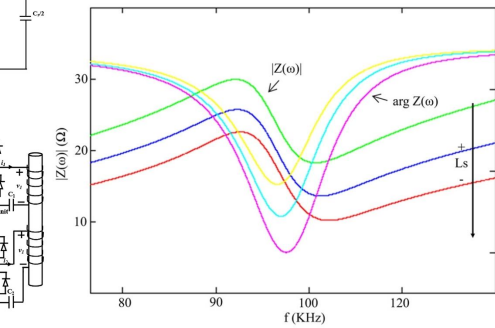
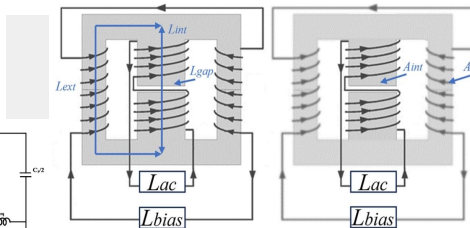
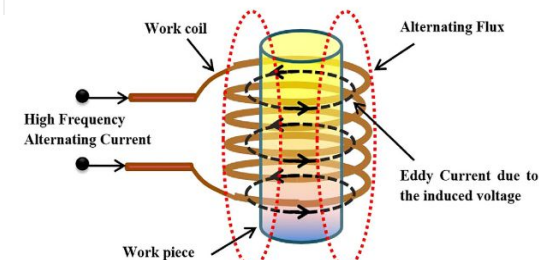
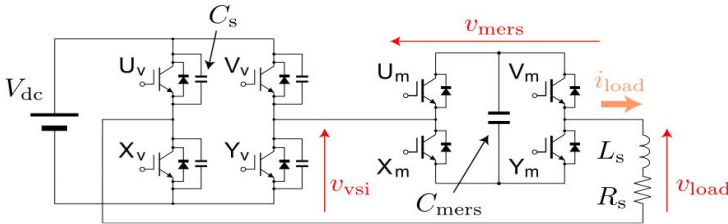
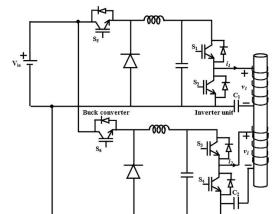
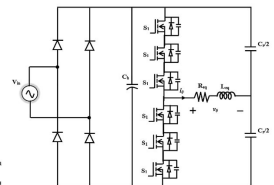
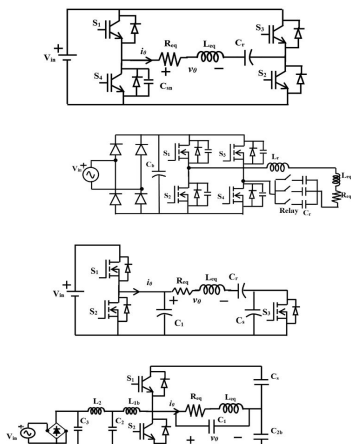
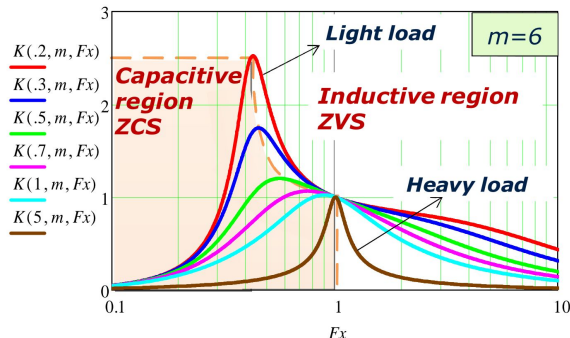
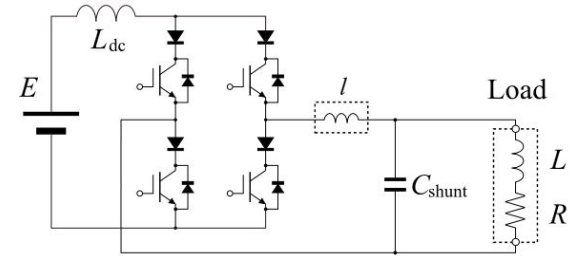
198.982kHz

CH2
Coupling
DC
BW Limit
OFF
Probe
1X
Invert
OFF
Volts/Div
Coarse
Unit
M

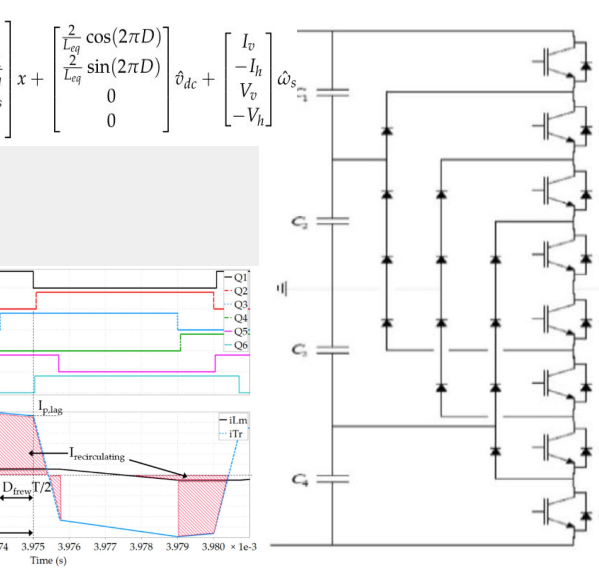
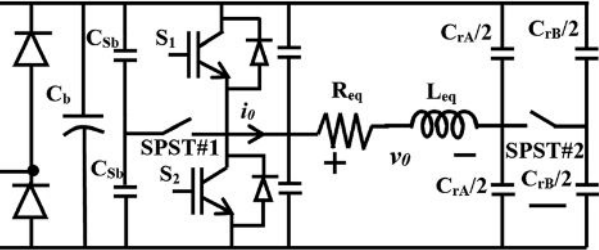
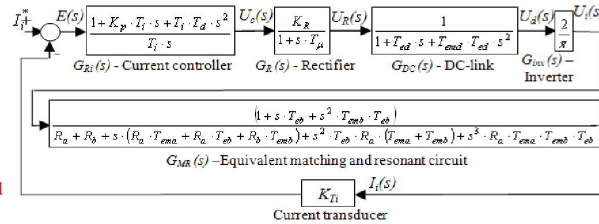
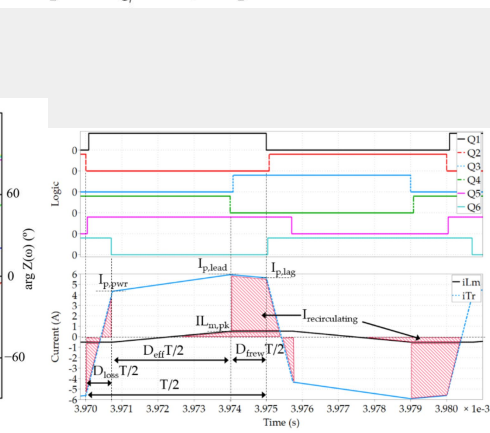
Cur: 48.714V Avg: 8.01V Max: 8.48V Min: 7.44V	Vpp Cur: ***** Avg: ***** Max: ***** Min: *****	Freq Cur: 3.85MHz Avg: 3.68MHz Max: 4.17MHz Min: 96.9kHz	Vpp Cur: 8.40V Avg: 8.01V Max: 8.48V Min: 7.44V	Rms Cur: ***** Avg: ***** Max: ***** Min: *****
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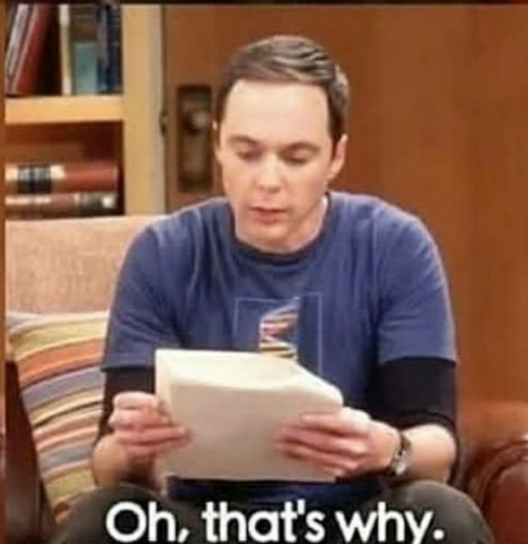
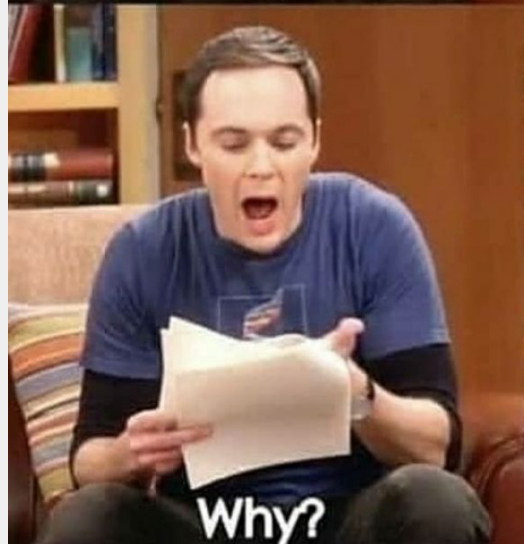
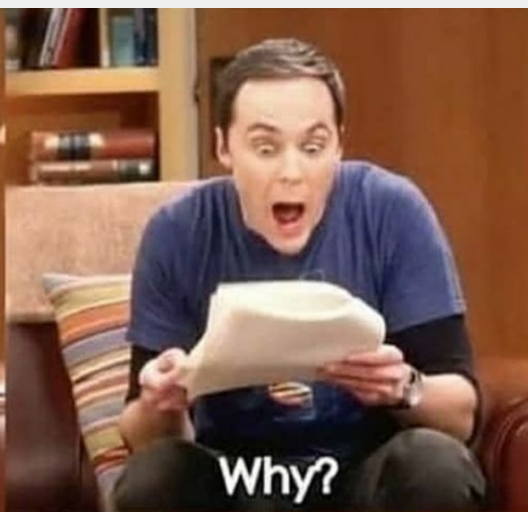
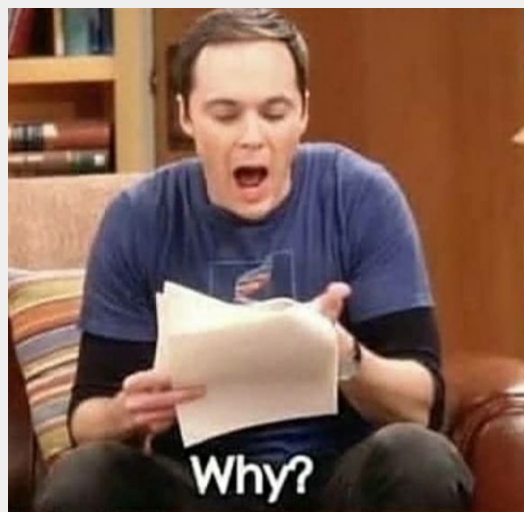
Trzeba poczytać trochę więcej

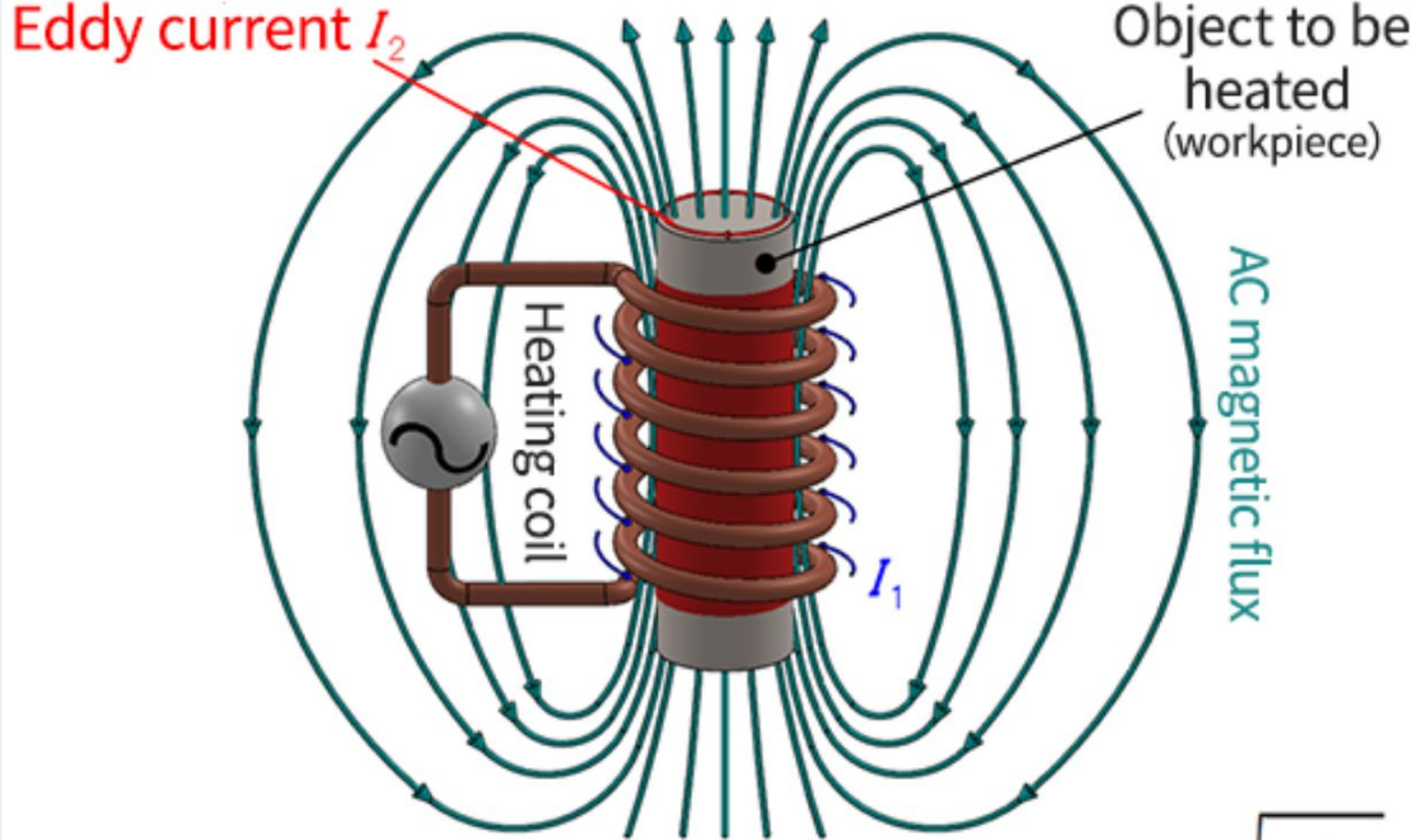
Przygoda numer 3.



$$\dot{X} = \begin{bmatrix} \frac{-R_{eq}}{L_{eq}} & \omega_s & \frac{-1}{L_{eq}} & 0 \\ -\omega_s & \frac{-R_{eq}}{L_{eq}} & 0 & \frac{-1}{L_{eq}} \\ \frac{1}{C_r} & 0 & \omega_s & 0 \\ 0 & \frac{1}{C_r} & -\omega_s & 0 \end{bmatrix} x + \begin{bmatrix} \frac{2}{L_{eq}} \cos(2\pi D) \\ \frac{2}{L_{eq}} \sin(2\pi D) \\ 0 \\ 0 \end{bmatrix} \hat{v}_{dc} + \begin{bmatrix} I_v \\ -I_h \\ V_v \\ -V_h \end{bmatrix} \hat{\omega}_s$$







Skin effect: Current penetration depth $\delta = \sqrt{\frac{1}{\pi f \mu \sigma}}$

Indukcja elektromagnetyczna – **zjawisko** powstawania **siły elektromotorycznej** w przewodniku na skutek zmian strumienia pola magnetycznego. Zmiana ta może być spowodowana zmianami **pola magnetycznego** lub względnym ruchem przewodnika i źródła pola magnetycznego. Zjawisko to zostało odkryte w 1831 roku przez angielskiego fizyka **Michaela Faradaya**^[1].

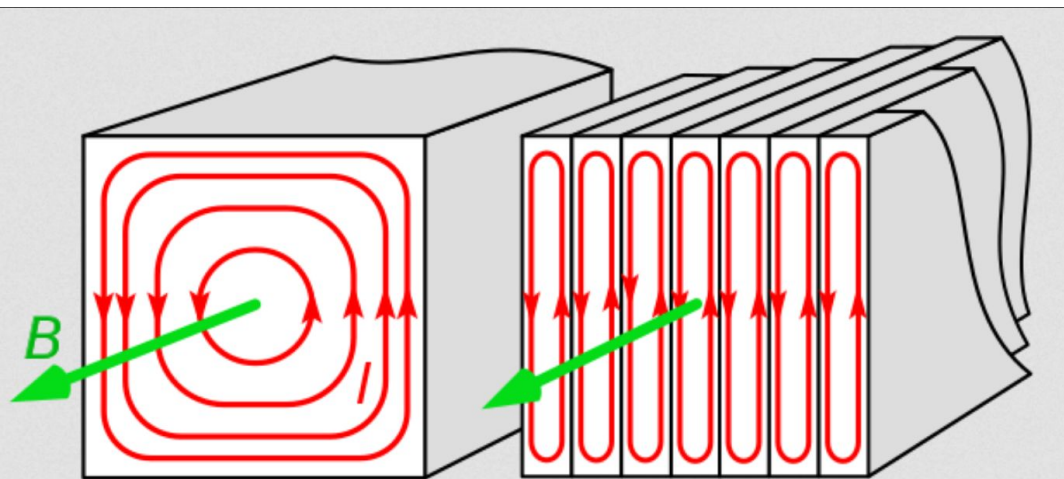
Zjawisko indukcji opisuje **prawo indukcji elektromagnetycznej Faradaya**^{[2][1]}:

$$\mathcal{E} = -\frac{d\Phi_B}{dt},$$

gdzie:

\mathcal{E} – indukowana **siła elektromotoryczna** (SEM) w **woltach**,

Φ_B – **strumień indukcji magnetycznej** przepływający przez **powierzchnię objętą przewodnikiem**.



$$P = \frac{\pi^2 B_p^2 d^2 f^2}{6k\rho D},$$

$$\begin{aligned} \delta &= \frac{1}{\alpha} = \sqrt{\frac{2\rho}{(2\pi f)(\mu_0\mu_r)}} \\ &= \frac{1}{\sqrt{\pi f\mu\sigma}} \approx 503 \sqrt{\frac{\rho}{\mu_r f}} \approx 503 \frac{1}{\sqrt{\mu_r f\sigma}}, \end{aligned}$$

Equation for Calculating AC (sinewave) Flux Density:

$$B_{max} = \frac{V_{rms} * 10^8}{4.44 f N A_e} \text{ gauss}$$

Where:

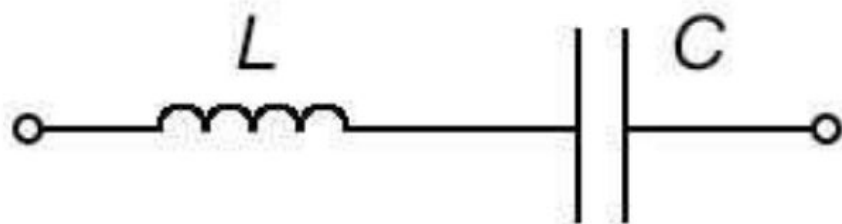
N = Number of Turns

f = Frequency (Hz)

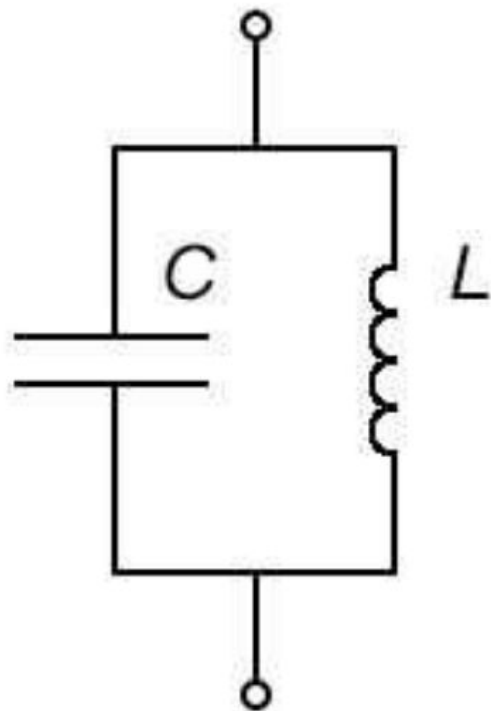
And from the Manufacturer's Datasheet or Website:

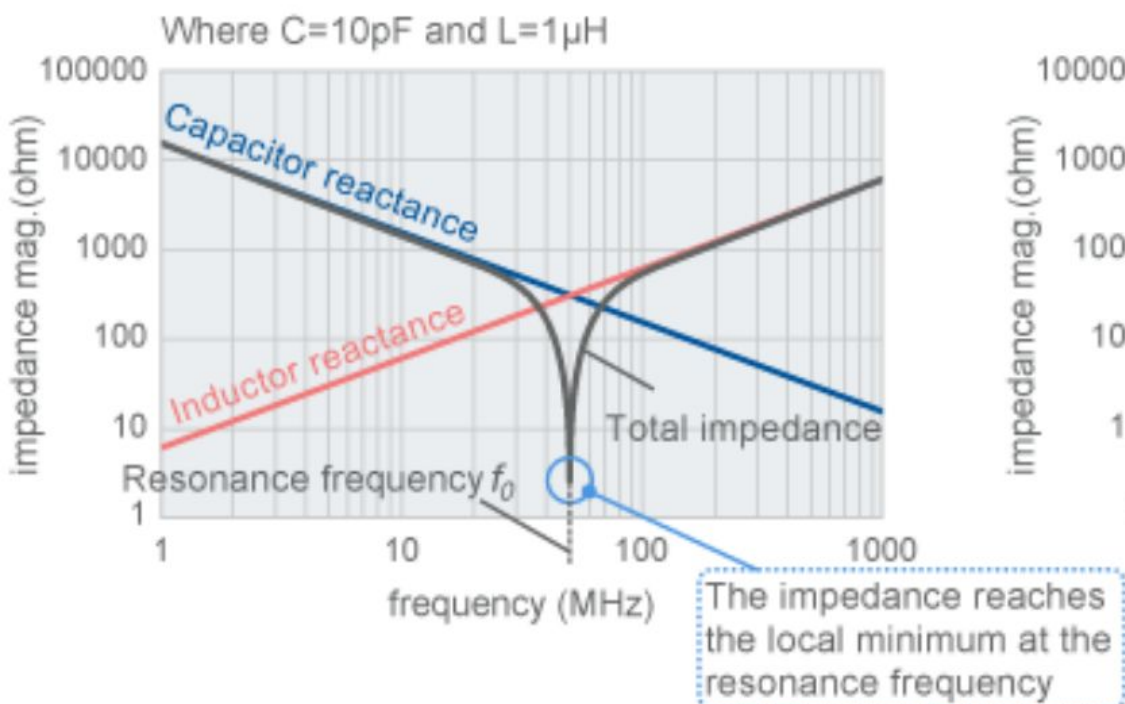
A_e = Effective Cross Sectional Area (cm²)

