Overlooked Loss Mechanisms In Flyback Transformers

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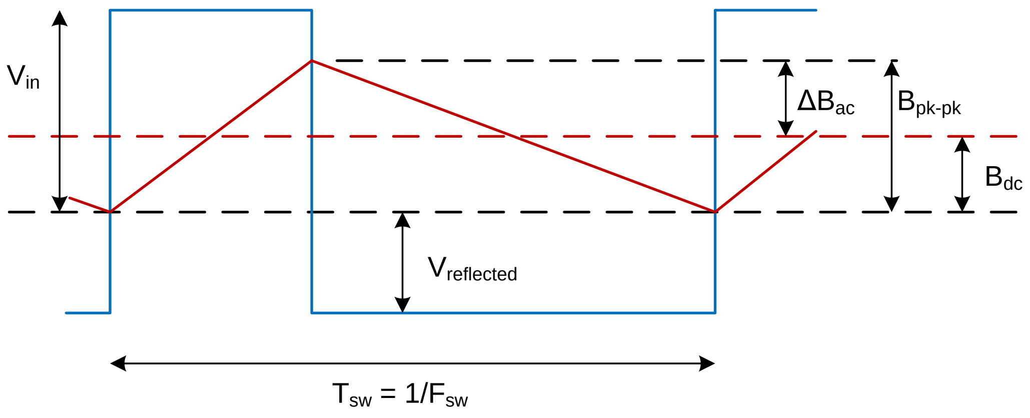
Agenda

- Flyback transformer basics
- Review of Flyback transformer losses:
  - Core loss
    - Dependence on DC bias
    - Effect of waveform and duty cycle
  - Effect of snubber clamp voltage on leakage losses
- Effect of input voltage range on the FB transformer power density

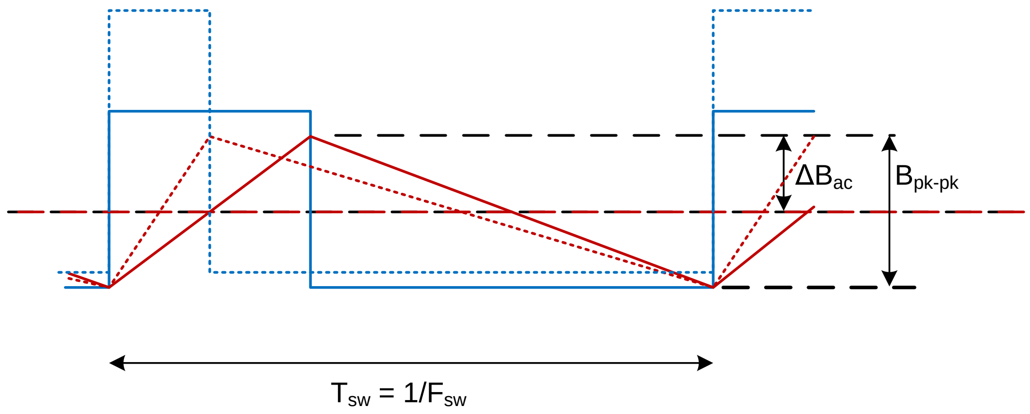
Core Loss – Effect of Waveform & DC Flux Bias

- **Traditional assumptions:**
  - DC Bias has no effect
  - Square-wave close to sine
- **Traditional method:**
  - Calculate ΔB_{ac} at F_{sw}, neglect B_{dc}
  - Core material manufacturer data sheet:
    - Read core loss at ΔB_{ac} and F_{sw}
    - Loss data provided for sine excitation
- **The reality:**
  - Waveform and duty cycle have significant impact on core loss
  - DC bias has significant impact on core loss
  - Several papers published on the subject
    - ***Reference [1] and [2] provide most useful information***

Flyback Waveforms at CCM/DCM Boundary



Flyback Waveforms, Neglect B_{dc} & D



1. *"A New Core Loss Model for Rectangular AC Voltages", Mingkai Mu, Fred C. Lee, CPES, Virginia Tech, ECCE 2014*
2. *"High Frequency Magnetic Core Loss Study", PhD Dissertation, Mingkai Mu, Virginia Tech, 2013*