LC Oscillator

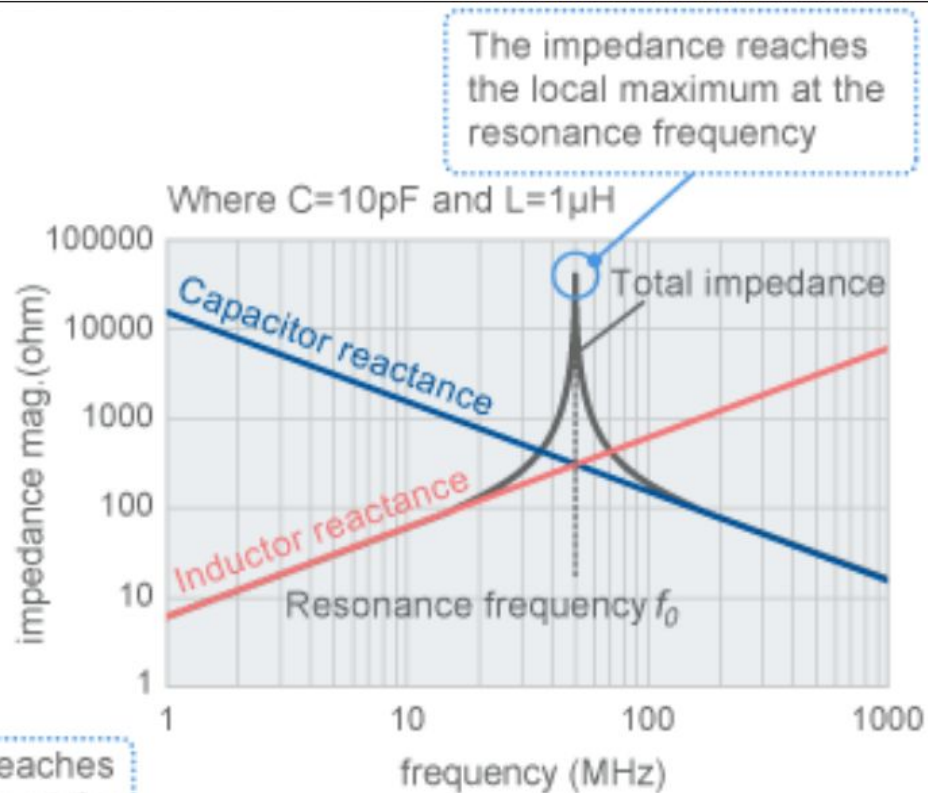


$$f = \frac{1}{2\pi\sqrt{LC}}$$

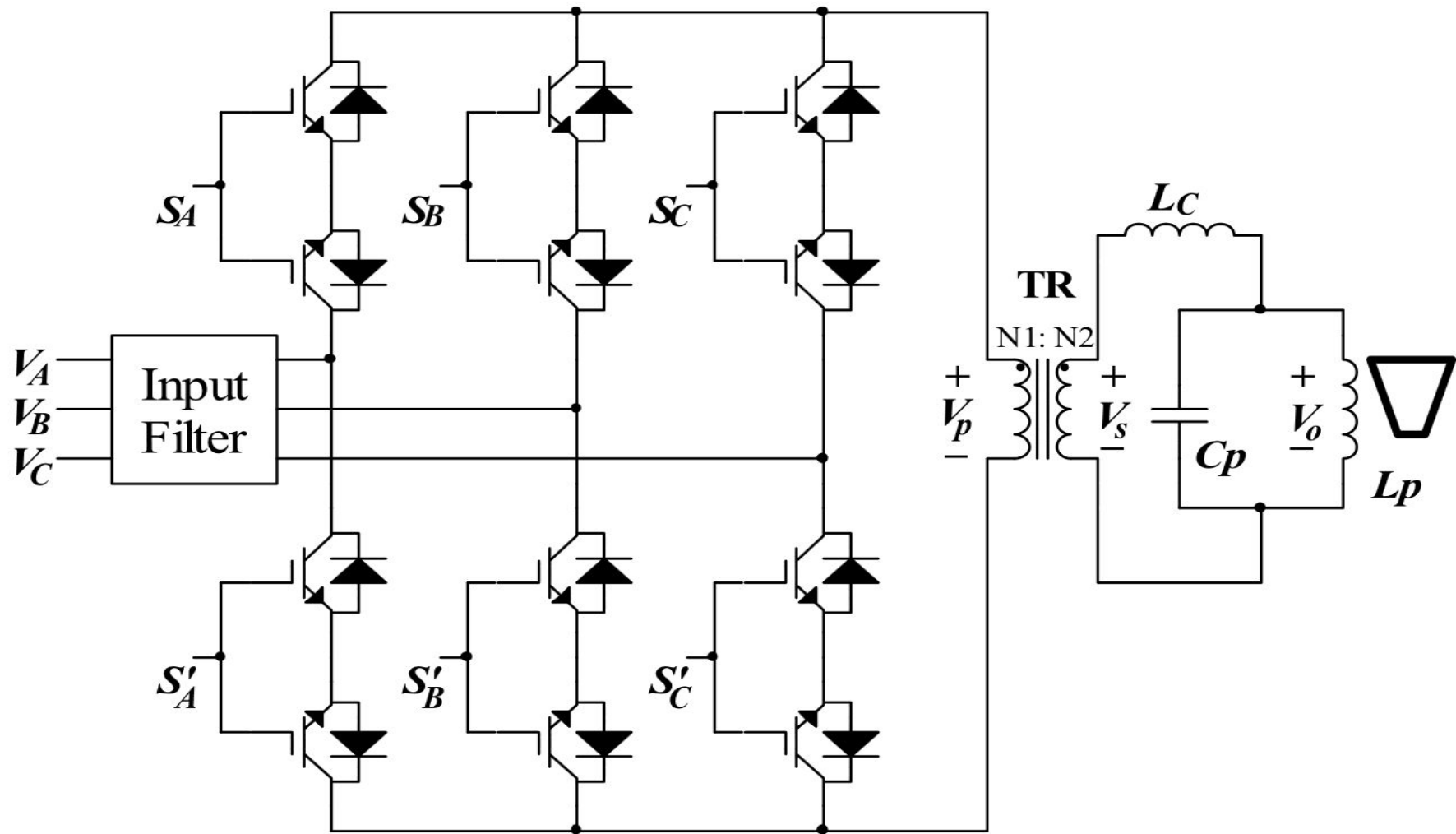


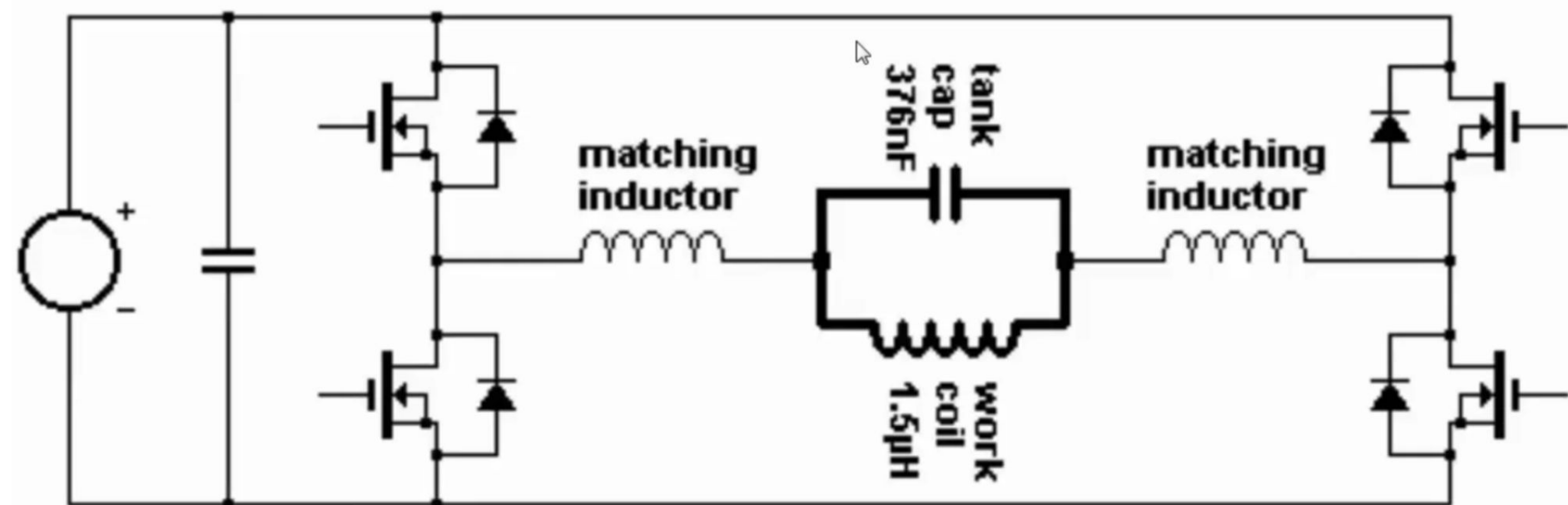


(a) Series resonant circuit

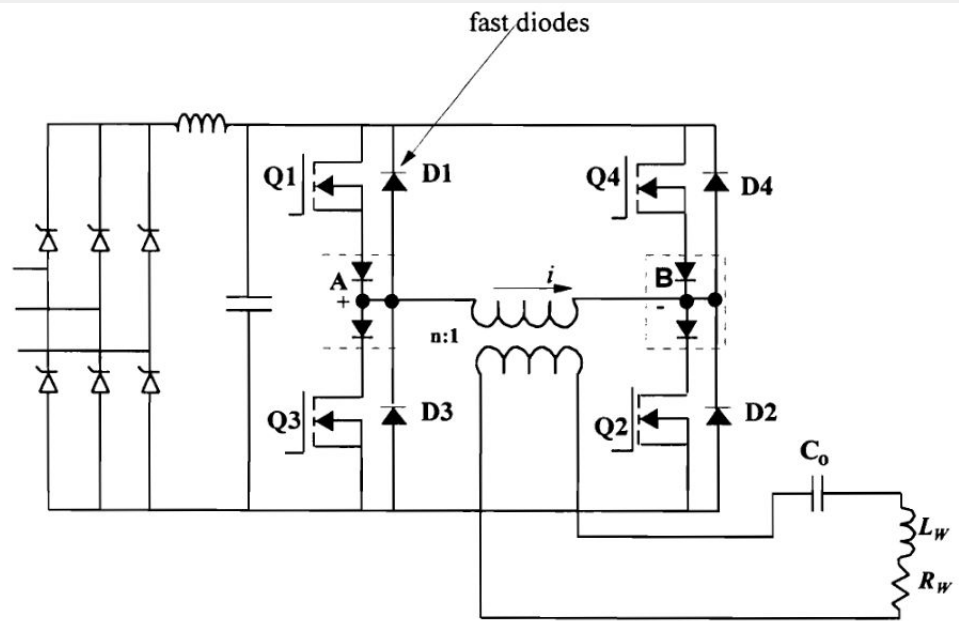
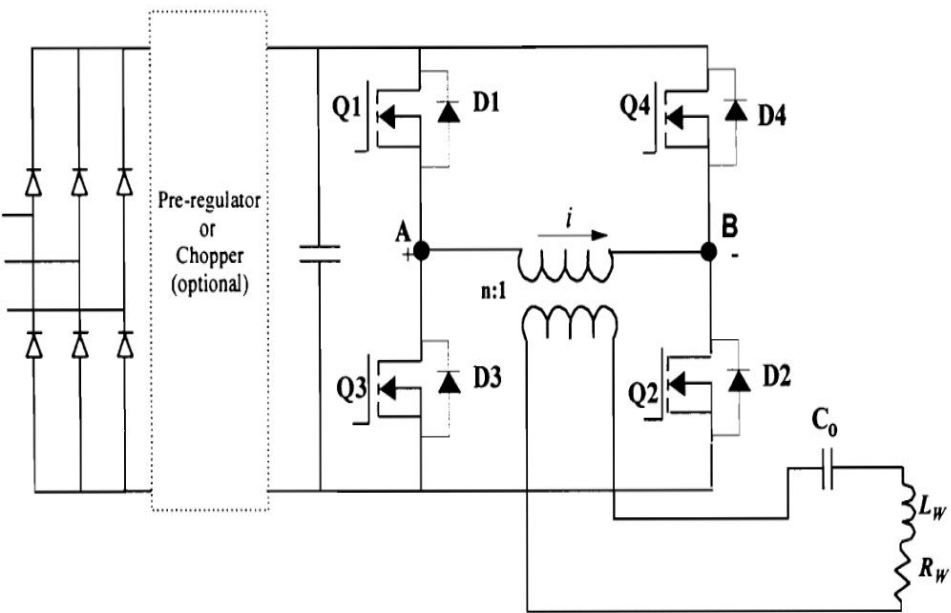


(b) Parallel resonant circuit





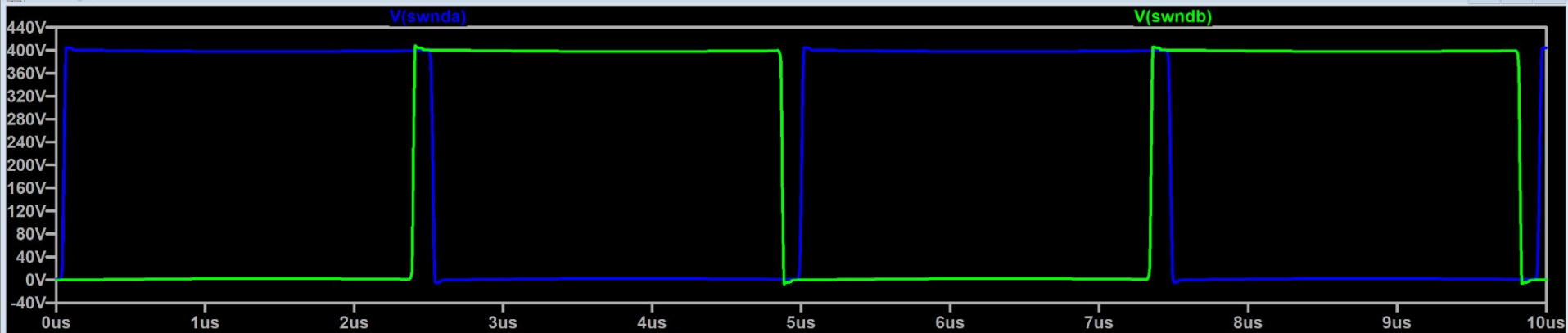
FULL BRIDGE INDUCTION HEATER USING "LCLR" WORK COIL



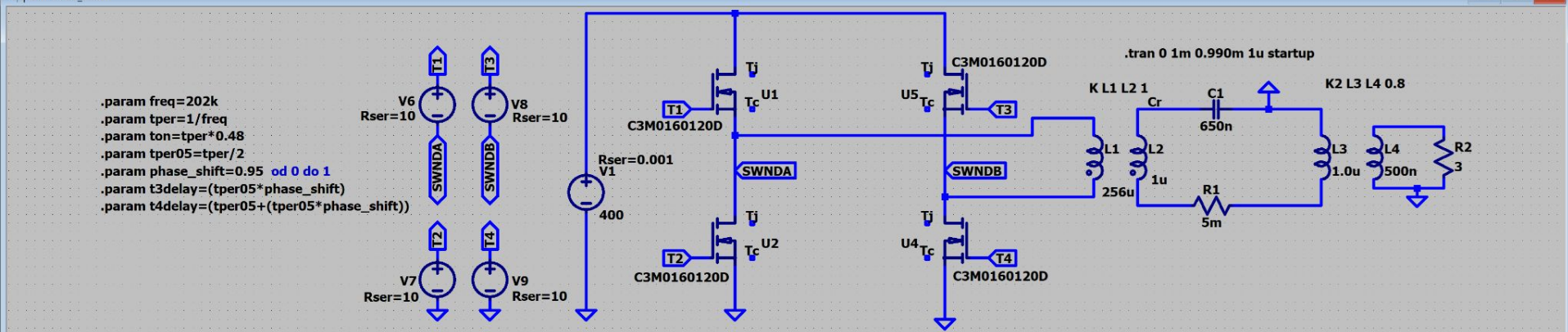
Symulacje PS-SRI

Przygoda numer 4.

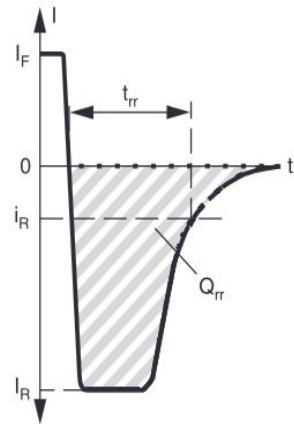
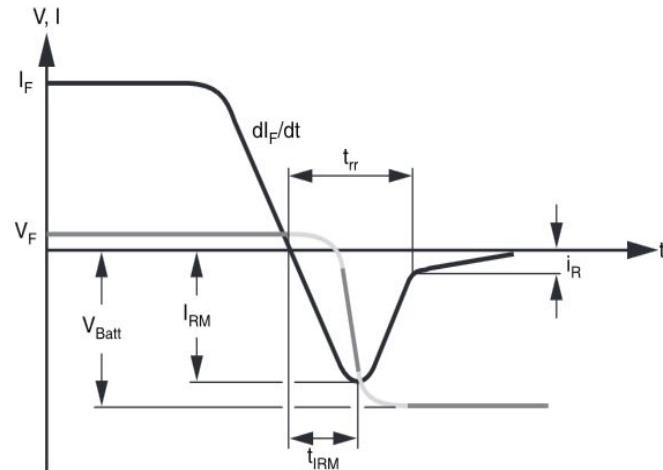
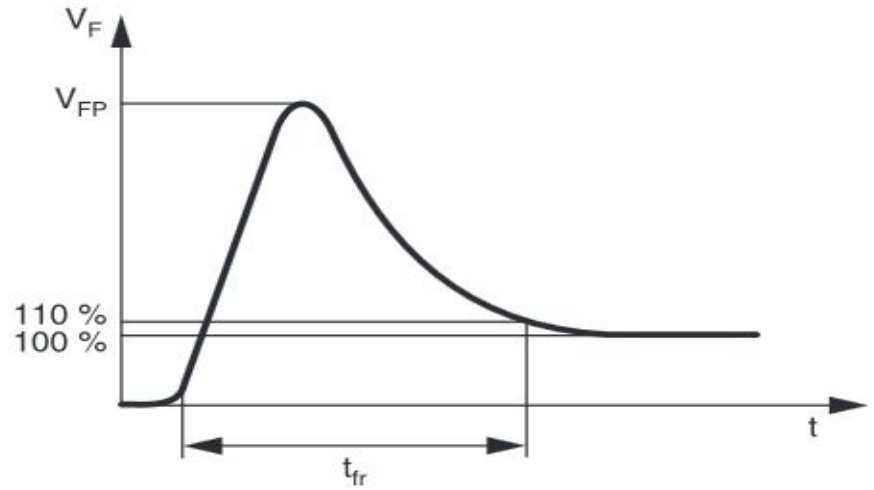
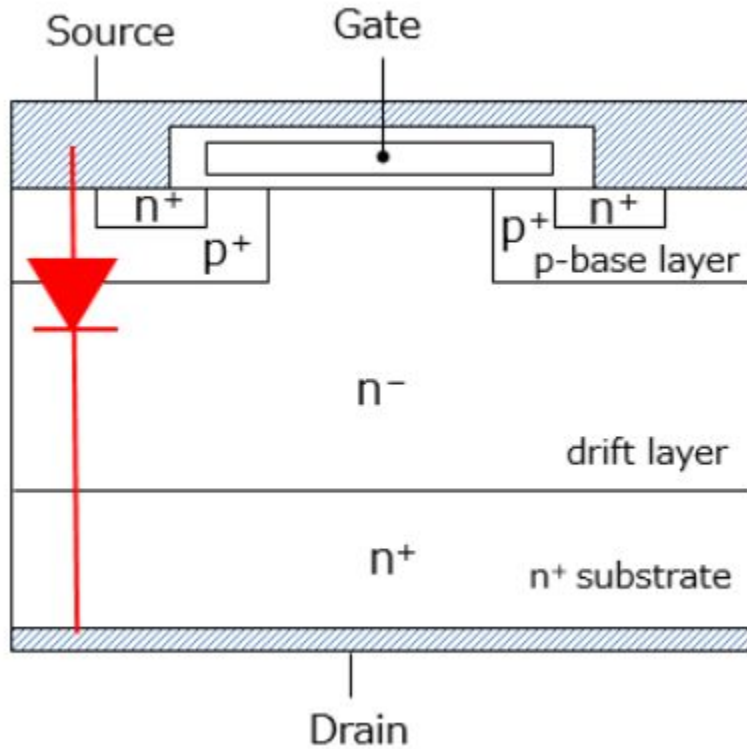
parameters_sri.raw

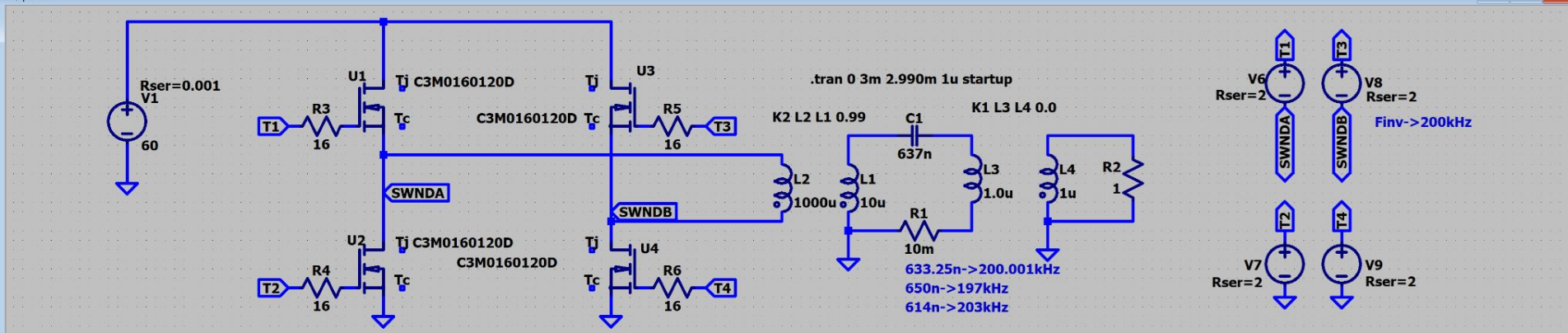
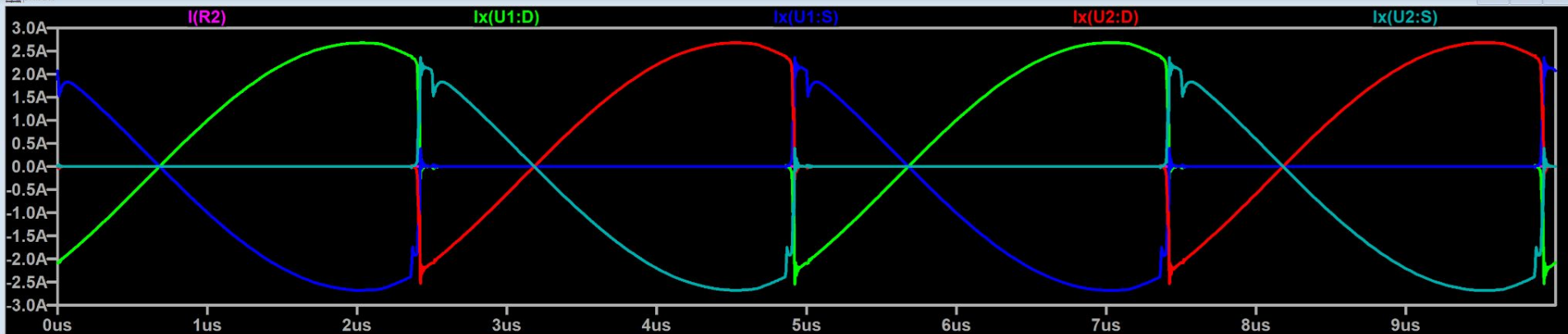