Effect of Waveform on Core Loss [1]

- Proposed curve fit equation for square-wave excitation, based on measured data:

$$\frac{P_{v\_rect}}{P_{v\_sine}} = F_{waveform} = \frac{8}{\pi^2 \cdot [4D \cdot (1-D)]^{\gamma+1}} \qquad (Eq.\ 1)$$

- ***P_{v_sine}*** – conventionally-calculated core loss
  - For sinewave excitation of equal flux swing (available from the material data sheet)
- ***D*** – duty cycle of square-wave
- ***γ*** – correction factor
  - Depends on material, frequency & temperature
  - Could be measured and provided by the magnetic material manufacturers
  - Values for several ferrites at 25°C empirically determined in [1]

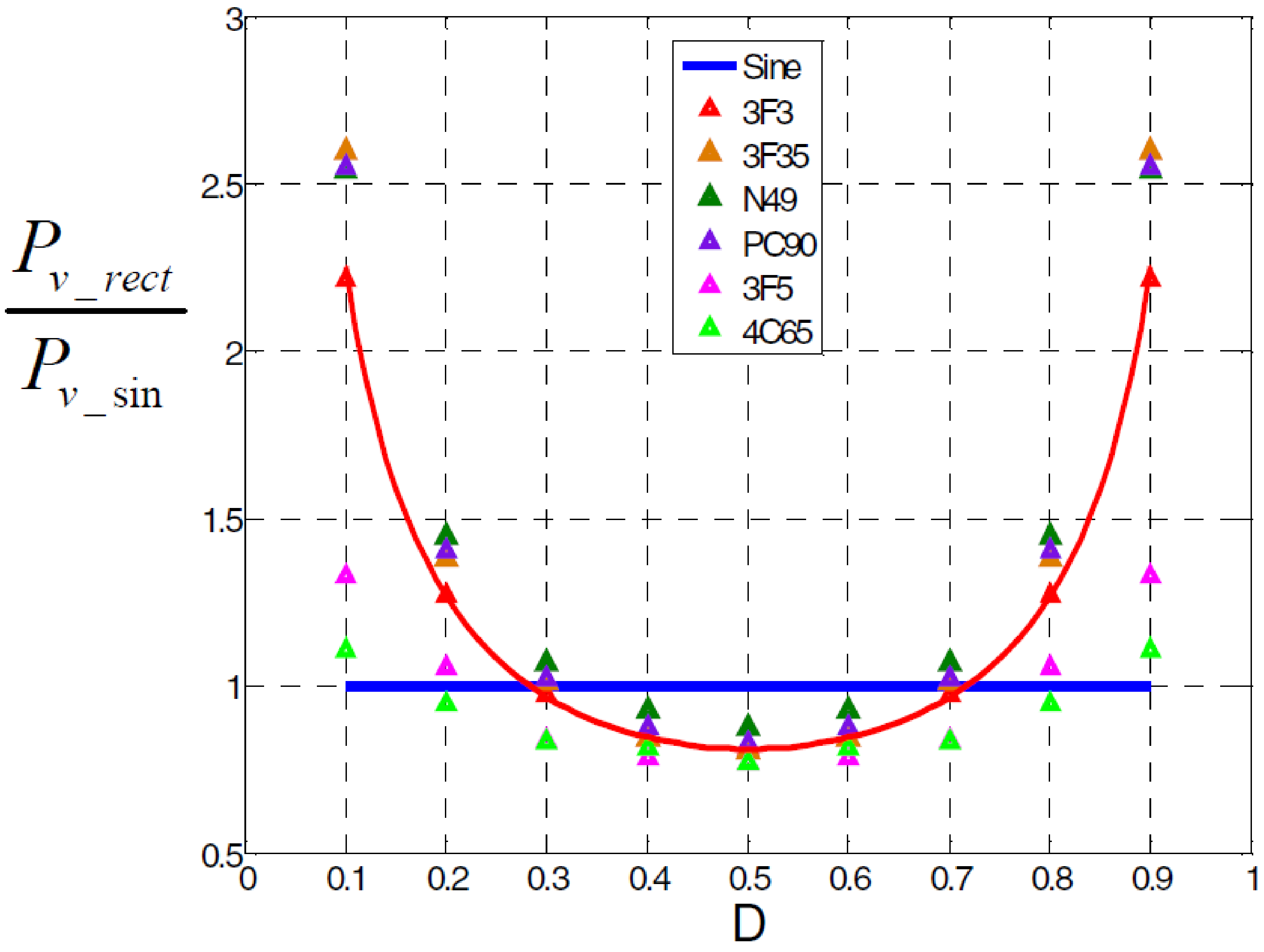
Table I. γ value derived from test data

	γ				
	200kHz	500kHz	1MHz	1.5MHz	3MHz
3C90	-0.37	-0.12	-	-	-