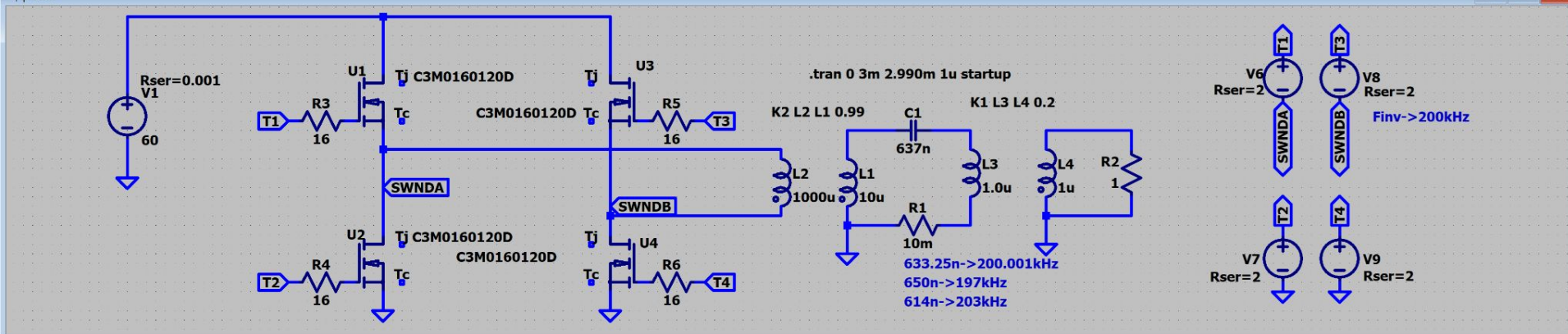
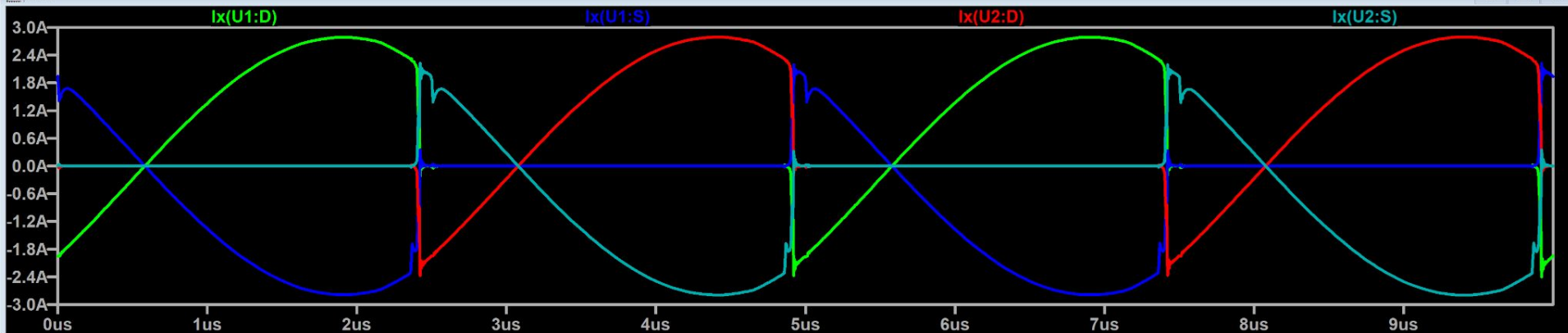
parameters_sri.asc

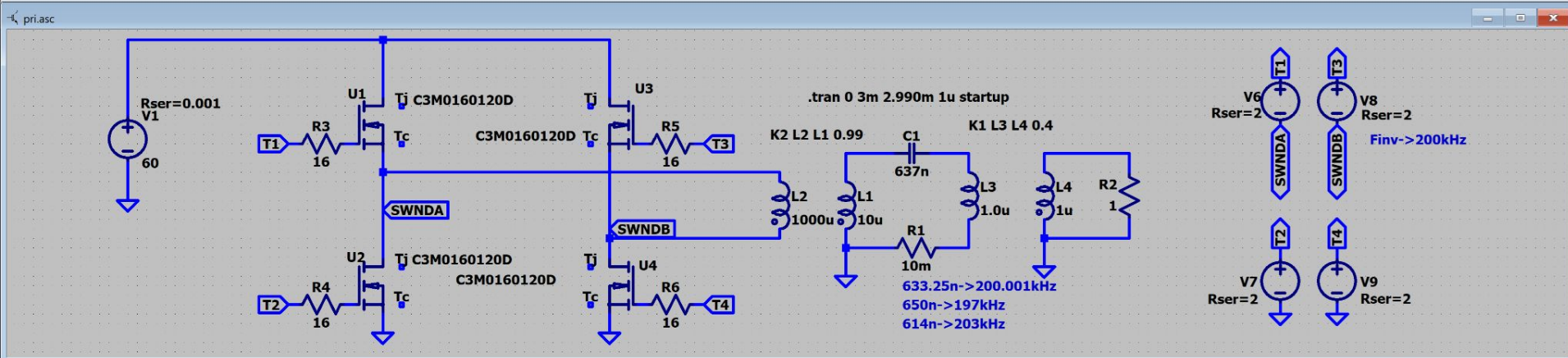
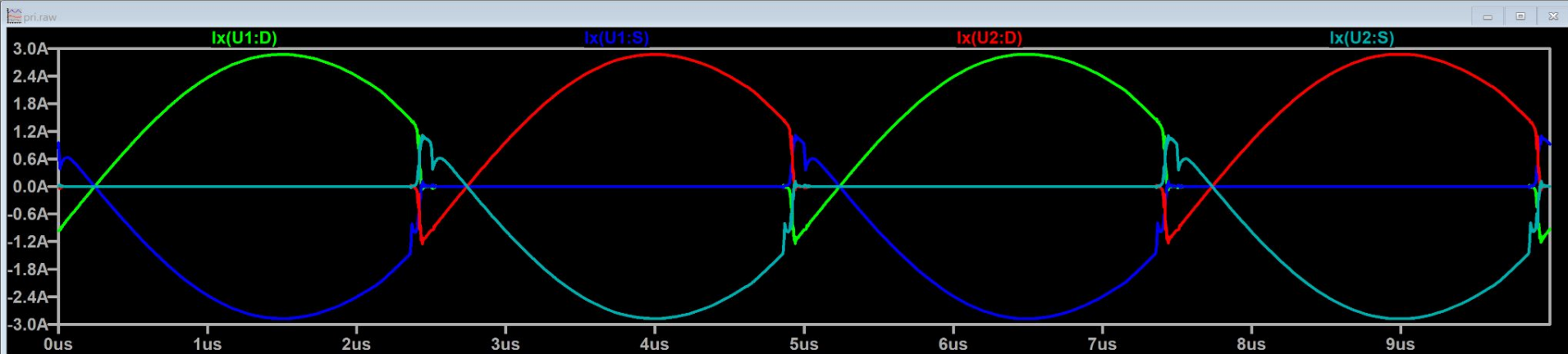


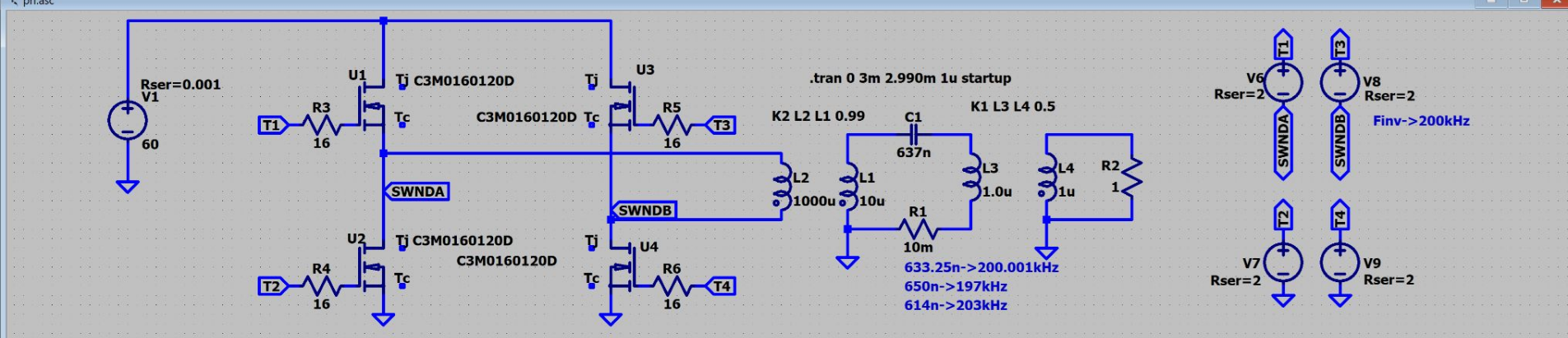
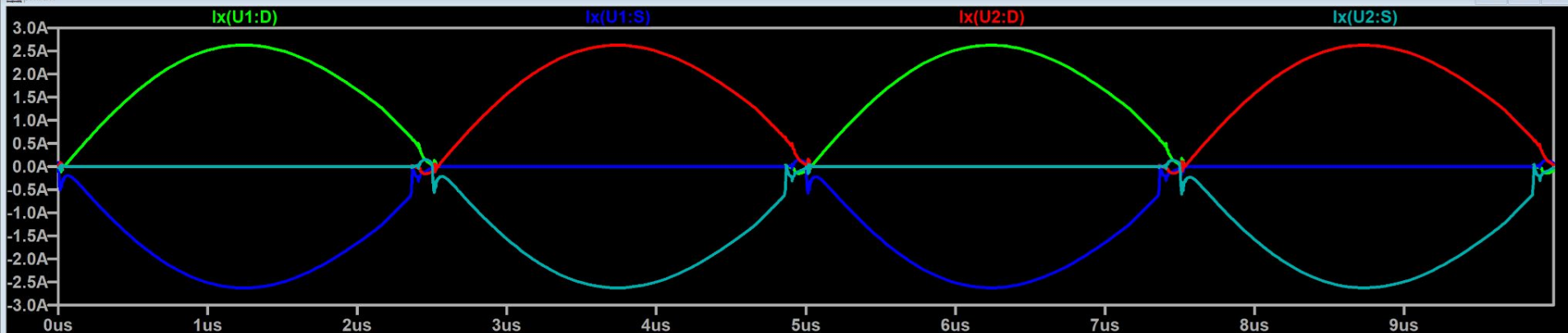
Diode Recovery Story



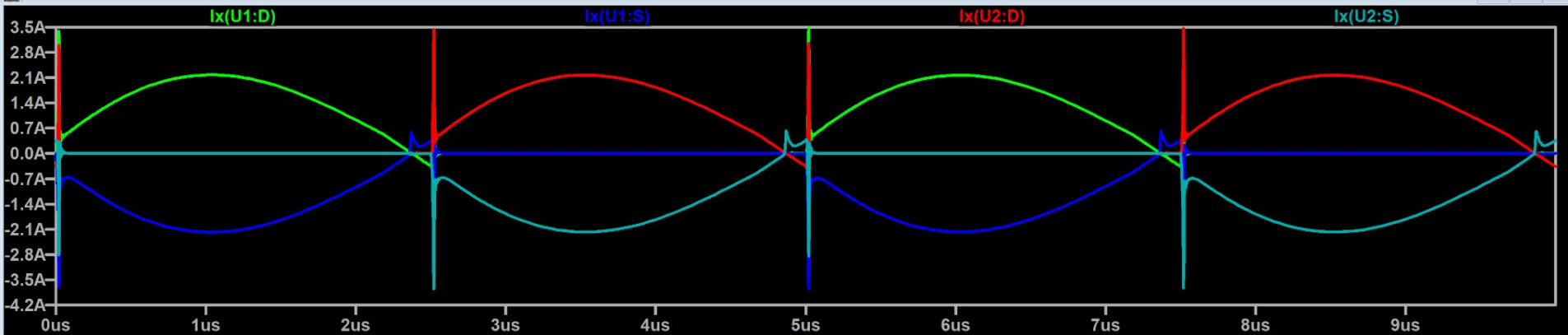




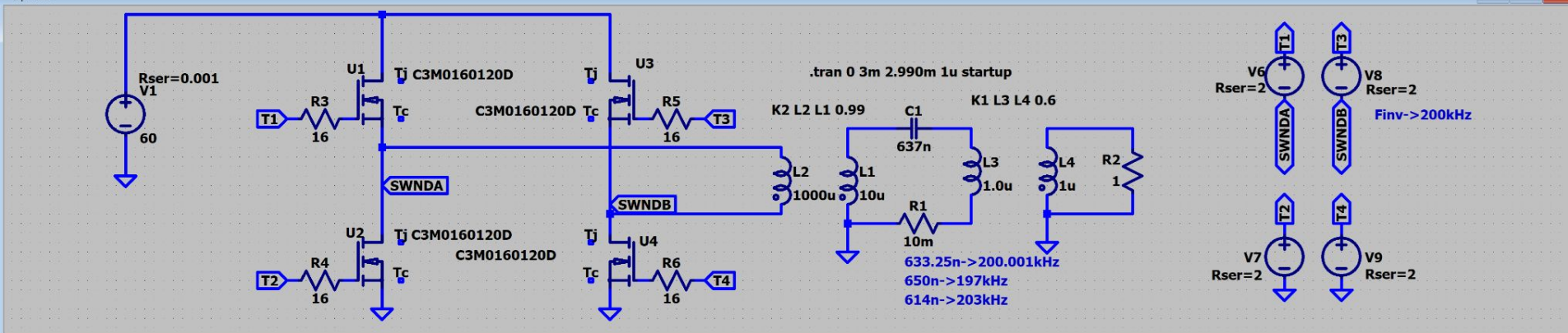


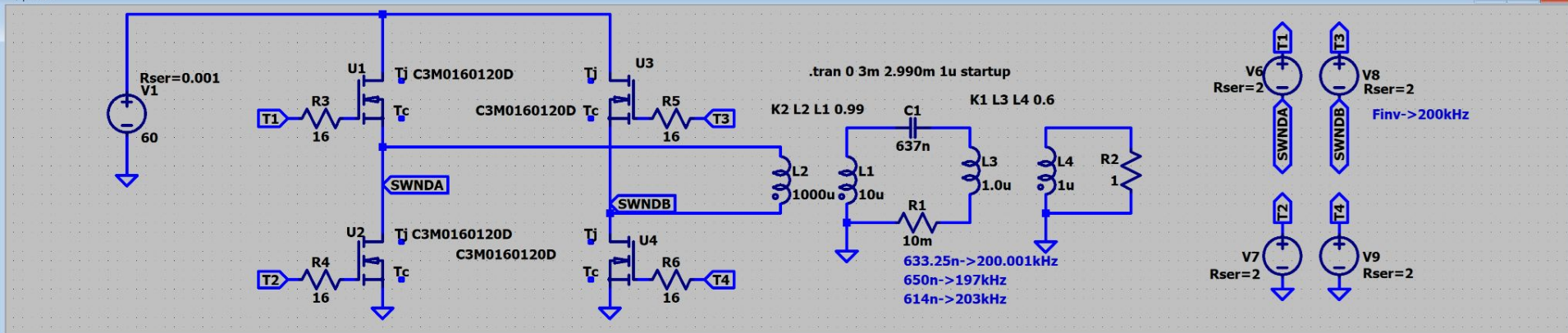
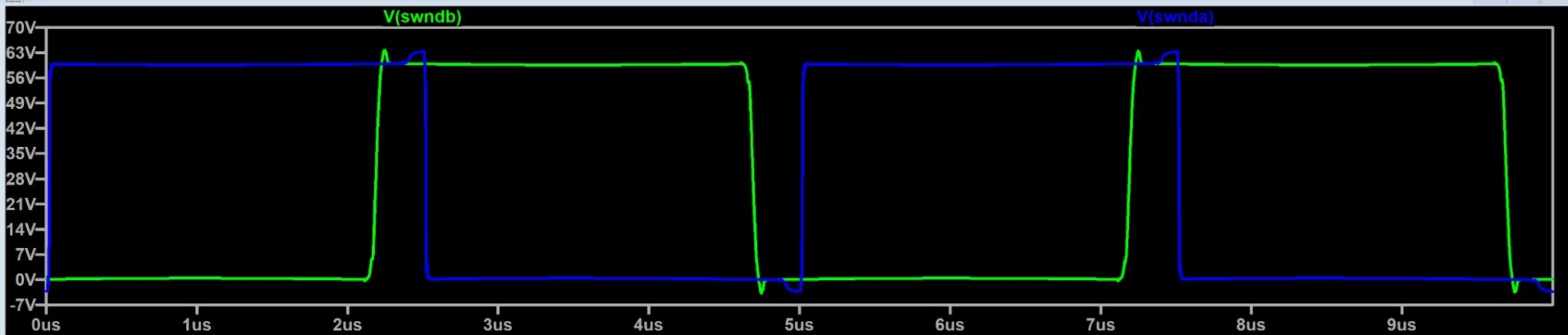


pri.raw



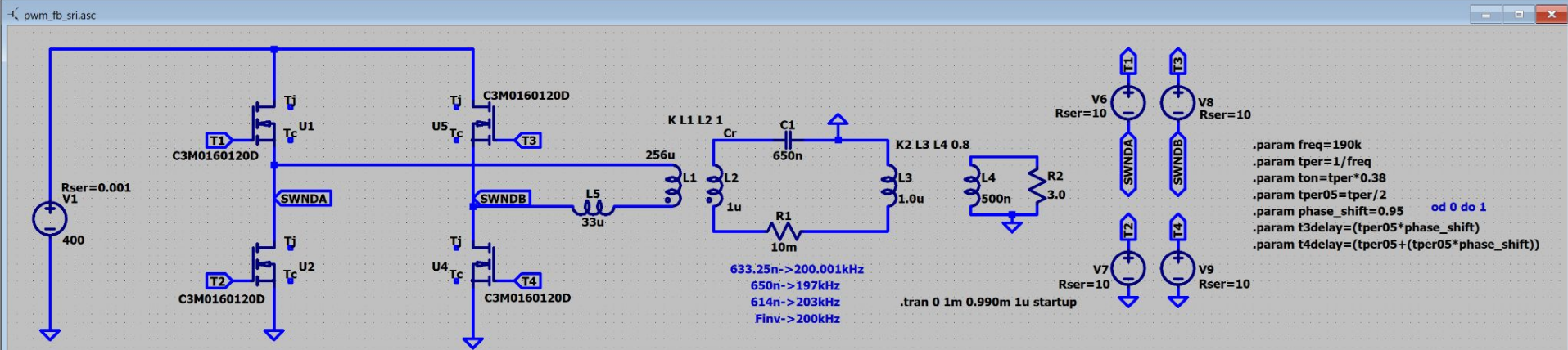
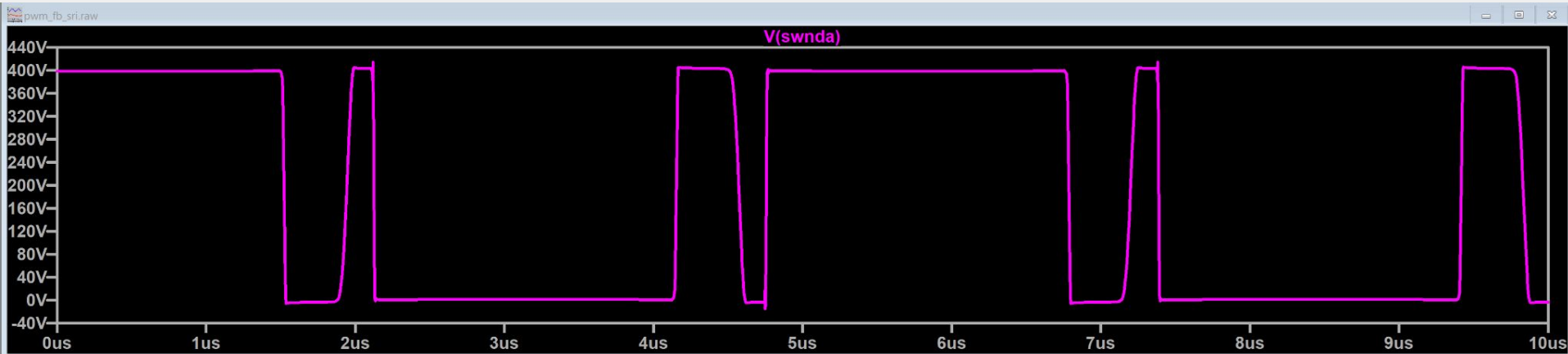
pri.asc

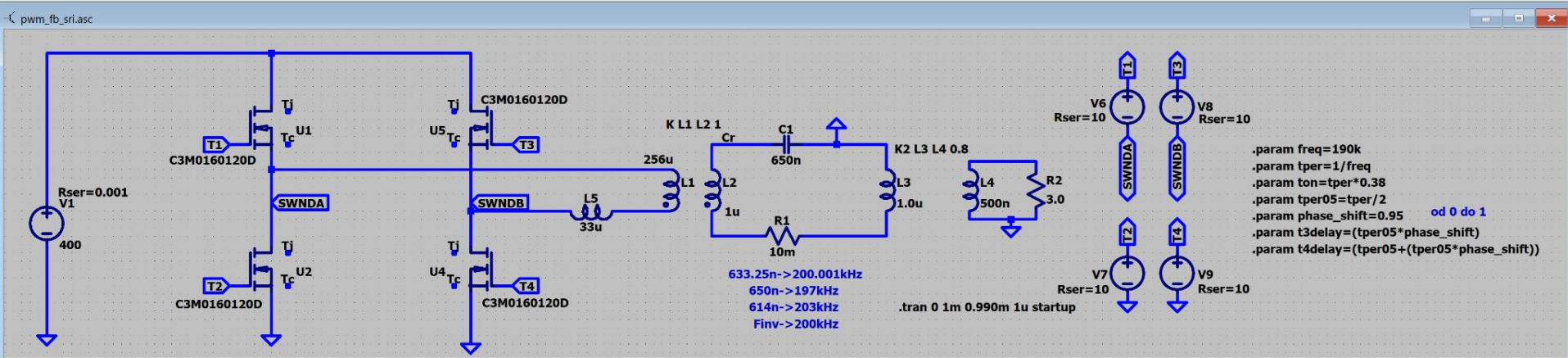
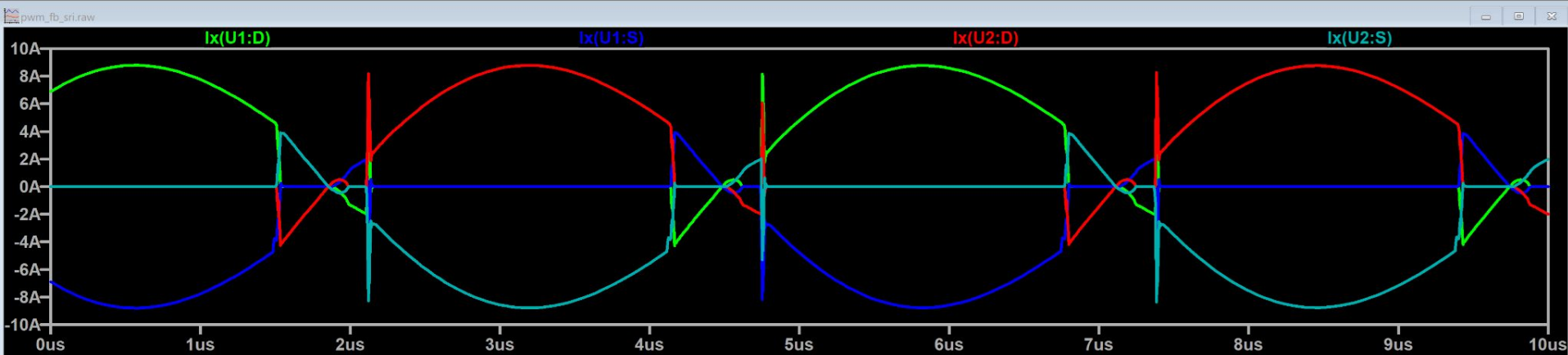




Symulacje PWM-SRI

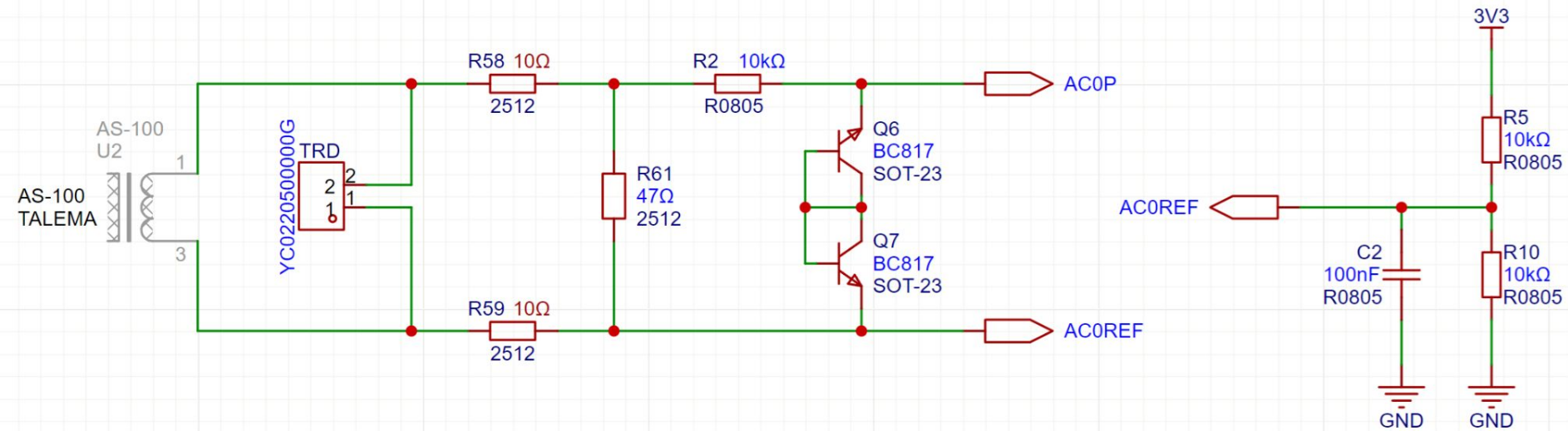
Przygoda numer -1.

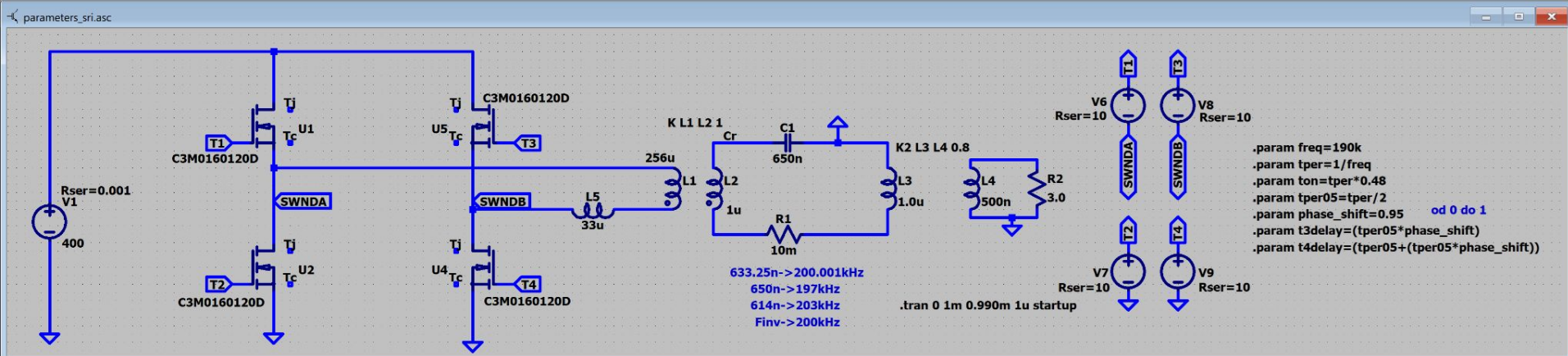
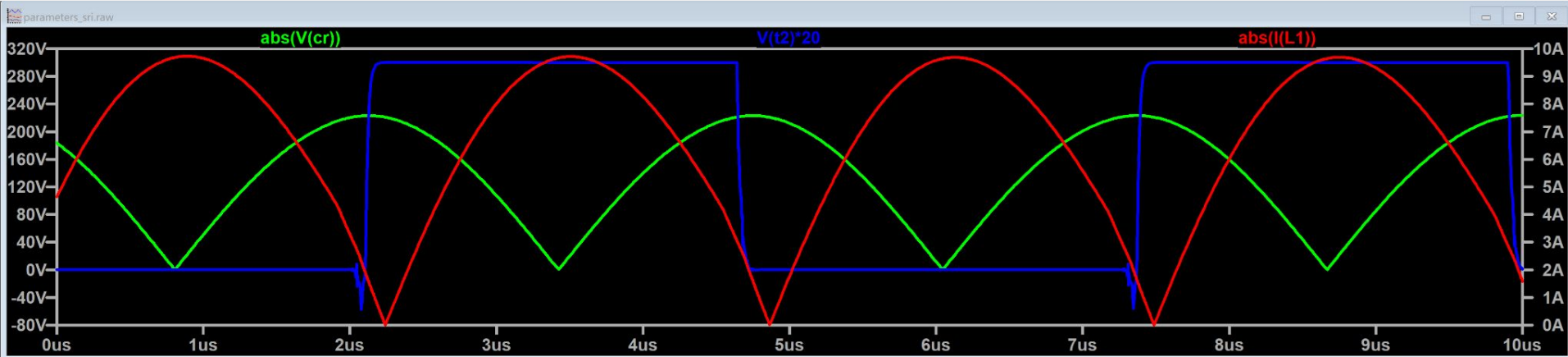




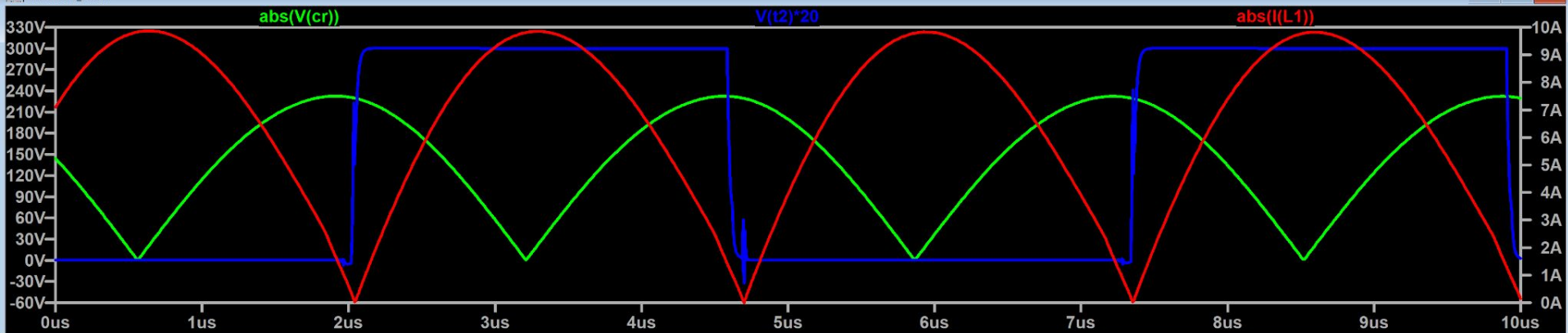
Synchronizacja PS-SRI

Przygoda numer 5.

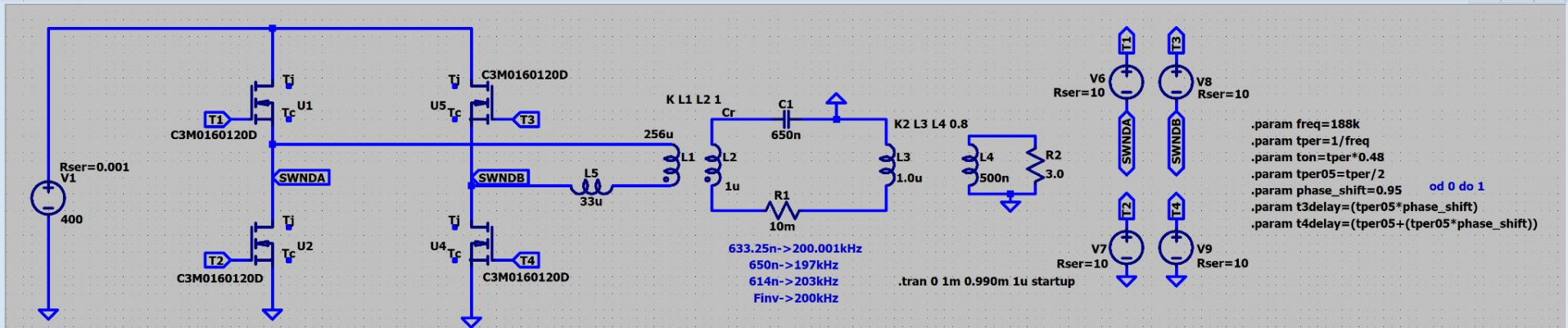


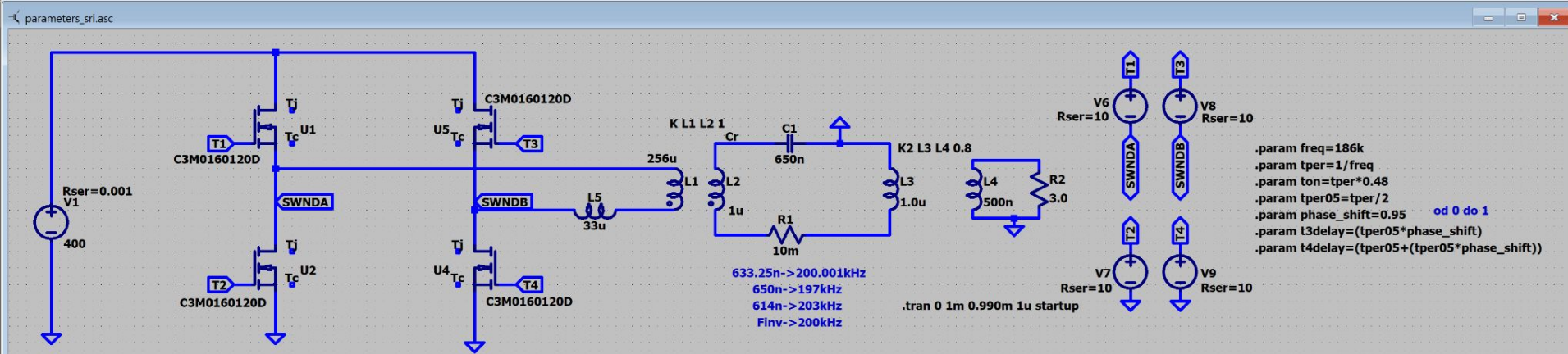
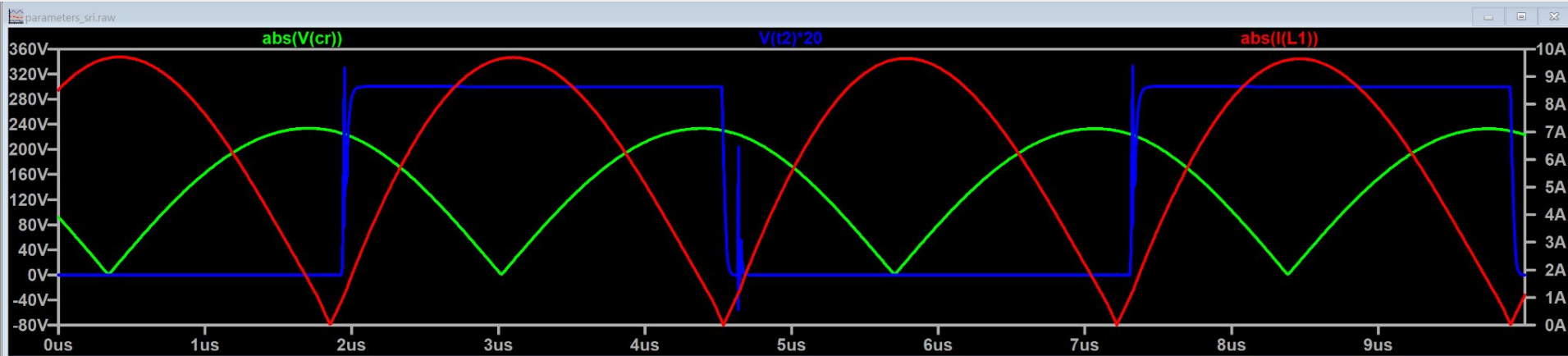