3F3	-0.37	-0.12	0	-	-
3F35	-	-0.12	0.15	0.18	-
3F5	-	-	-0.5	-0.05	-
N49	-0.35	0.16	0.15	-	-
DMR50B	-0.4	0.2	-	-	-
4C65	-	-	-0.7	-	-0.7

1. "A New Core Loss Model for Rectangular AC Voltages", Mingkai Mu, Fred C. Lee, CPES, Virginia Tech, ECCE 2014

$F_{waveform}$ for Square-wave vs. D at F_{sw} 1 MHz [1]

- 50% duty-cycle
  -> lower loss than sine
- Significant loss increase as duty cycle approaches 100% or 0%
- Some new HF materials perform noticeably better at duty cycle extremes:
  - 3F5
  - 4C65
- ***Recommendation***
  – make your own in-circuit measurements
  – ask TI for help

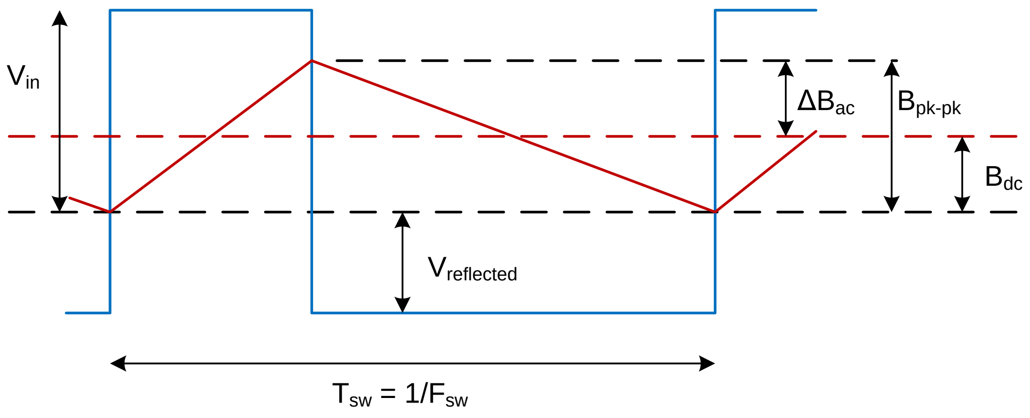


1. "A New Core Loss Model for Rectangular AC Voltages", Mingkai Mu, Fred C. Lee, CPES, Virginia Tech, ECCE 2014

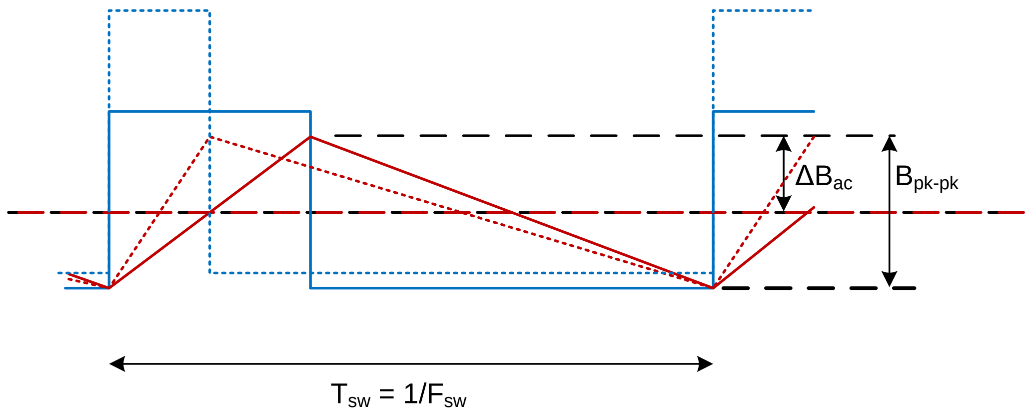
Effect of DC Bias [2]