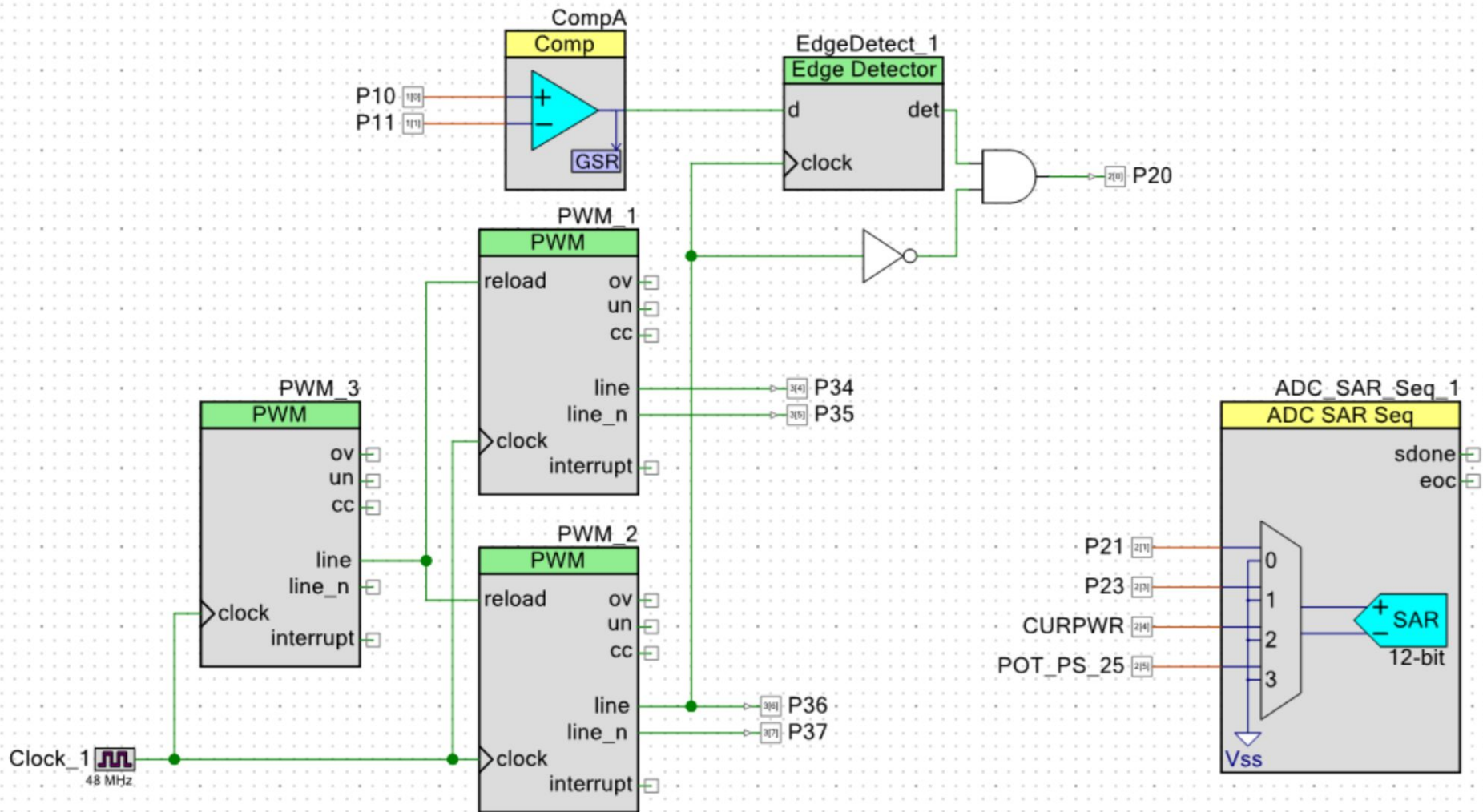
parameters_sri.raw

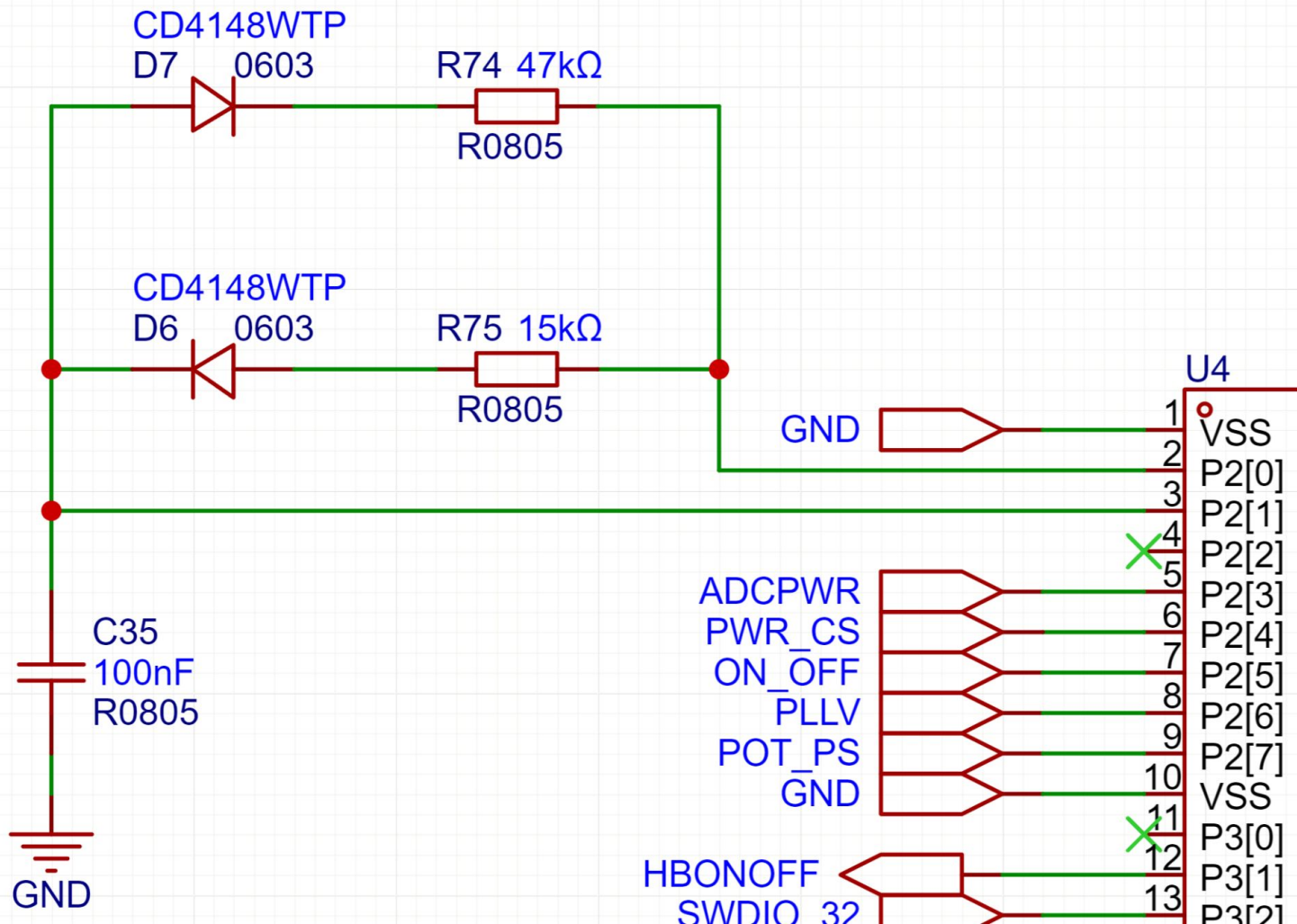


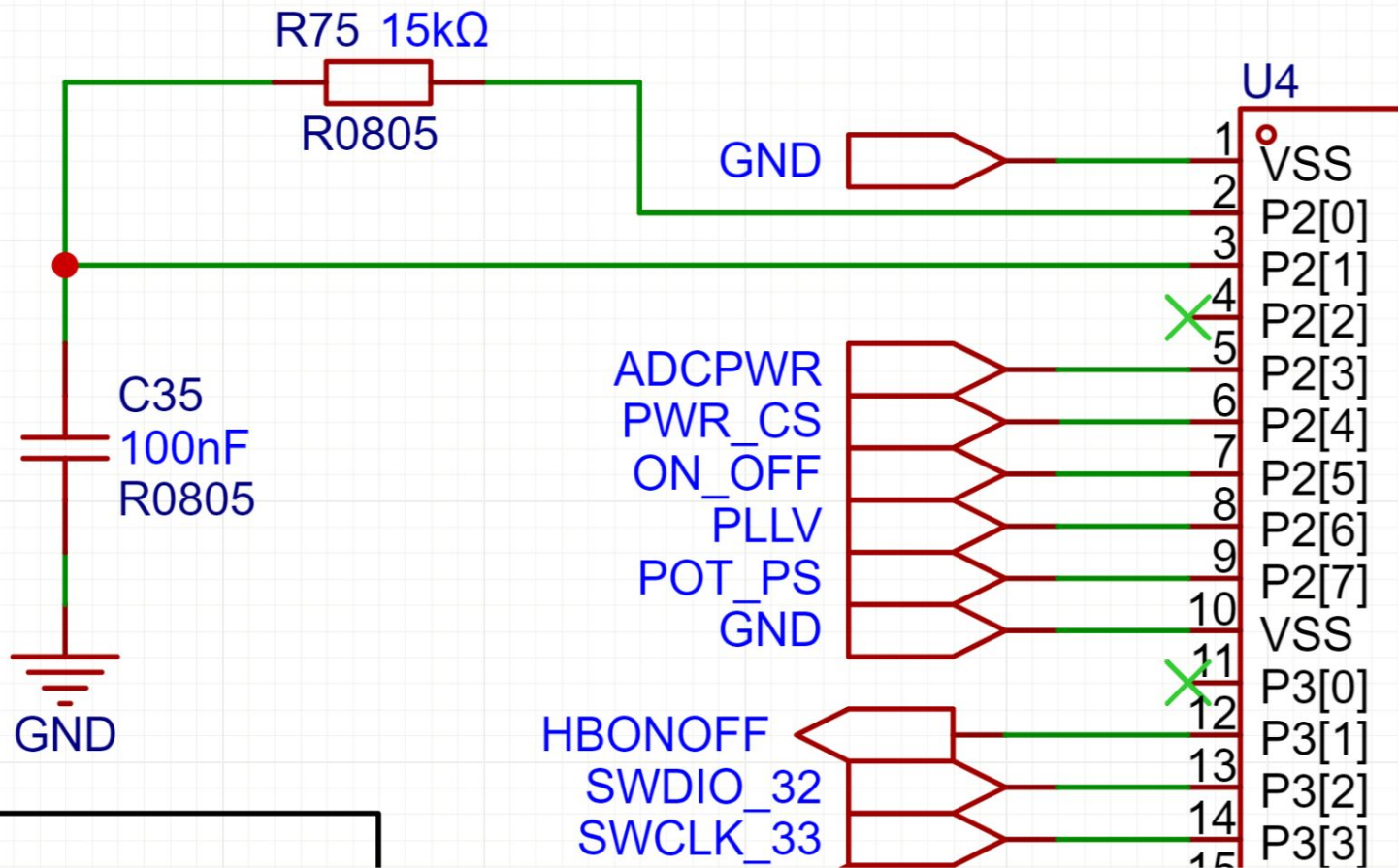
parameters_sri.asc

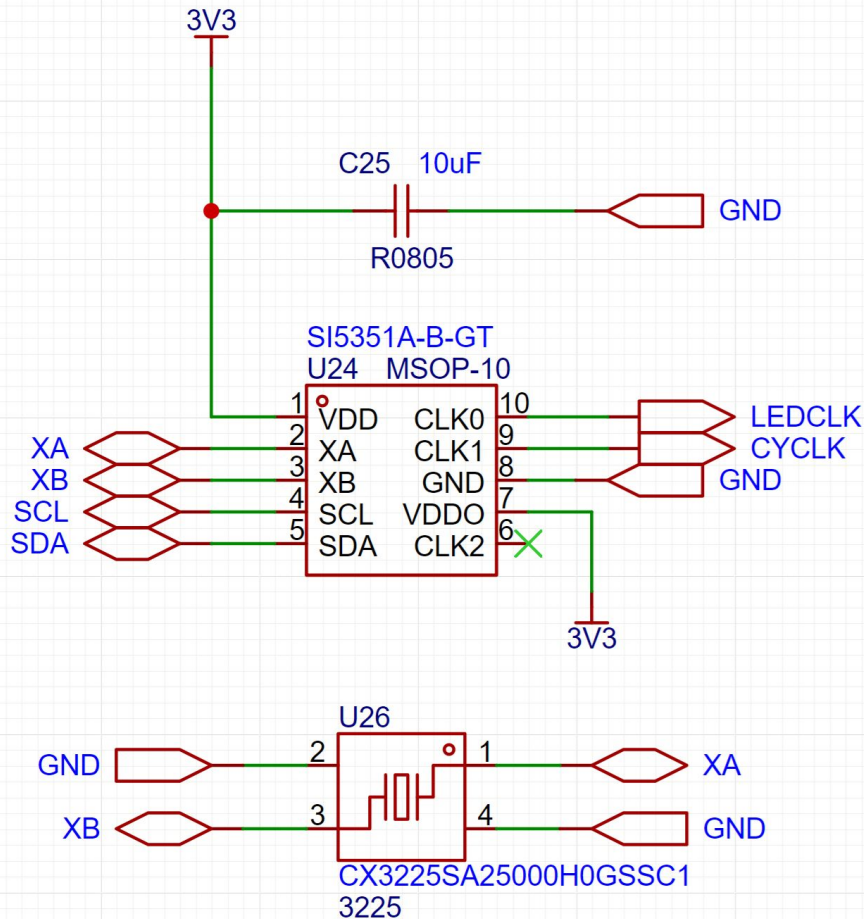












```

102 // only if pll_a = 800 MHz
103 void calc_new_msth1(msth1* m, uint32_t freq){
104
105     uint64_t u1 = (uint64_t)(1048575)*(uint64_t)(800000000) / (uint64_t)freq;
106     uint64_t ua = (uint64_t)(u1 / 1048575);
107     uint64_t u2 = ua * 1048575;
108     uint64_t u3 = u1 - u2;
109     uint64_t u4 = u3 * 524288;
110     uint64_t u5 = (uint64_t)(u4) / (uint64_t)(1048575);
111
112     m->a = ua;
113     m->c = 524288;
114     m->b = u5;
115
116     if(m->c == 0){
117         m->b = 0x80000;
118         m->c = 0x80000;
119     };
120
121     // opt recalculate uart clock divider
122     uint32_t uart_clk = 153600; // Hz
123     uclk_div = (uint16_t)(freq / uart_clk);
124     UCLK_SetDivider(uclk_div);
125 };
126

```

```

if(adcv < 100){
    desif += 500000;
    phase_pid.wynik = 0;
}else{
    phase_pid.pomiar = adcv;
    pid_compute(&phase_pid);
    int32_t pidr = phase_pid.wynik;
    desif += pidr;
};

if(desif > 48000000){
    desif = 48000000;
};

if(desif < 32000000){
    desif = 32000000;
};

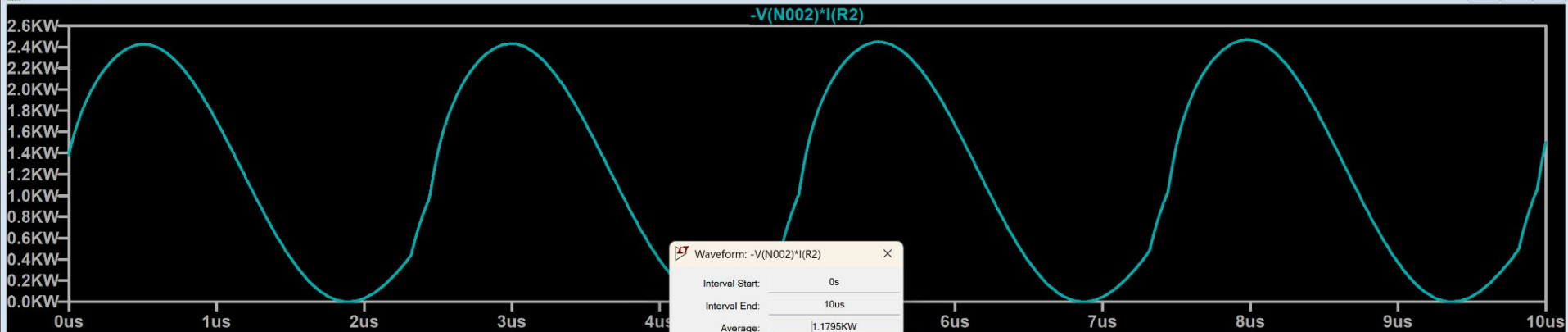
calc_new_msth1(&plldv, desif);
si53_setupMultisynth(1, SI5351_PLL_A, plldv.a, plldv.b, plldv.c);
CyDelay(7);

```

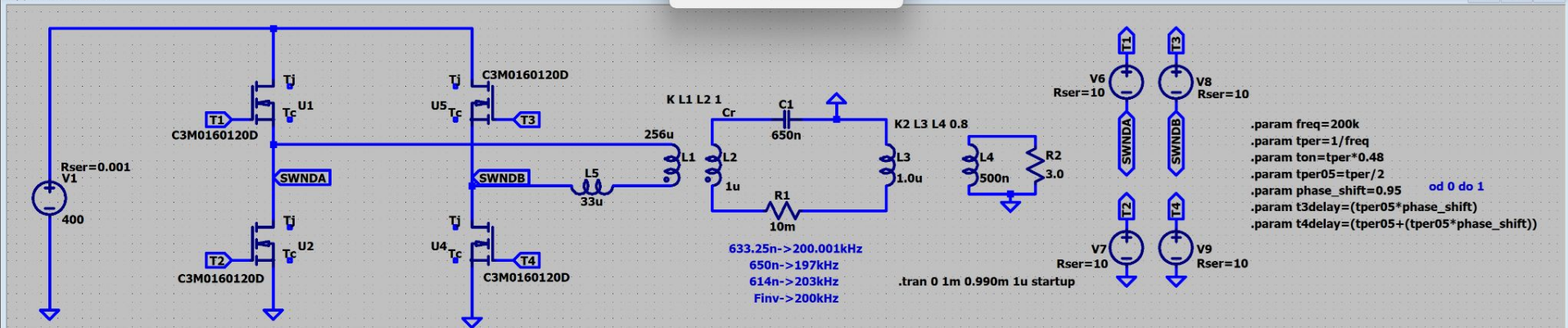
Moc a częstotliwość

Przygoda numer 6.

parameters_sri.raw

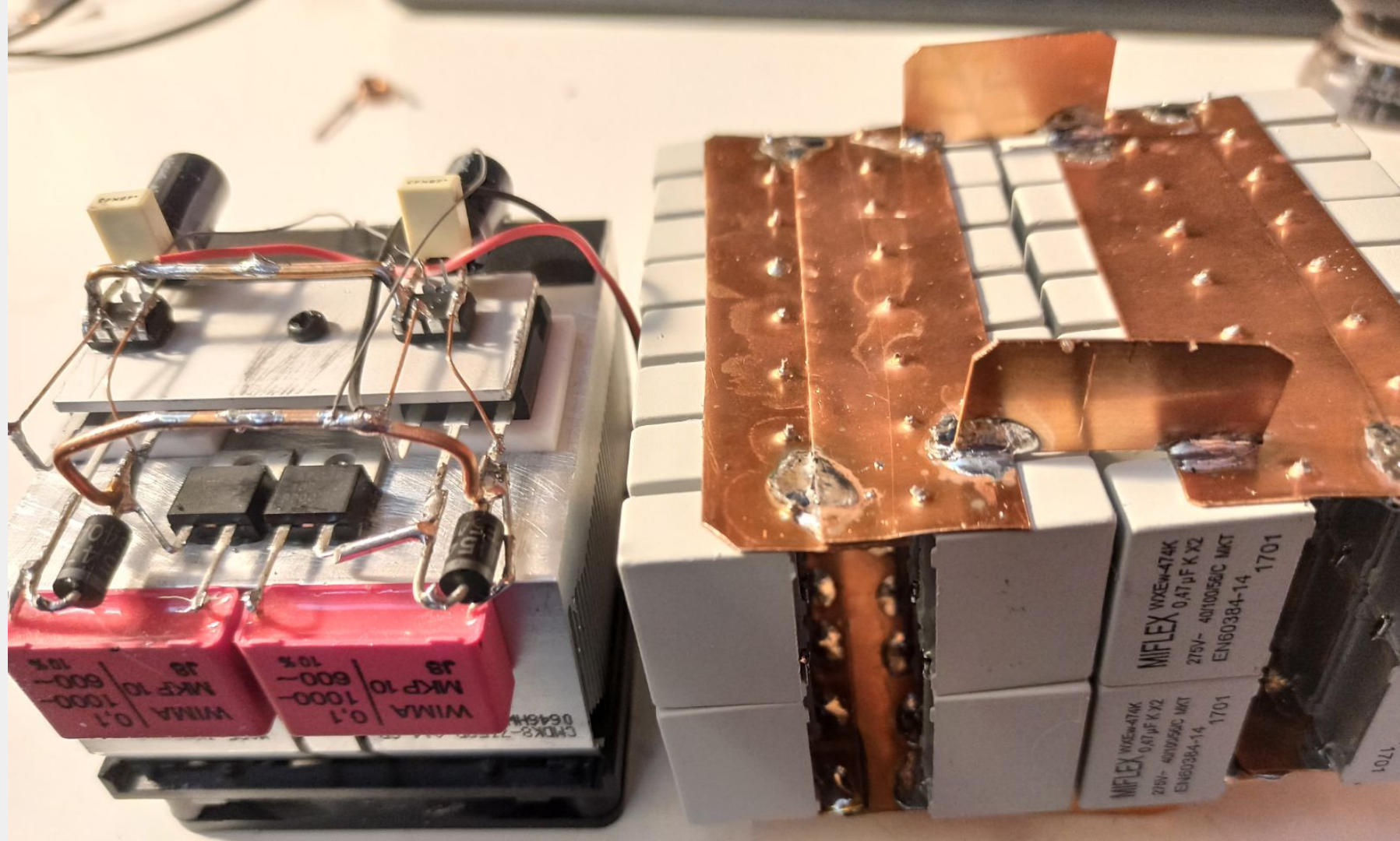


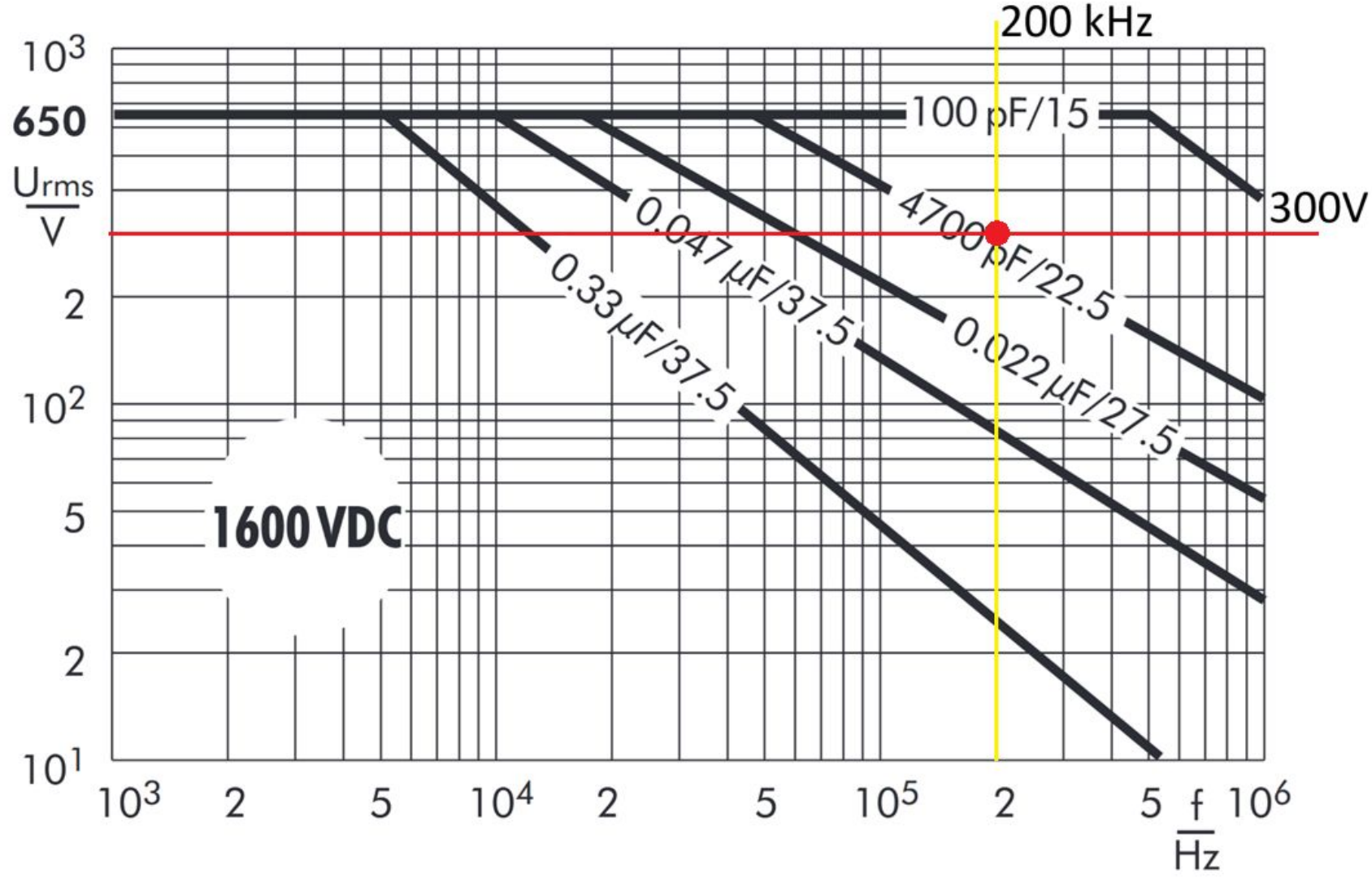
parameters_sri.asc

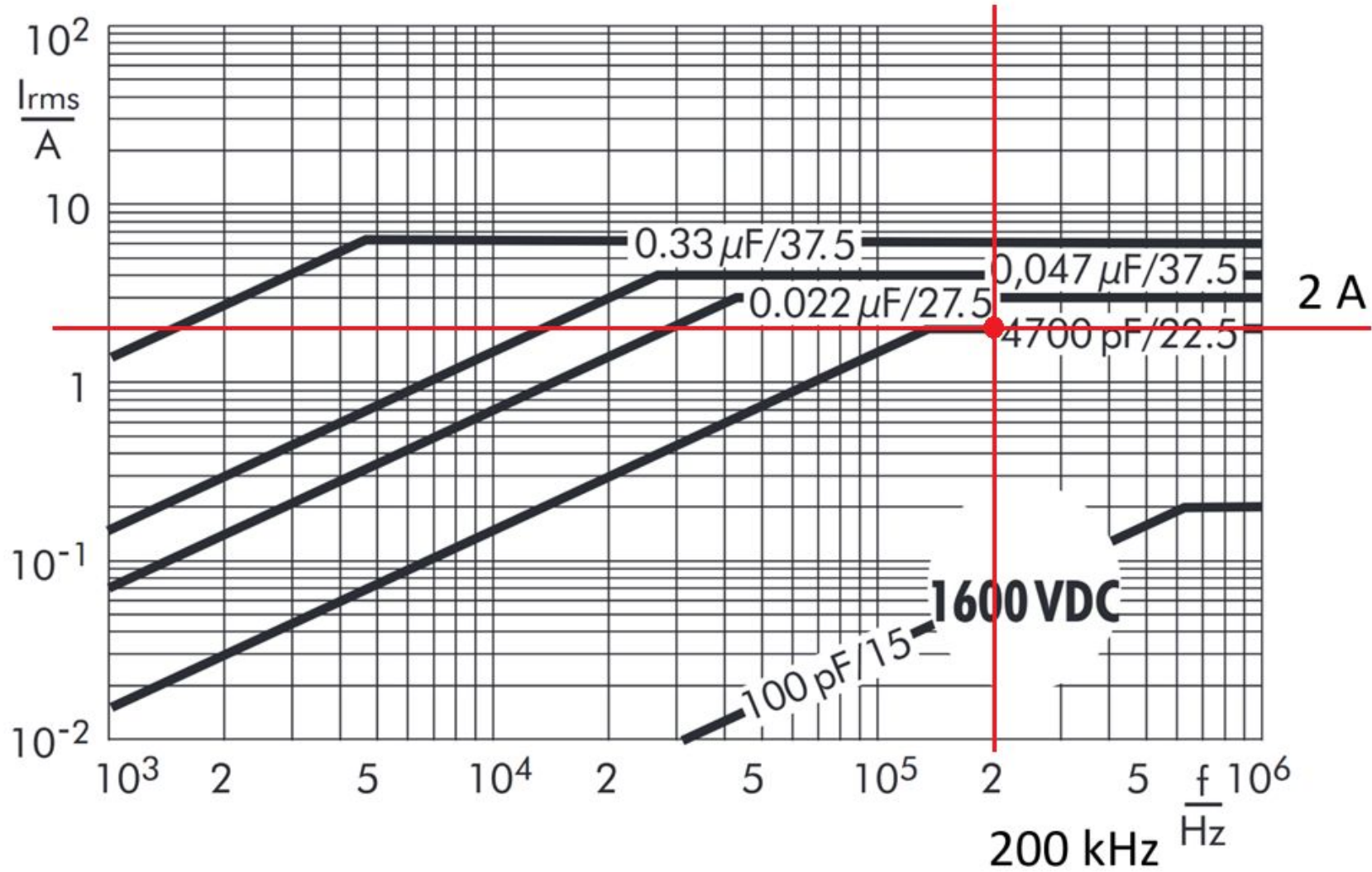


Kondensatory

Przygoda numer 7.

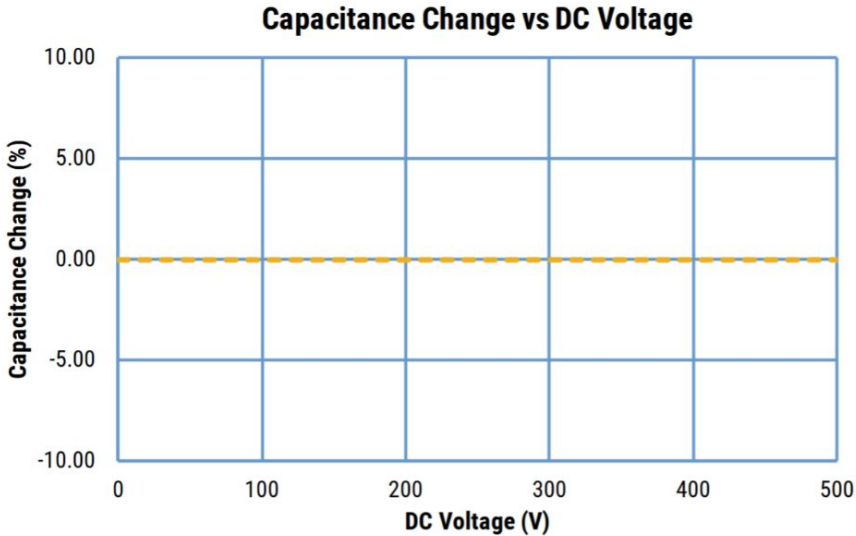
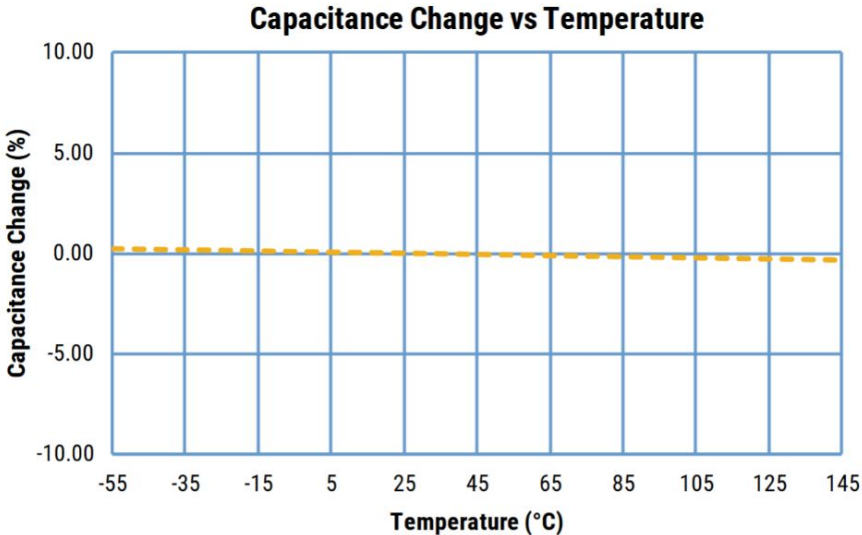