- DC Bias shown to have significant impact on core loss
  - Many different papers published
- The effect is measured and quantified for two ferrite core materials:
  - 3F35
  - PC90
- A function $F(H_{dc})$ is developed (by curve fit to measured data)
- Enables calculation of core loss under DC bias

Flyback Waveforms at CCM/DCM Boundary

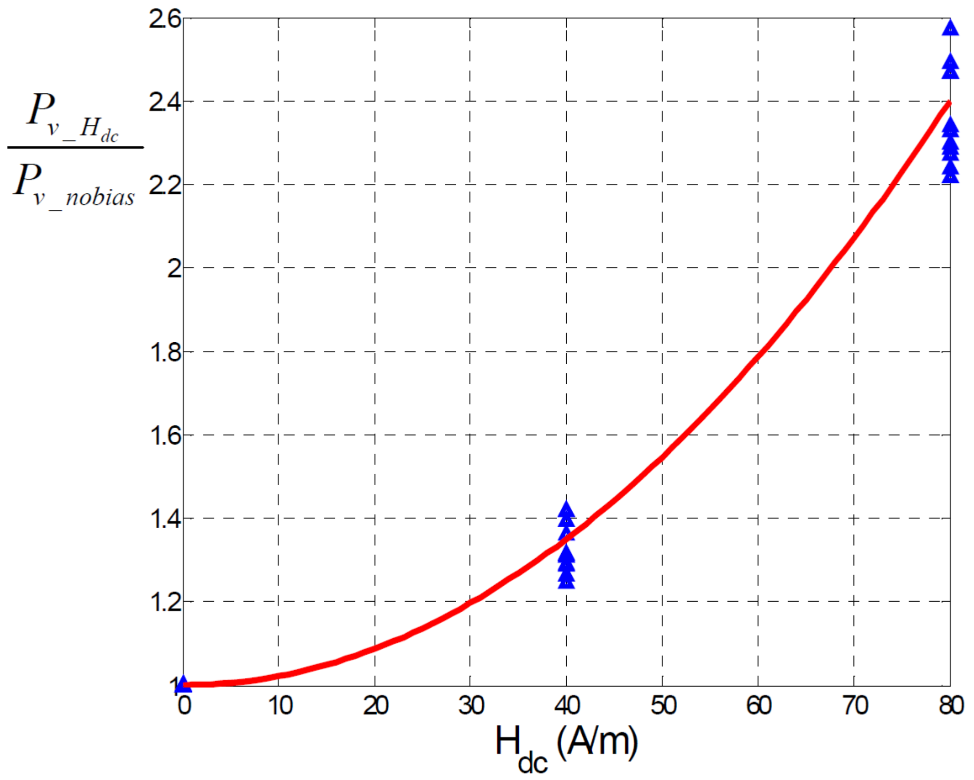


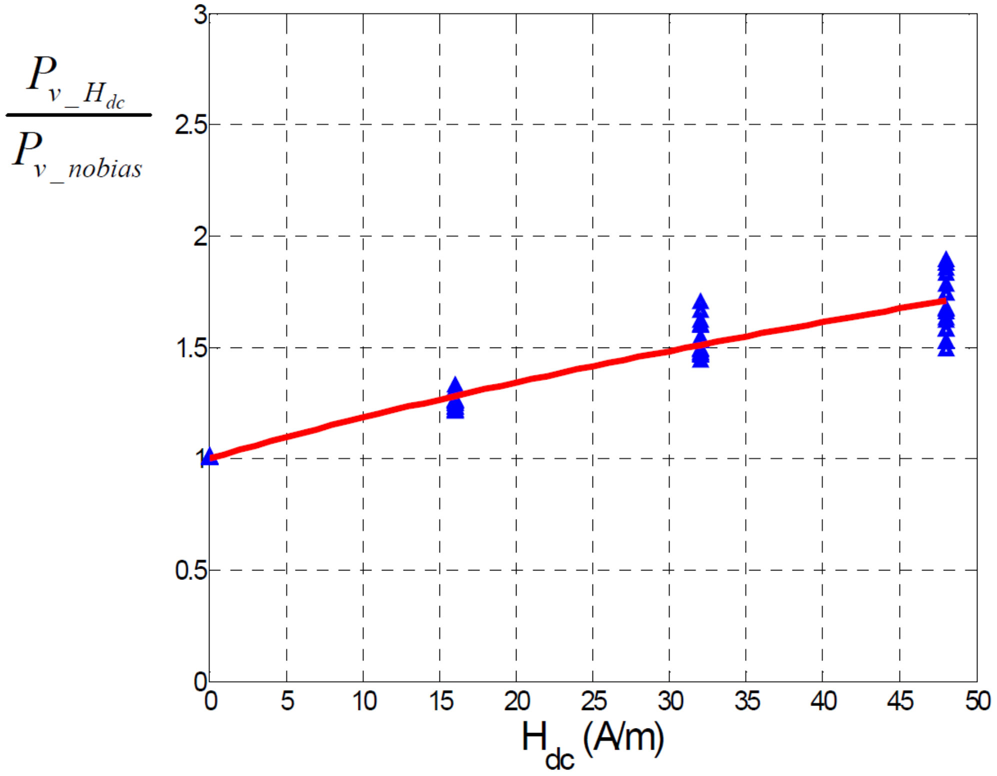
Flyback Waveforms, Neglect B_{dc} & D