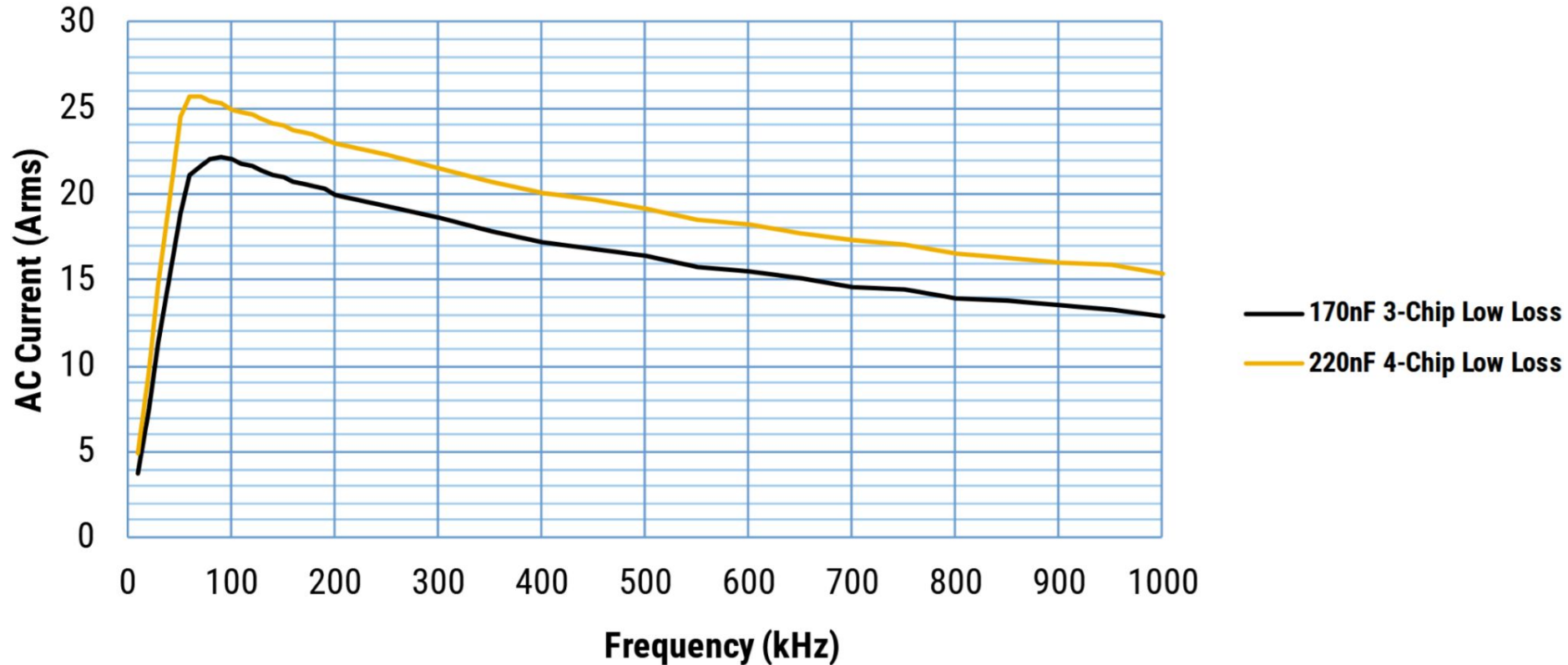


Capacitance (±10%)	μF	1.4	3	4	6.3	8.5	10	21	27	37
Sinusoidal Voltage	Vrms	1100	750	900	700			500	550	500
Peak Voltage	Vpeak	1560	1060	1270	990			710	780	710
Max. Current	Arms	600	800	700	1000					
Max. Power	kVAr	500								
Freq Range @ Full Power	kHz	47-82	47-68	25-39	26-51	19-37	16-32	15-15	10-12	9-9

Number of Chips	Mounting Configuration	Typical ESR at 25°C, 100 kHz	Typical ESL at 25°C	Typical Ripple Current
2	Standard	< 2.5 mΩ	< 1.5 nH	See Typical Performance Curves Below
3	Standard	< 2.5 mΩ	< 2.2 nH	
3	Low Loss	< 1.6 mΩ	< 0.75 nH	
4	Standard	< 2.5 mΩ	< 2.7 nH	
4	Low Loss	< 1.1 mΩ	< 0.45 nH	



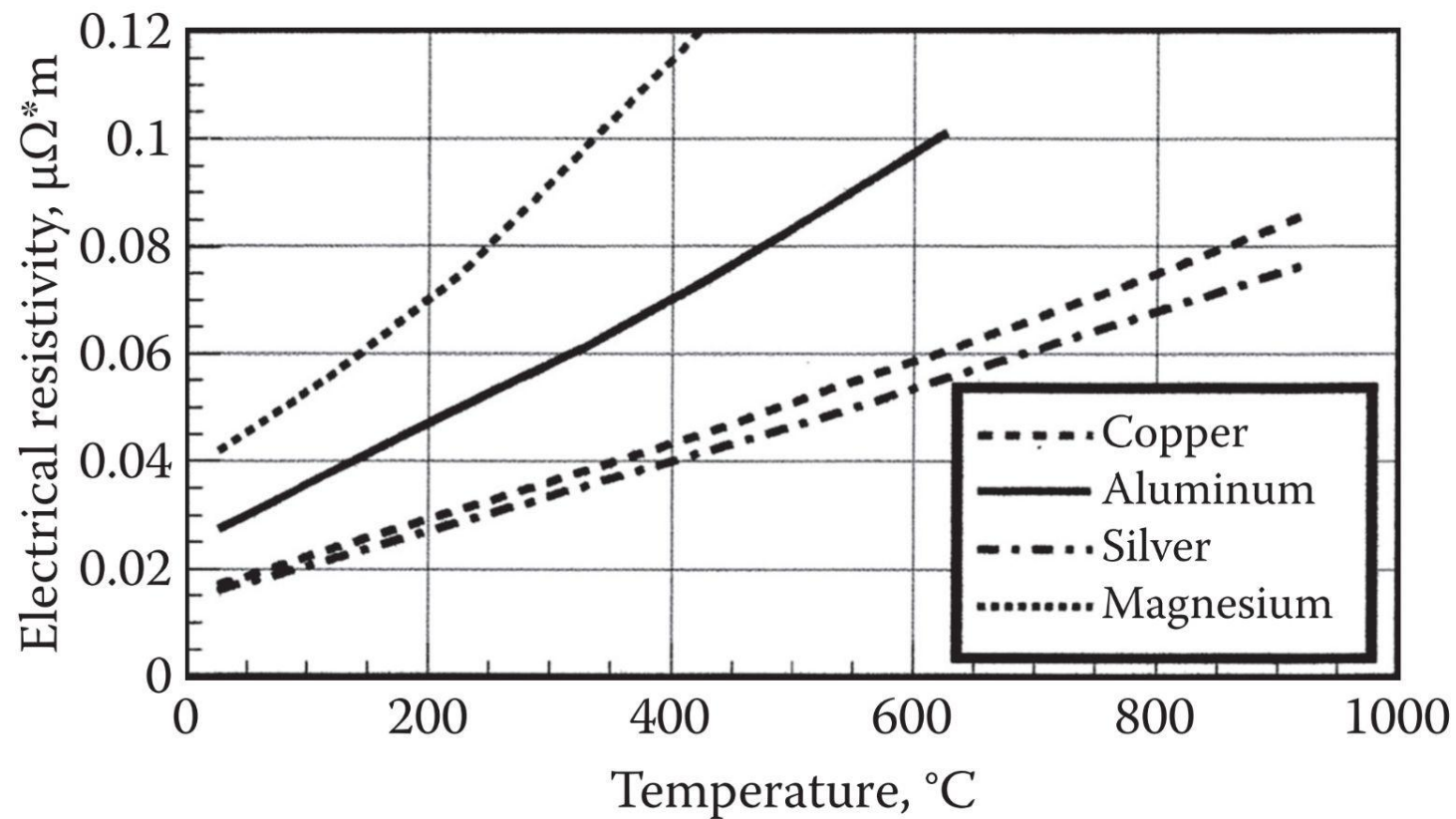
Typical AC Current Performance 1000V Low Loss Orientation

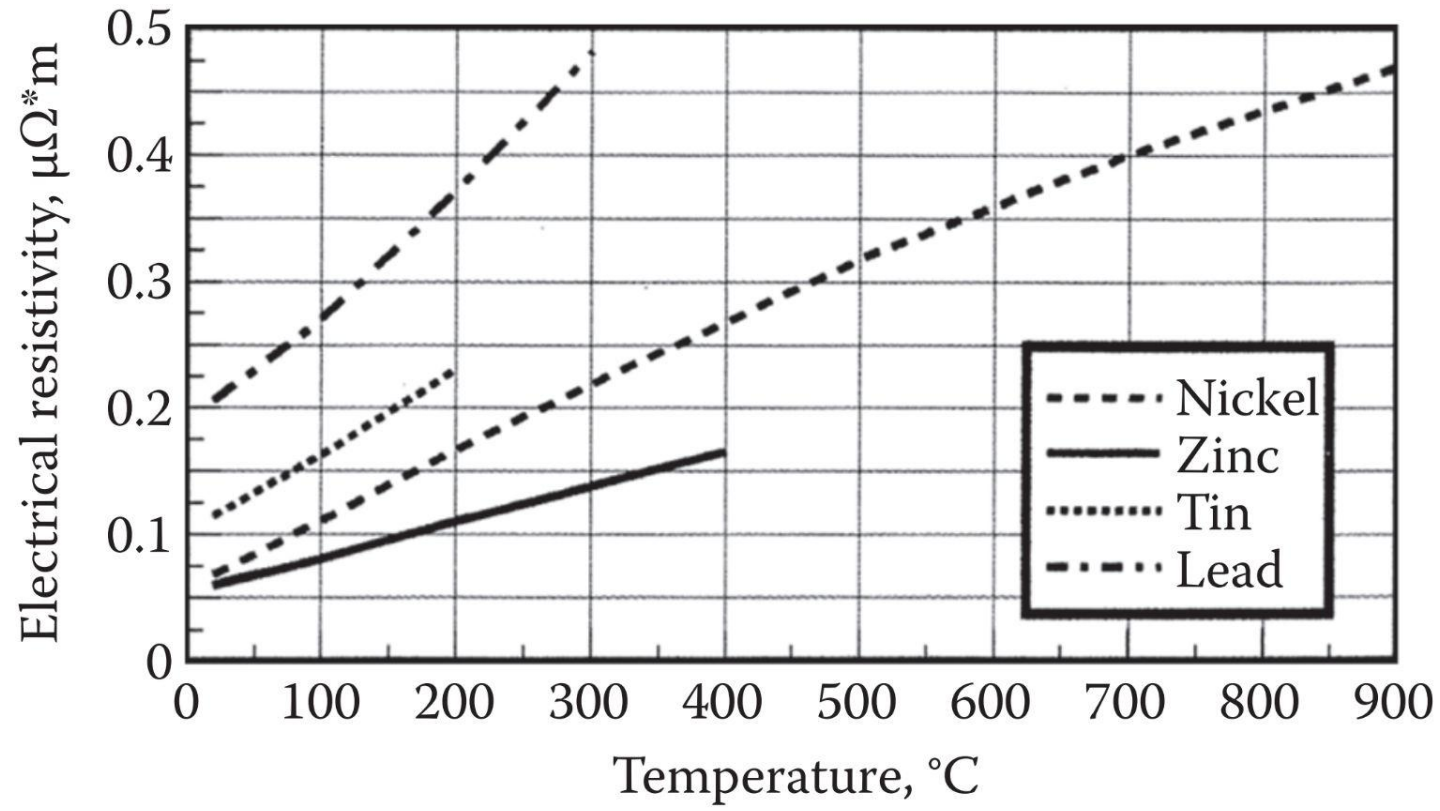


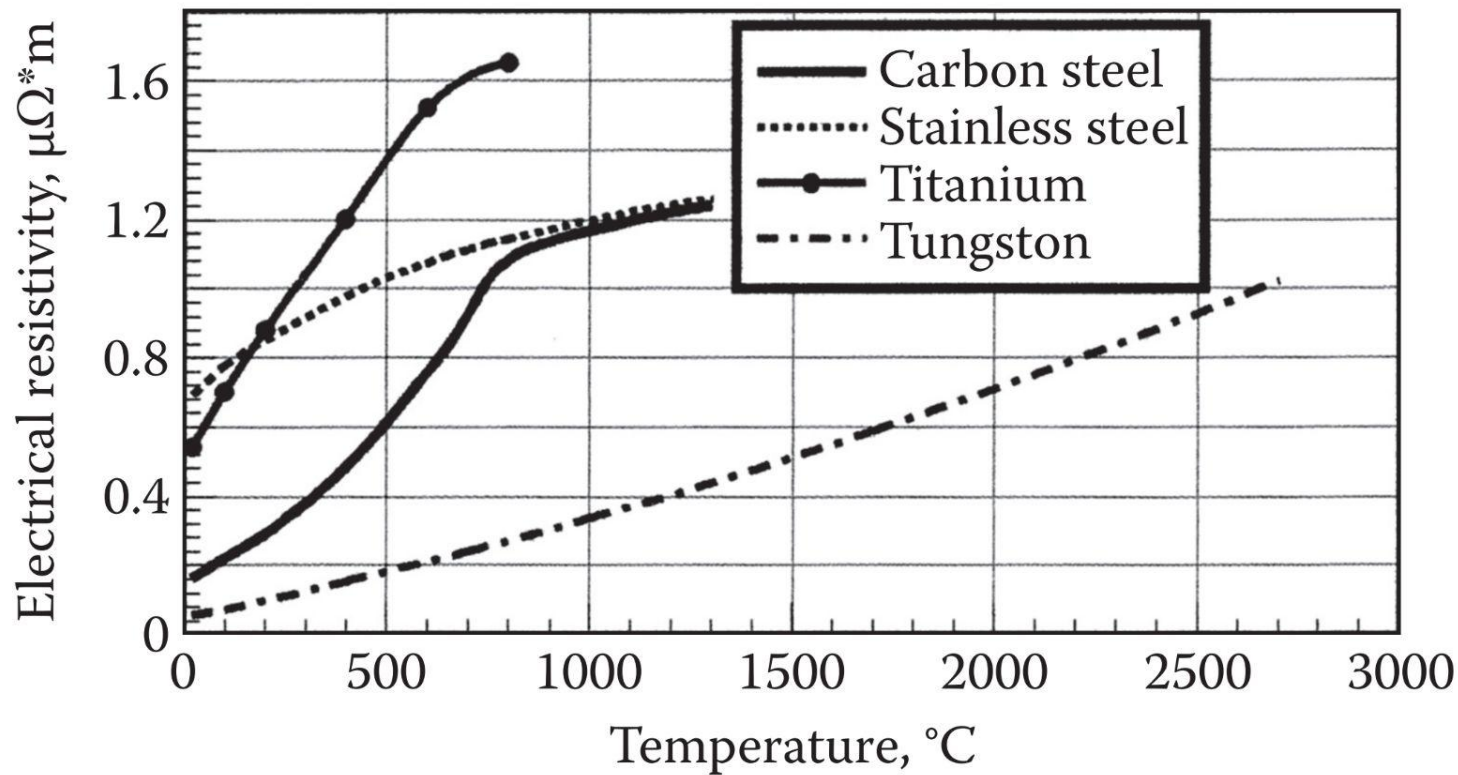


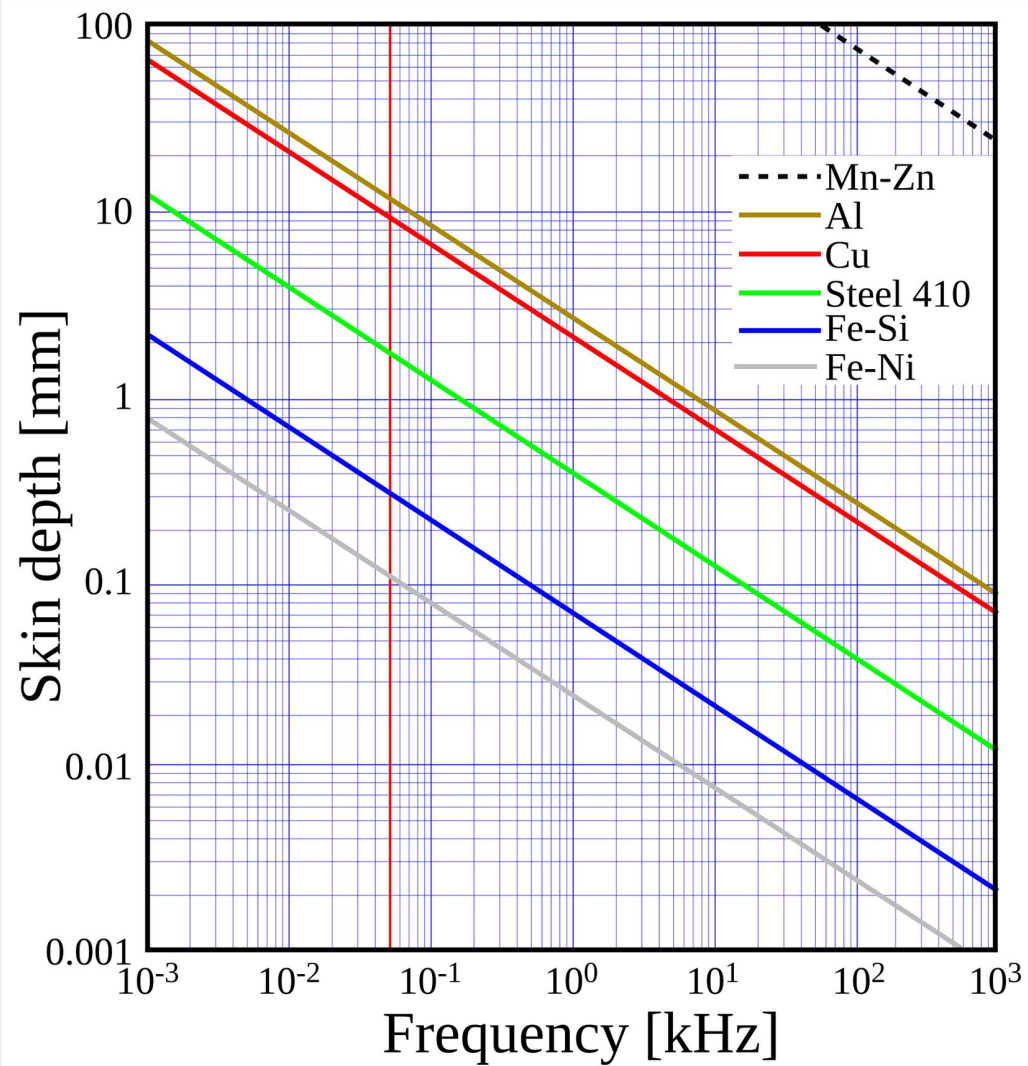
Wszystko płynie inaczej

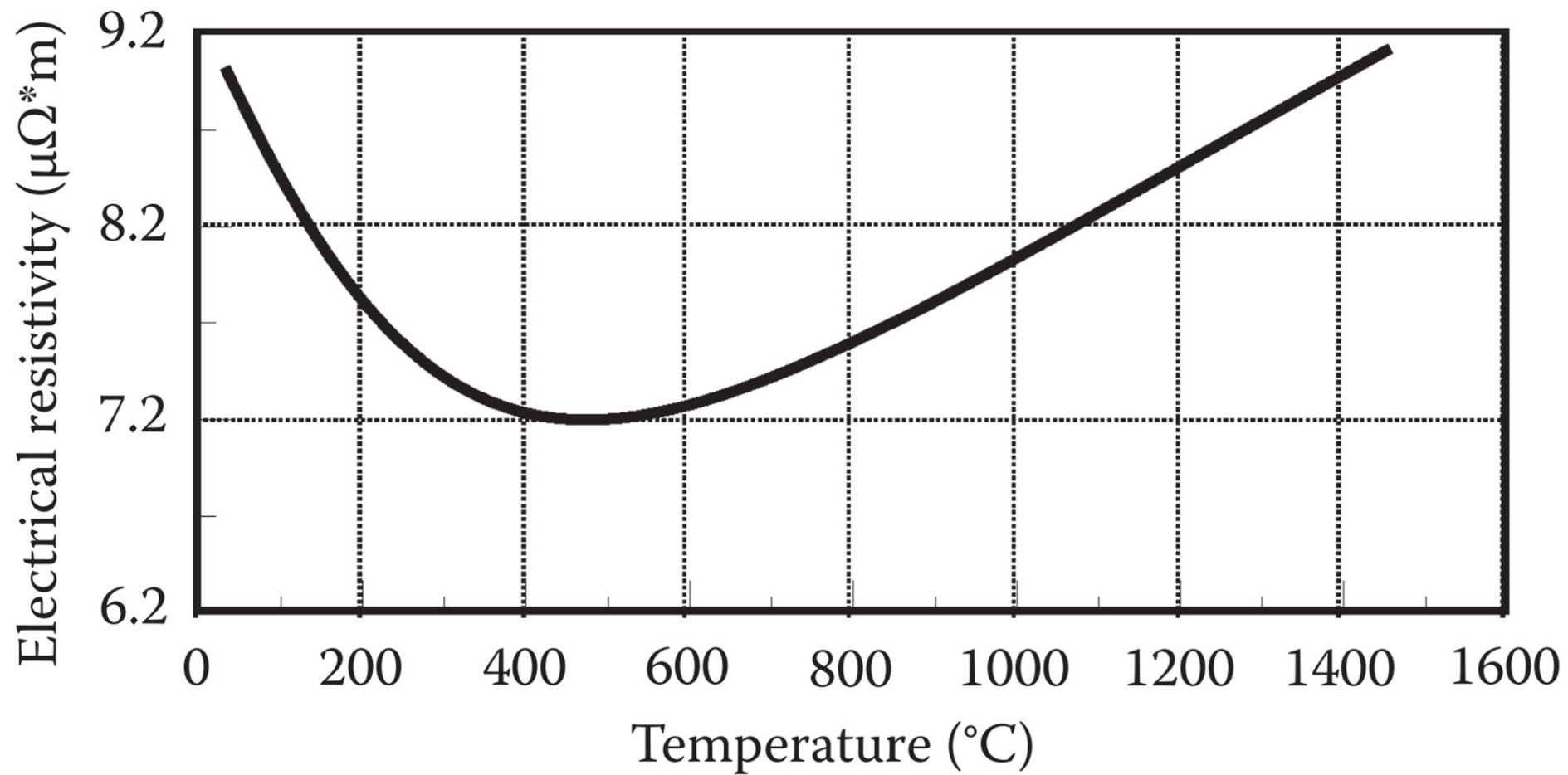
Przygoda numer -2.

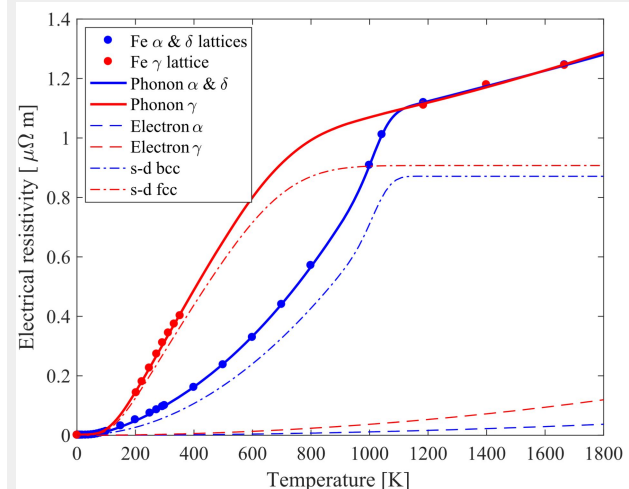
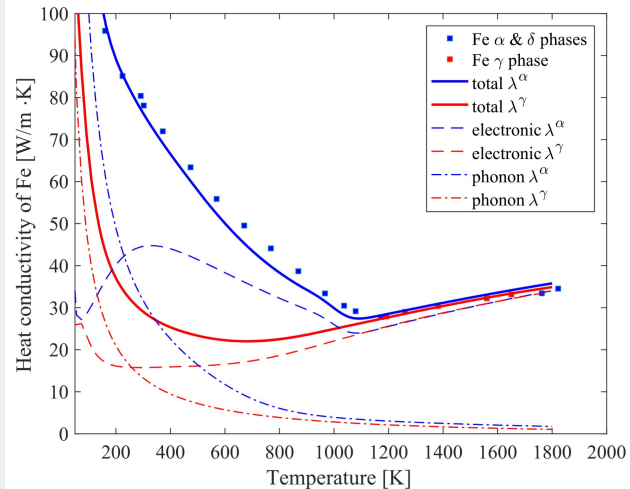
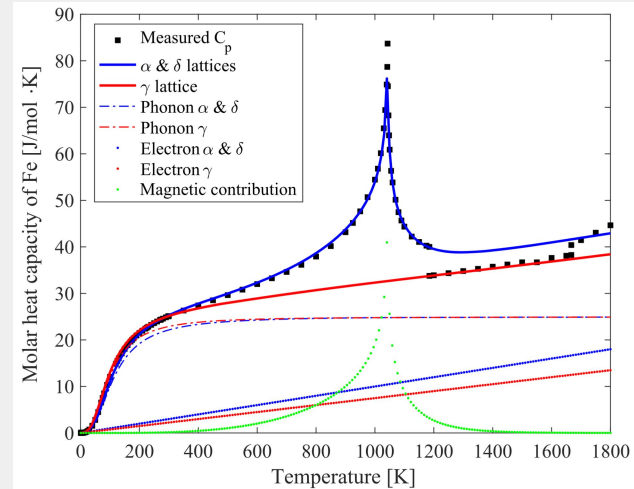












Kilka wykresów z właściwościami żelaza i innych metali

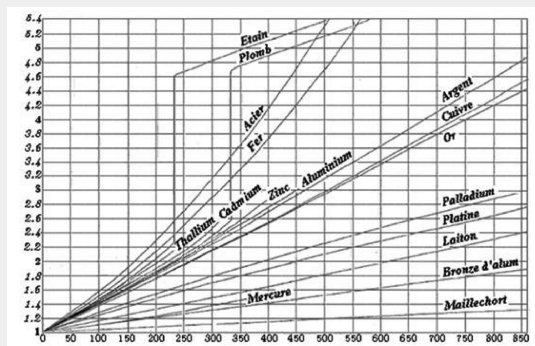
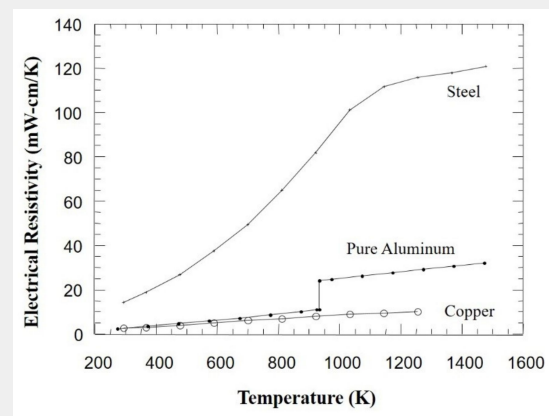
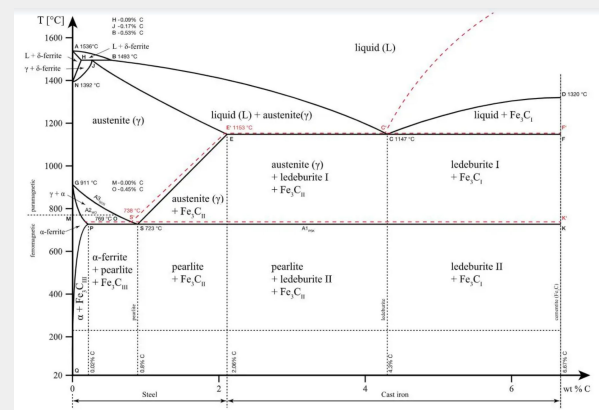
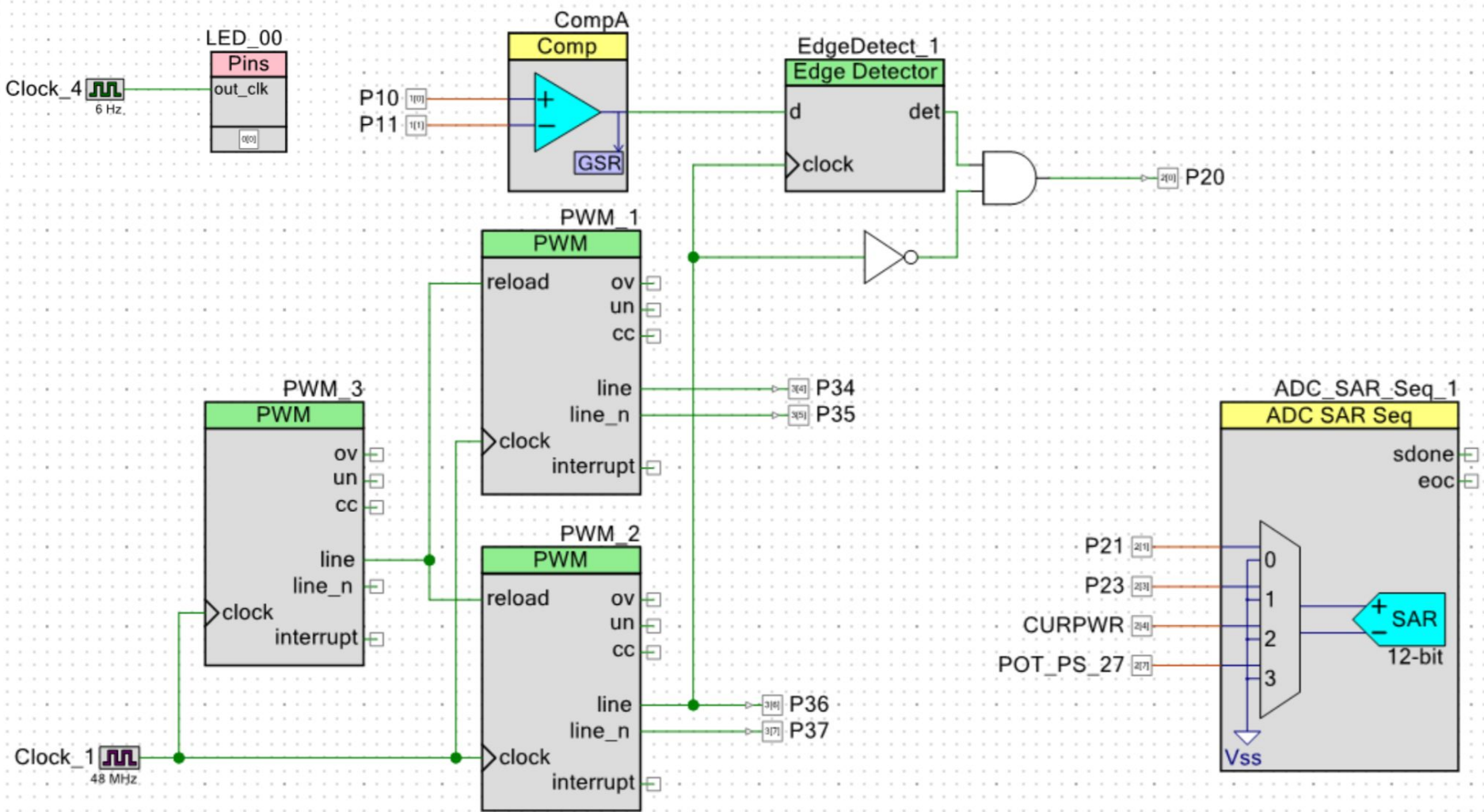


Figure 11 - Graphical behavior of resistance according the Benoit's results. Credit: Ref. [35].



Mój piec

Przygoda numer 7.



Configure 'PWM_3' ? X

Name: PWM_3

Configuration **PWM** Built-in 4 ▸

Prescaler: 1x

PWM align: Left align

PWM mode: PWM

Dead time cycle: 3

Stop signal event: Don't stop on kill

Kill signal event: Asynchronous

Output line signal: Direct output

Output line_n signal: Direct output

Input	Present	Mode
reload	<input type="checkbox"/>	Rising edge
start	<input type="checkbox"/>	Rising edge
stop	<input type="checkbox"/>	Rising edge
switch	<input type="checkbox"/>	Rising edge
count	<input type="checkbox"/>	Level

	Register	Swap	RegisterBuf
Period	200	<input type="checkbox"/>	65535
Compare	10	<input type="checkbox"/>	65535

Interrupt

☐ On terminal count

☐ On compare/capture count

PWM, left aligned

Datasheet OK Apply Cancel

Configure 'PWM_1' ? X

Name: PWM_1

Configuration **PWM** Built-in 4 ▸

Prescaler: 1x

PWM align: Left align

PWM mode: PWM with dead time insertion

Dead time cycle: 3

Stop signal event: Don't stop on kill

Kill signal event: Asynchronous

Output line signal: Direct output

Output line_n signal: Direct output

Input	Present	Mode
reload	<input checked="" type="checkbox"/>	Rising edge
start	<input type="checkbox"/>	Rising edge
kill	<input type="checkbox"/>	Rising edge
switch	<input type="checkbox"/>	Rising edge
count	<input type="checkbox"/>	Level

	Register	Swap	RegisterBuf
Period	200	<input type="checkbox"/>	65535
Compare	100	<input type="checkbox"/>	65535

Interrupt

☐ On terminal count

☐ On compare/capture count

PWM, left aligned

Datasheet OK Apply Cancel

Configure 'PWM_2' ? X

Name: PWM_2

Configuration **PWM** Built-in 4 ▸

Prescaler: 1x

PWM align: Left align

PWM mode: PWM with dead time insertion

Dead time cycle: 3

Stop signal event: Don't stop on kill

Kill signal event: Asynchronous

Output line signal: Direct output

Output line_n signal: Direct output

Input	Present	Mode
reload	<input checked="" type="checkbox"/>	Falling edge
start	<input type="checkbox"/>	Rising edge
kill	<input type="checkbox"/>	Rising edge
switch	<input type="checkbox"/>	Rising edge
count	<input type="checkbox"/>	Level

	Register	Swap	RegisterBuf
Period	200	<input type="checkbox"/>	65535
Compare	100	<input type="checkbox"/>	65535

Interrupt

☐ On terminal count

☐ On compare/capture count

PWM, left aligned

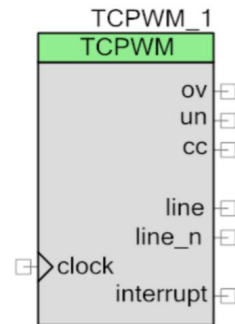
Datasheet OK Apply Cancel

PSoC 4 Timer Counter Pulse Width Modulator (TCPWM)

2.10

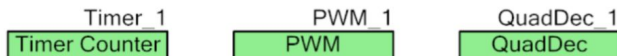
Features

- 16-bit fixed-function implementation
- Timer/Counter functional mode
- Quadrature Decoder functional mode
- Pulse Width Modulation (PWM) mode
- PWM with configurable dead time insertion
- Pseudo random PWM
- Run-time customization



General Description

The TCPWM component is a multifunction component that implements core microcontroller functionality, including Timer/Counter, PWM, and Quadrature Decoder using the PSoC 4 TCPWM block. Each is available as a pre-configured schematic macro in the PSoC Creator Component Catalog, labeled as “TCPWM Mode.”

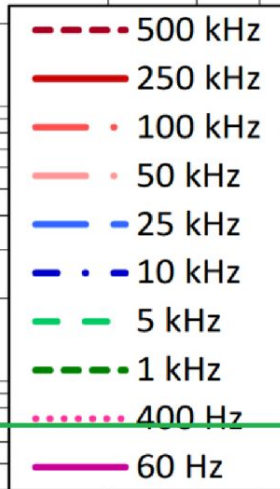


```
49 void SetHeaterParam(void){
50
51     if(main_cnt > main_cnt_max_48){
52         main_cnt = main_cnt_max_48;
53     };
54
55     if(main_cnt < main_cnt_min_48){
56         main_cnt = main_cnt_min_48;
57     };
58
59     if(main_pwr > ((main_cnt/2)-pwr_cor)){
60         main_pwr = (main_cnt/2)-pwr_cor;
61     };
62
63     if(main_pwr < pwr_cor){
64         main_pwr = pwr_cor;
65     };
66
67     PWM_1_WritePeriod(main_cnt);
68     PWM_1_WriteCompare(main_cnt/2);
69
70     PWM_2_WritePeriod(main_cnt);
71     PWM_2_WriteCompare(main_cnt/2);
72
73     PWM_3_WritePeriod(main_cnt);
74     PWM_3_WriteCompare(main_pwr);
75 }
```

26	sztuk	3	
27	Ae	1.99	cm2
28	aeef	5.97	cm2
29			
30			
31	Uz	400	V
32	Fr	150000	Hz
33	Ae eff	5.97	cm2
34	K	4	
35	Nt	44	zw
36			
37	Licznik	400000000000	
38	mianownik	157608000	
39	B	253.7942236	G
40	B (T)	0.02537942236	T
41	B (mT)	25.37942236	mT
42			

Core Loss vs. B_{pk} - Sendust 75 μ

Core Loss (mW/cm³)

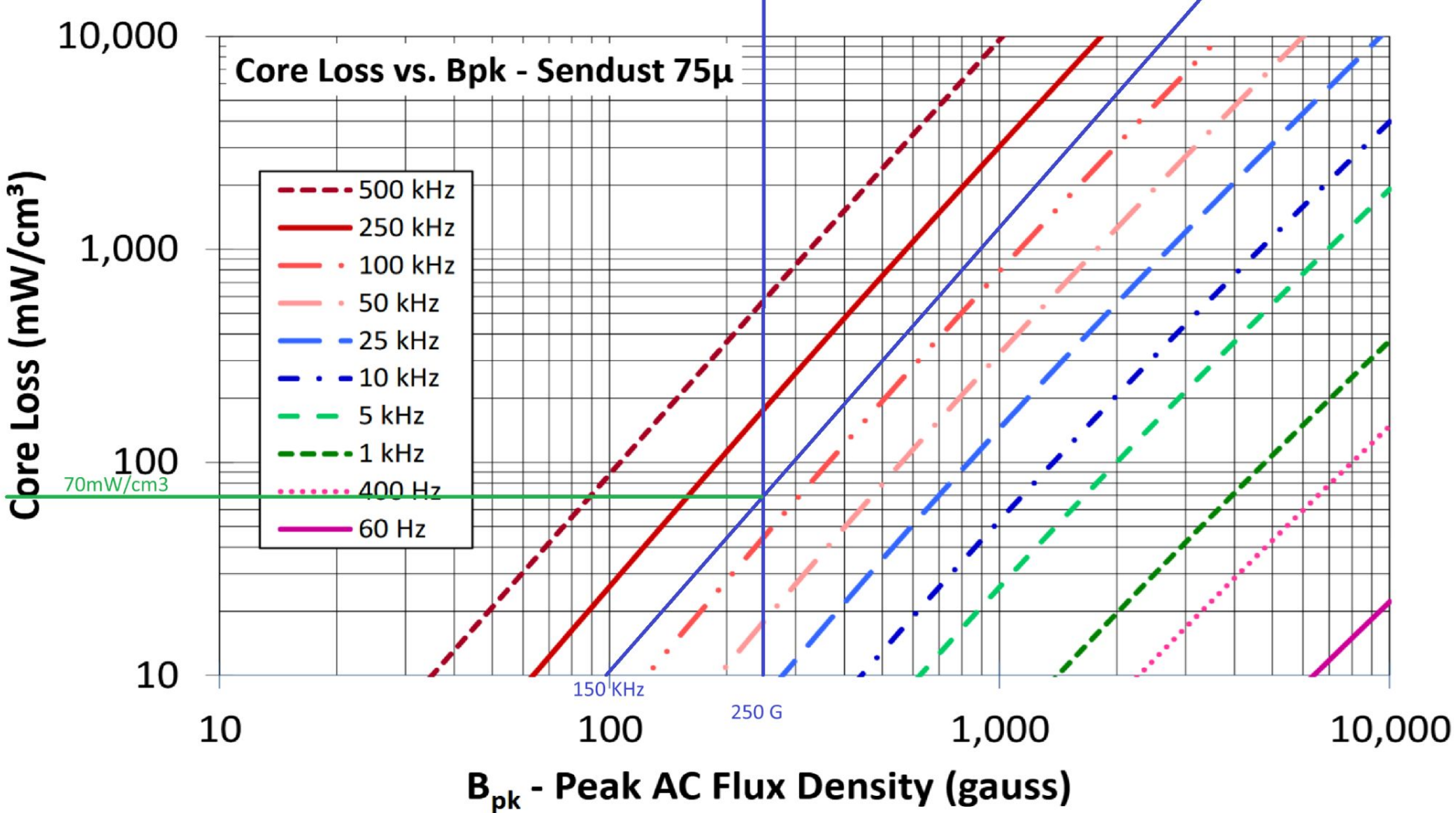


70mW/cm³

150 kHz

250 G

B_{pk} - Peak AC Flux Density (gauss)



a	7.89E+09
b	7.11E+08
c	8.98E+06
d	2.85E-14
B	250 gauss
B2	62500
f	150000 Hz
f2	2.25E+10
a/Bpk^3	5.05E+02
b/Bpk^2.3	2.17E+03
c/Bpk^1.65	9.92E+02
a+b+c	3.67E+03
f/abc	4.09E+01
d Bpk^2 f^2	4.00E+01
Core Losses	80.91 mW/cm3

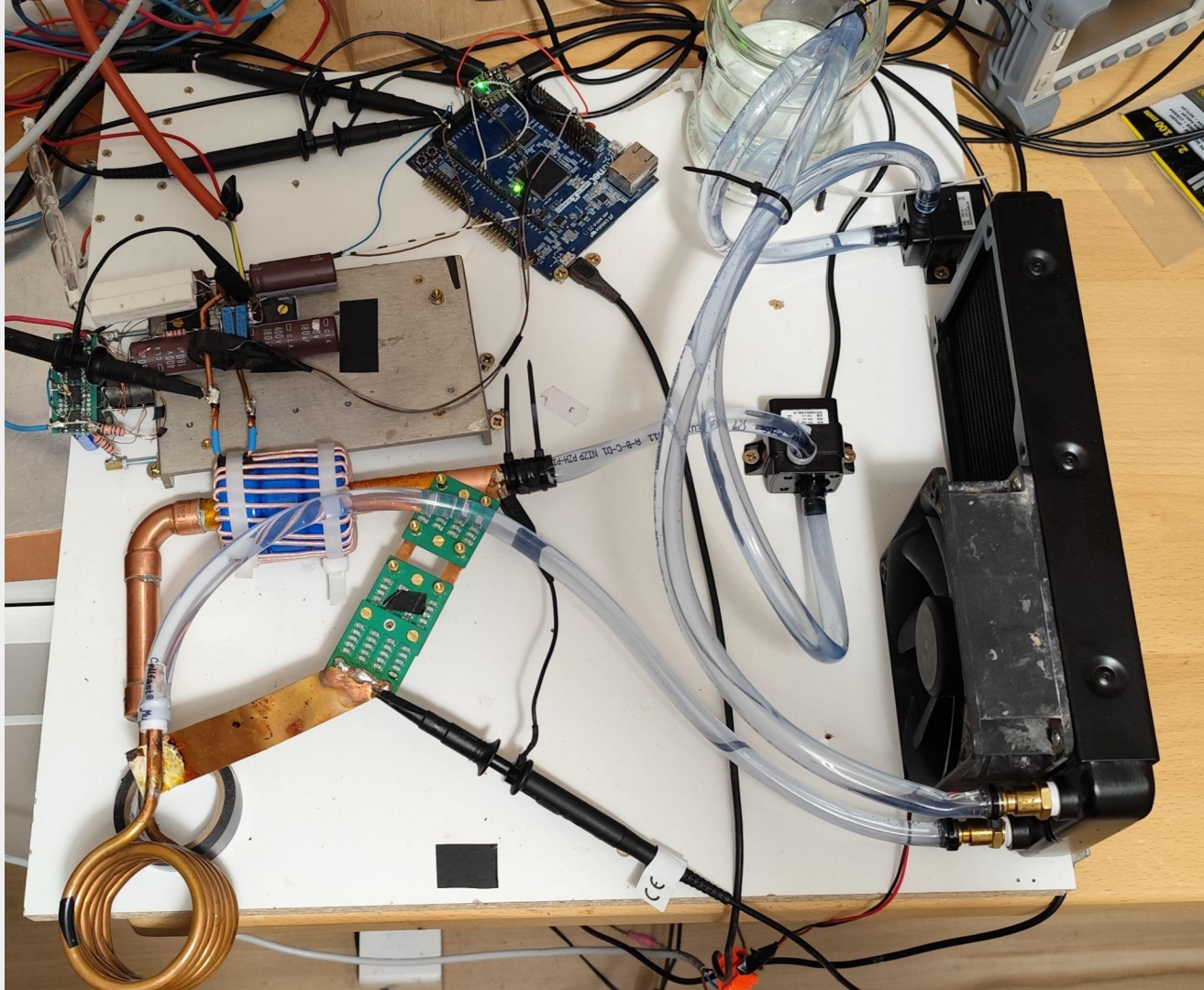
Core Loss

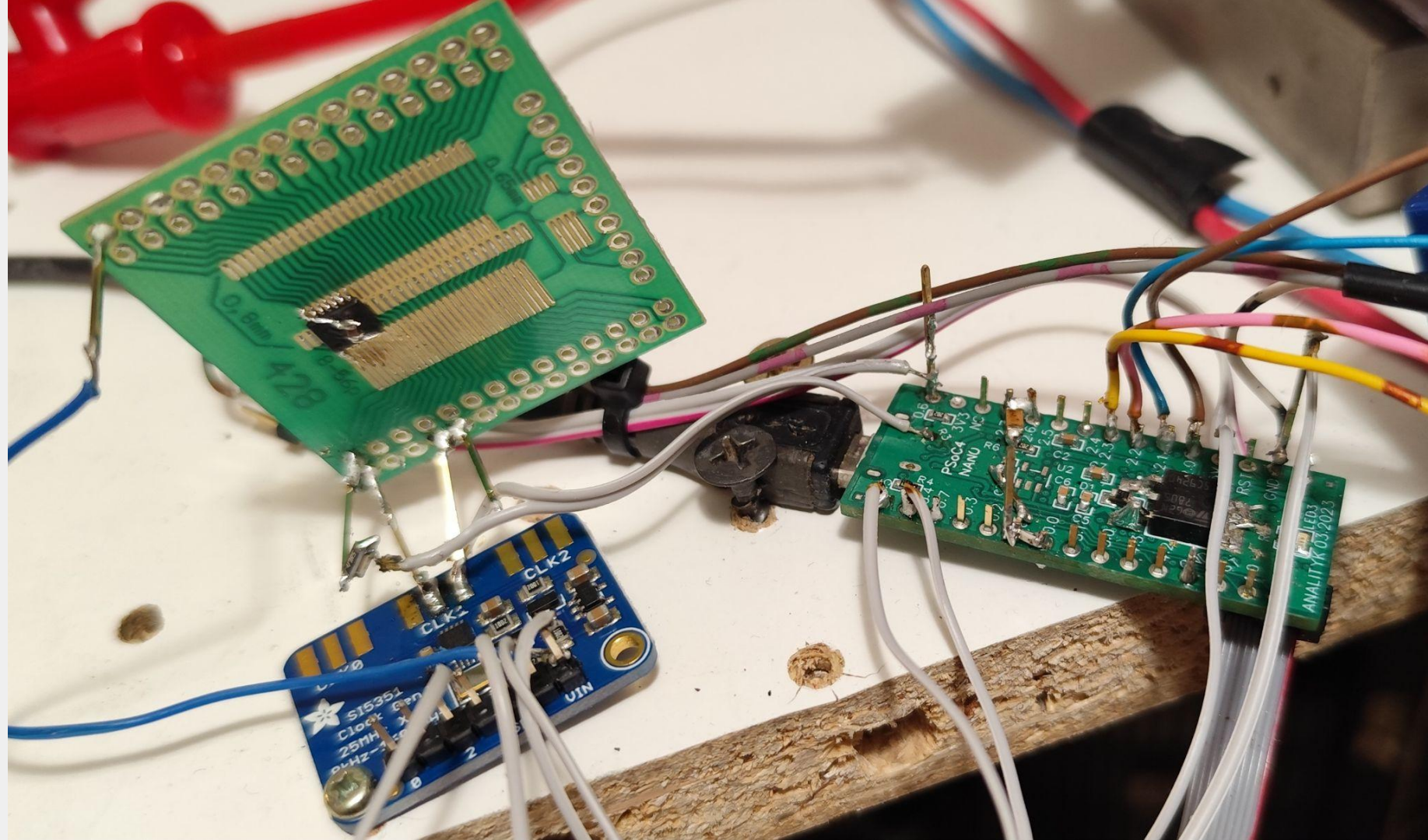
$$\text{Core Loss (mW/cm}^3\text{)} = \frac{a}{B_{pk}^3} + \frac{b}{B_{pk}^{2.3}} + \frac{c}{B_{pk}^{1.65}} + d \cdot B_{pk}^2 \cdot f^2$$