2. *"High Frequency Magnetic Core Loss Study", PhD Dissertation, Mingkai Mu, Virginia Tech, 2013*

Loss vs. DC Bias Normalized to zero DC Bias [2]





3F35 @ 500 kHz, vary B_{pk}, D

Curve fit: $F(H_{dc}) = 2.1875\times10^{-4} H_{dc}^2 + 1$

PC90 @ 1 MHz, vary B_{pk}, D

Curve fit: $F(H_{dc}) = \sqrt{0.04\times H_{dc} + 1}$

Core Loss Discussion Points

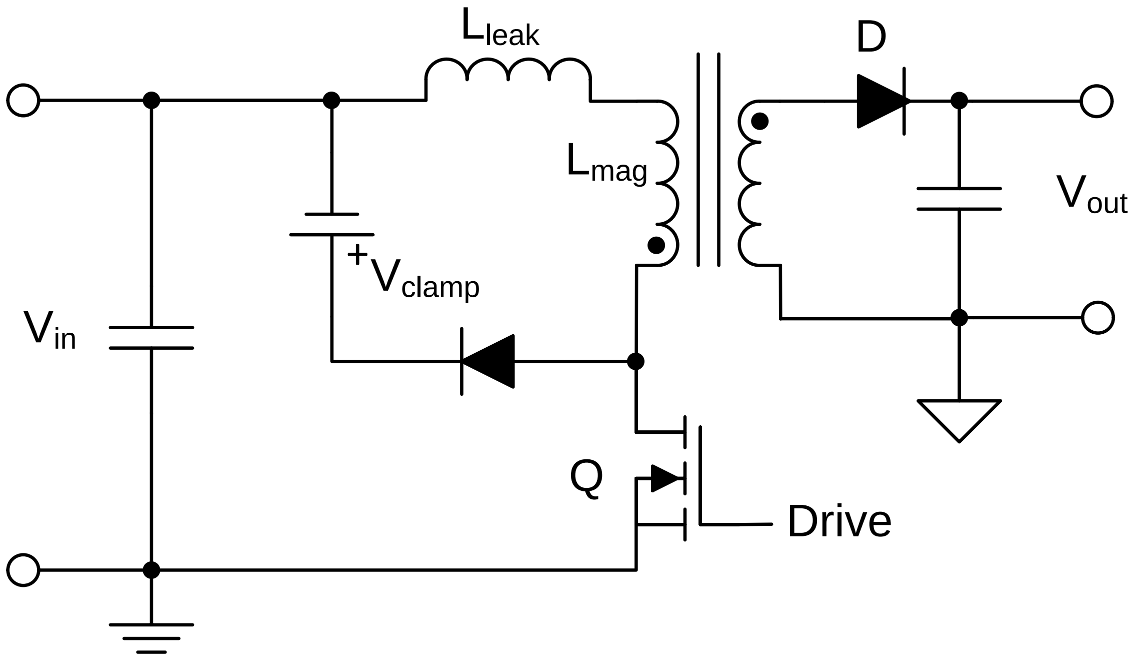
- DC bias, wave-shape & Duty-cycle cannot be neglected!
  - *May help to explain excess core loss in some situations*
- Practical method to account for effects:

$$P_{v\_total} = P_{v\_sine} \cdot F_{waveform}(\gamma, D) \cdot F_{DC}(H_{DC}) \qquad \textit{(Eq. 2)}$$

- Effect of extreme duty cycles on loss
  - Often-neglected penalty for wide input and/or output voltage range
  - ***Advantage of Flyback over Forward:*** **Lower D range for same input voltage variation**
- Effect of DC bias on core loss
  - Effect on materials other than ferrite not known.
  - May significantly reduce the benefit of deep CCM operation
  - Illustrates advantage of double-ended topologies over single-ended
- **Users need to insist that ferrite manufacturers provide γ and F_{DC} data!**
- **Recommend making your own in-circuit measurements**

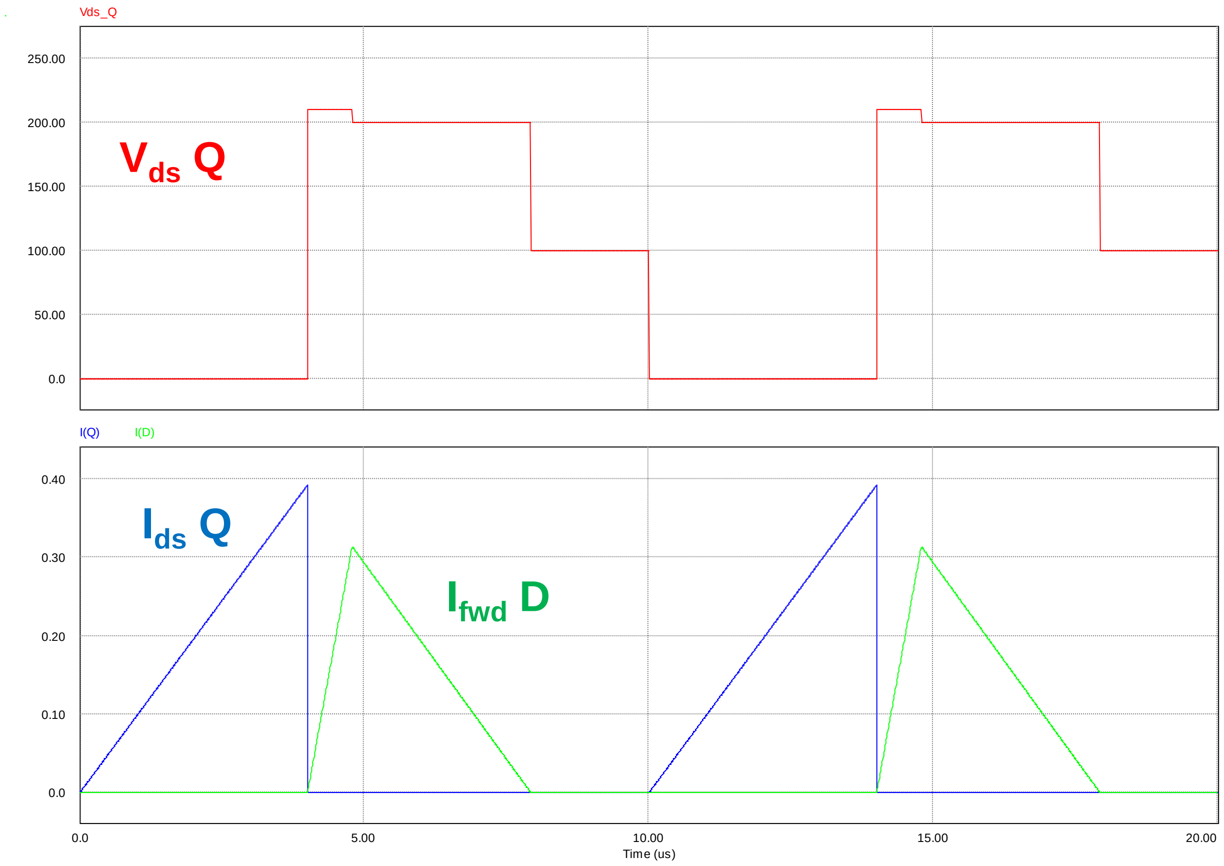
Impact of Snubber Clamp Voltage

- Switch Q turn-off :
  - Energy -> clamp until L_{leak} current -> zero
  - Time depends on ($V_{clamp} – V_{reflected}$) difference & on L_{leak} value
  - Also magnetising energy -> clamp
  - Smaller difference ($V_{clamp} – V_{reflected}$) => more magnetising energy absorbed by the clamp
- Lower clamp voltage
  - Lower voltage FET, lower R_{dson}
  - But extra clamp loss
    - ***Clamp loss can out-weigh FET loss saving***
- Higher clamp voltage
  - Higher voltage FET => higher R_{dson}