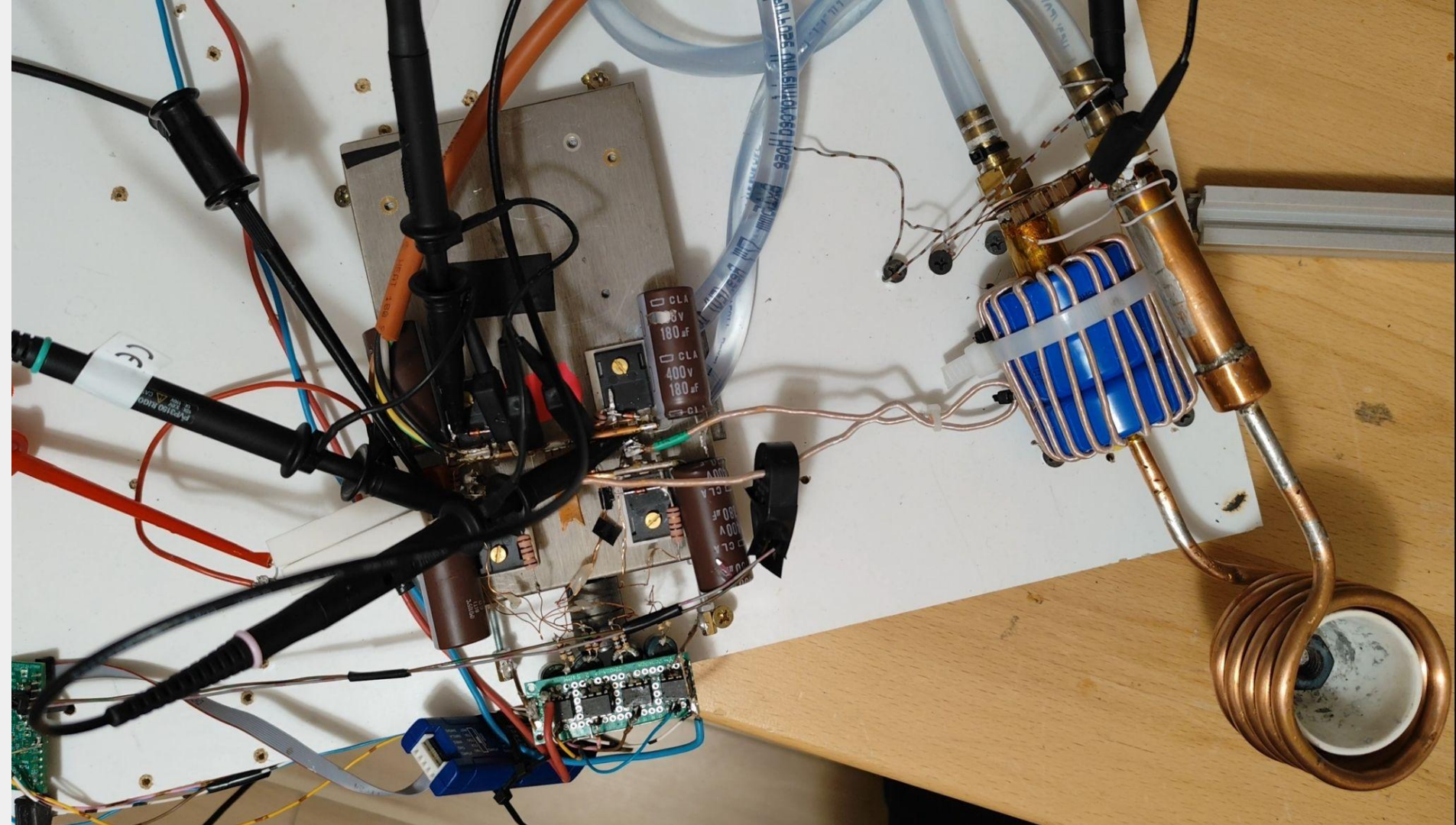
where B_{pk} expressed in gauss, f expressed in hertz, and:
 $a=7.890E+09$, $b=7.111E+08$, $c=8.980E+06$, $d=2.846E-14$

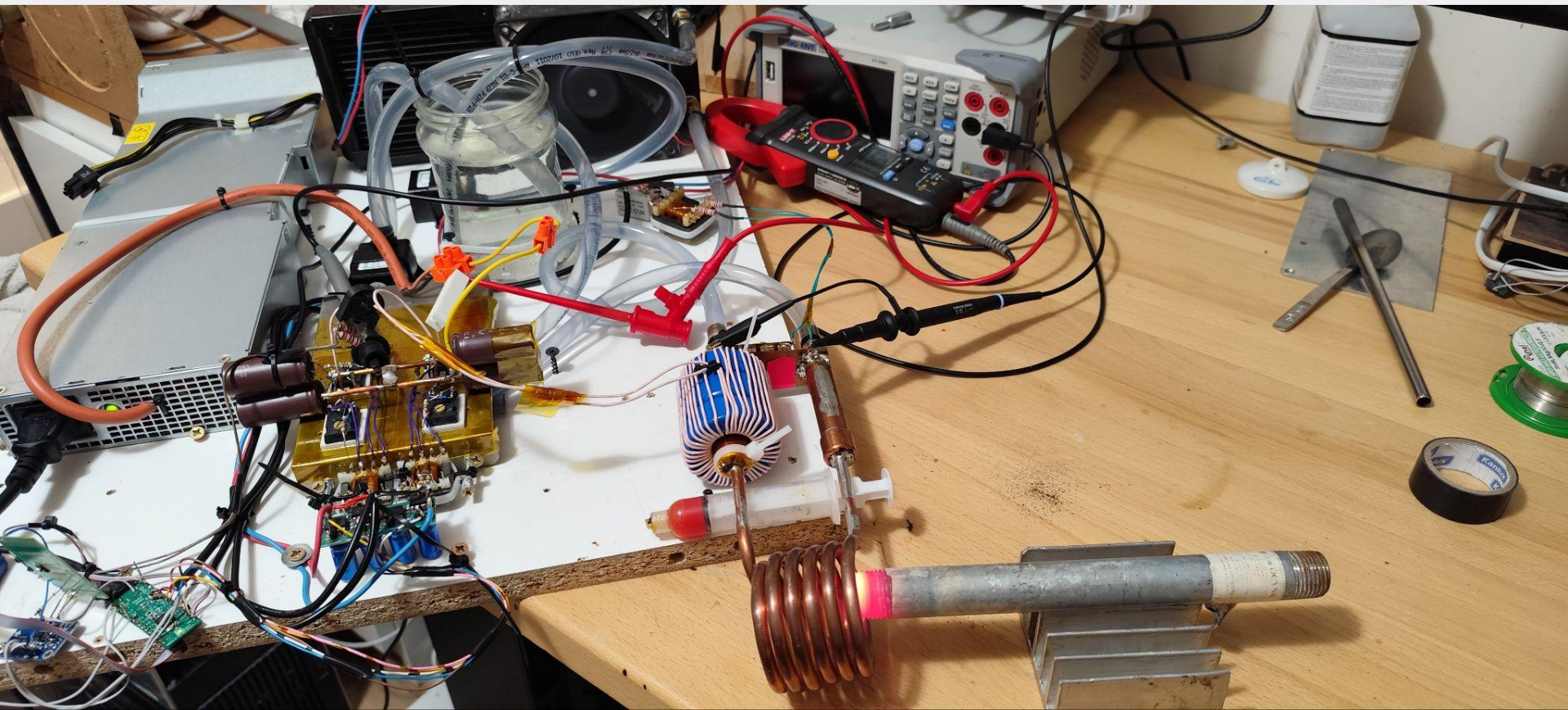
B_{pk}	1000	G
frequency	50 k	Hz
Core Loss (nominal)	323	mW/cm ³
Core Loss (maximum)	372	mW/cm ³

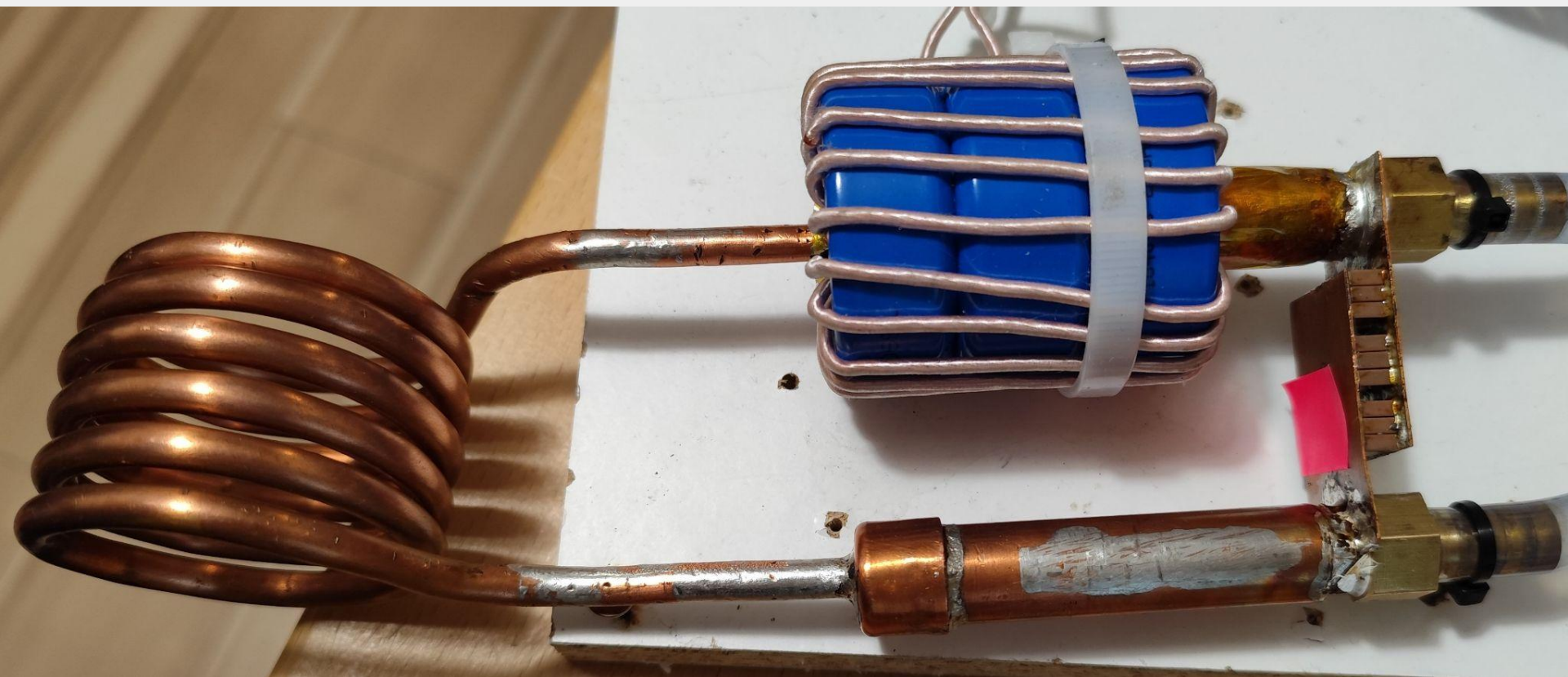
Ve	21.4	cm3
3 cores	64.2	cm3
Total core losses	5194.542758	mW
	5.194542758	W
Nominal losses	20.7366	W

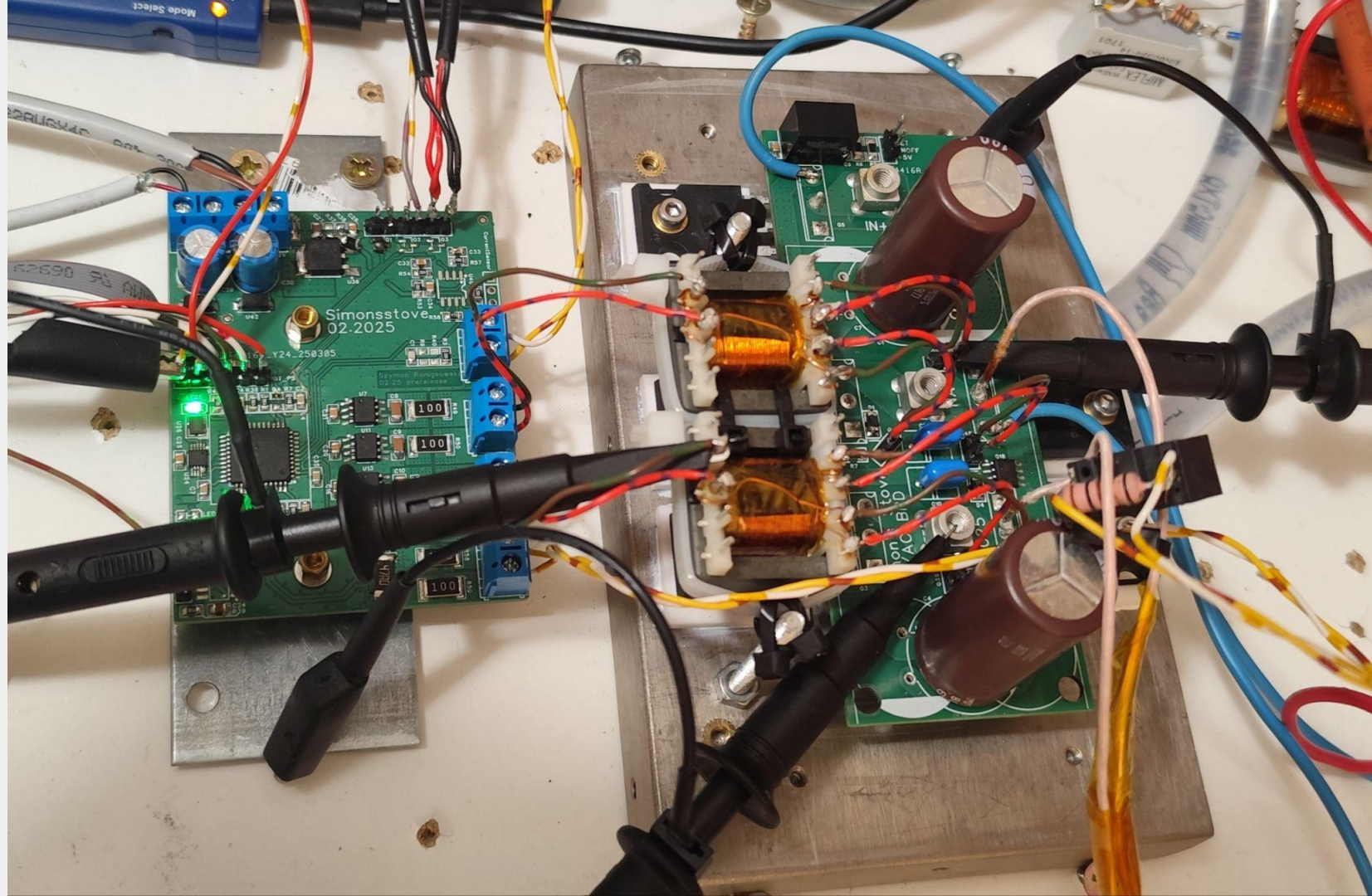


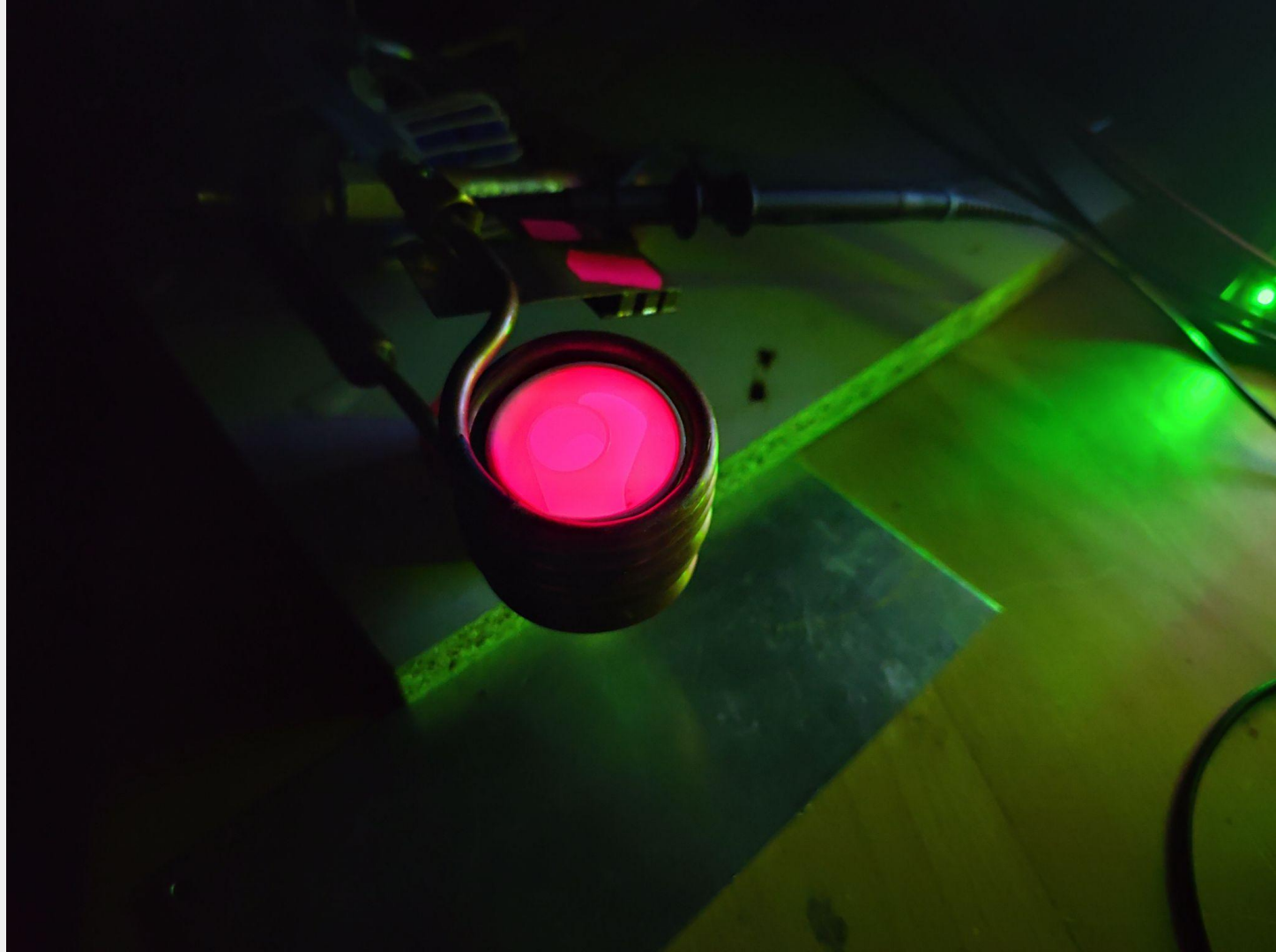










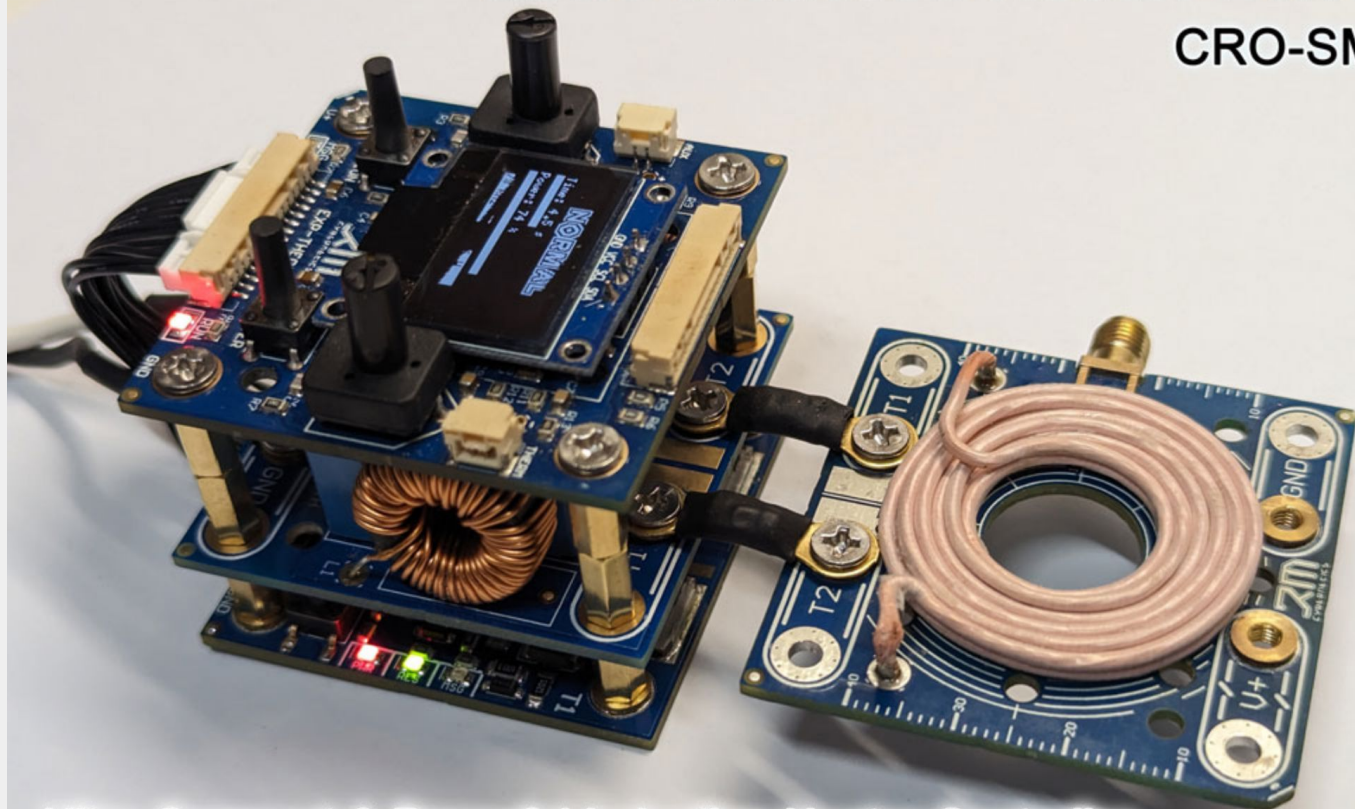




Made in the UK

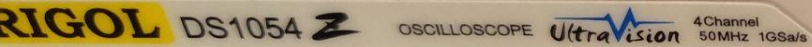
Micro Induction Heater Driver

CRO-SM3



Ultra Compact & Powerful Induction Heater Controller
Only 50mm x 50mm x 7mm
Digital interface & RS-232 for advanced control

SM
CYBERNETICS



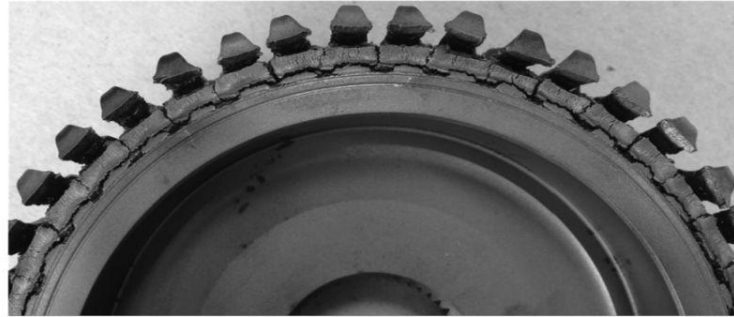


FIGURE 4.188

Example of applying an excessive power density and the use of very low frequency when hardening gears using encircling coil.

Szymon Romanowski

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