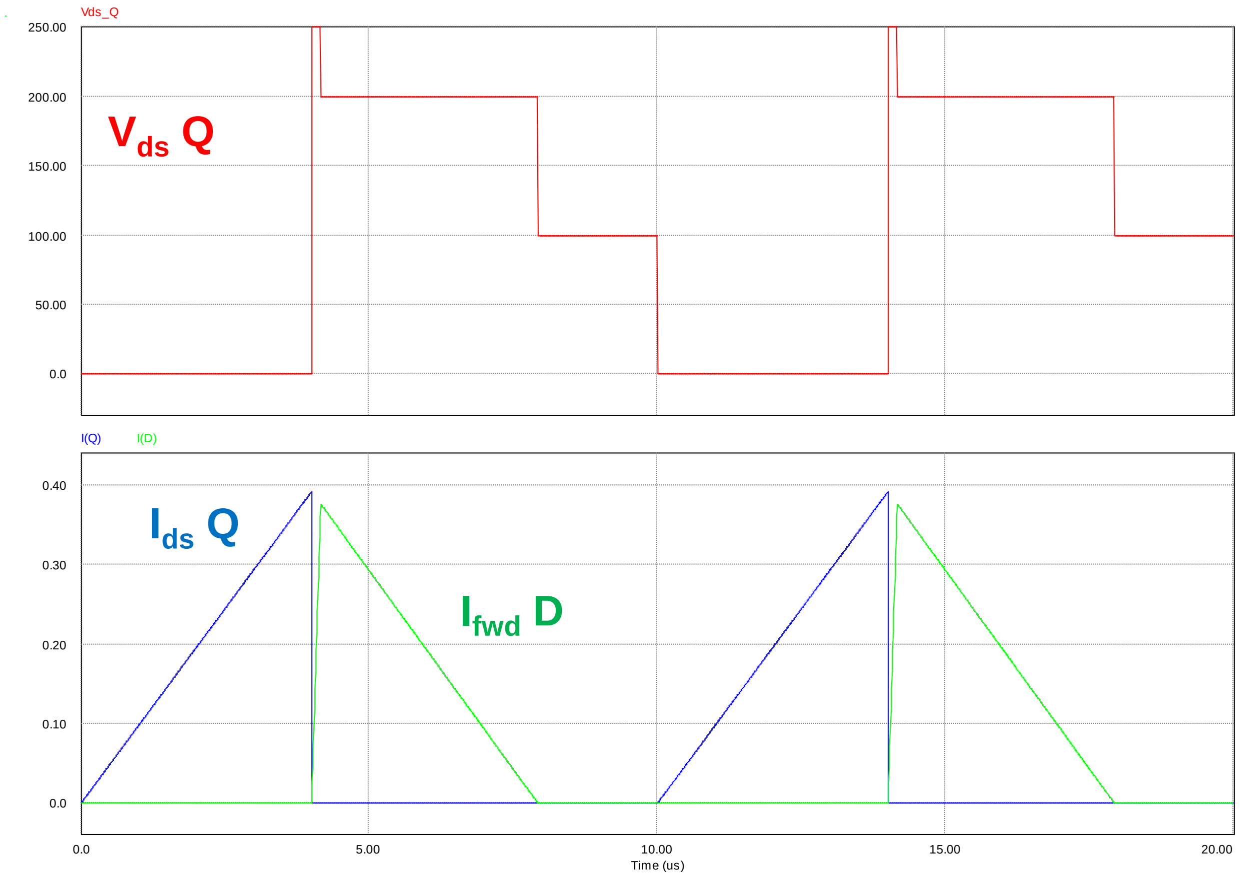


Comparison of Clamp Level Effect

Vclamp/Vo*1.1 (Np/Ns=1)



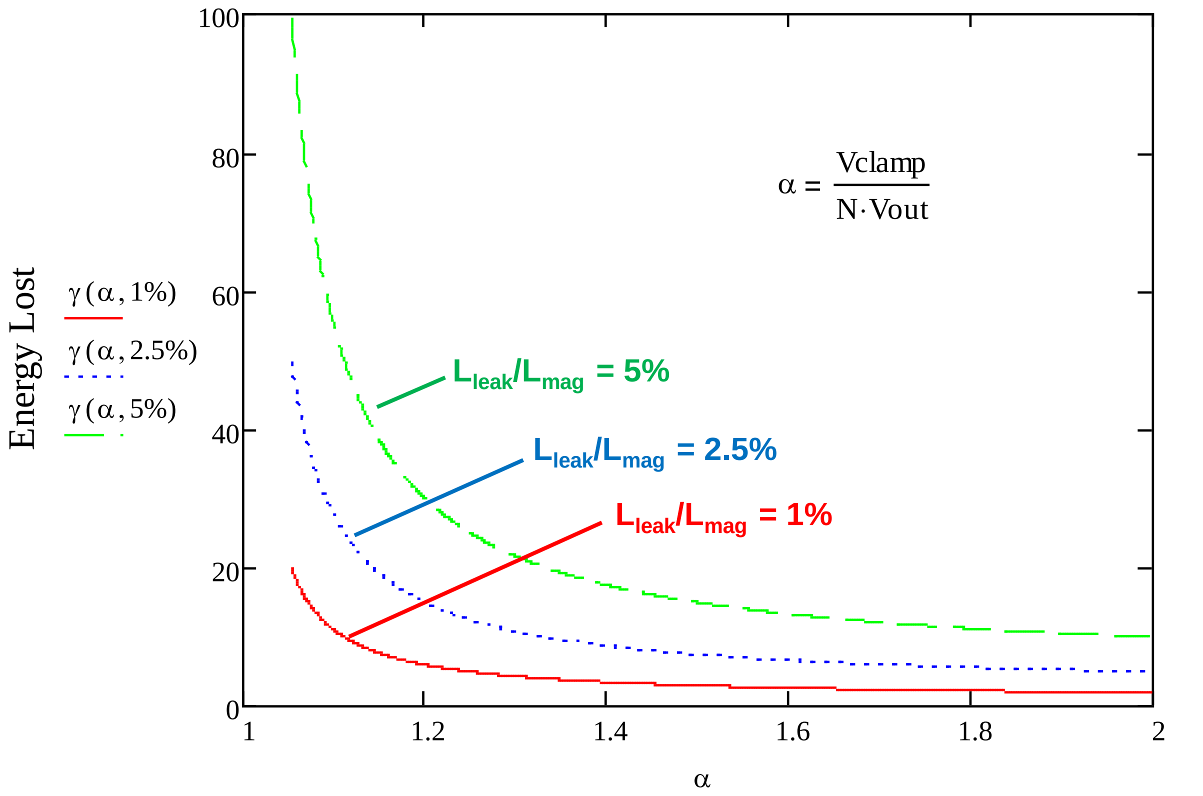
Vclamp/Vo*1.5 (Np/Ns=1)



Effect of Clamp Voltage on Energy Loss

- Lower clamp voltage attracts more magnetizing energy to the clamp!
- Can defeat, or even out-weigh, benefit of lower R_{dson}

% Magnetizing Energy Lost to Clamp

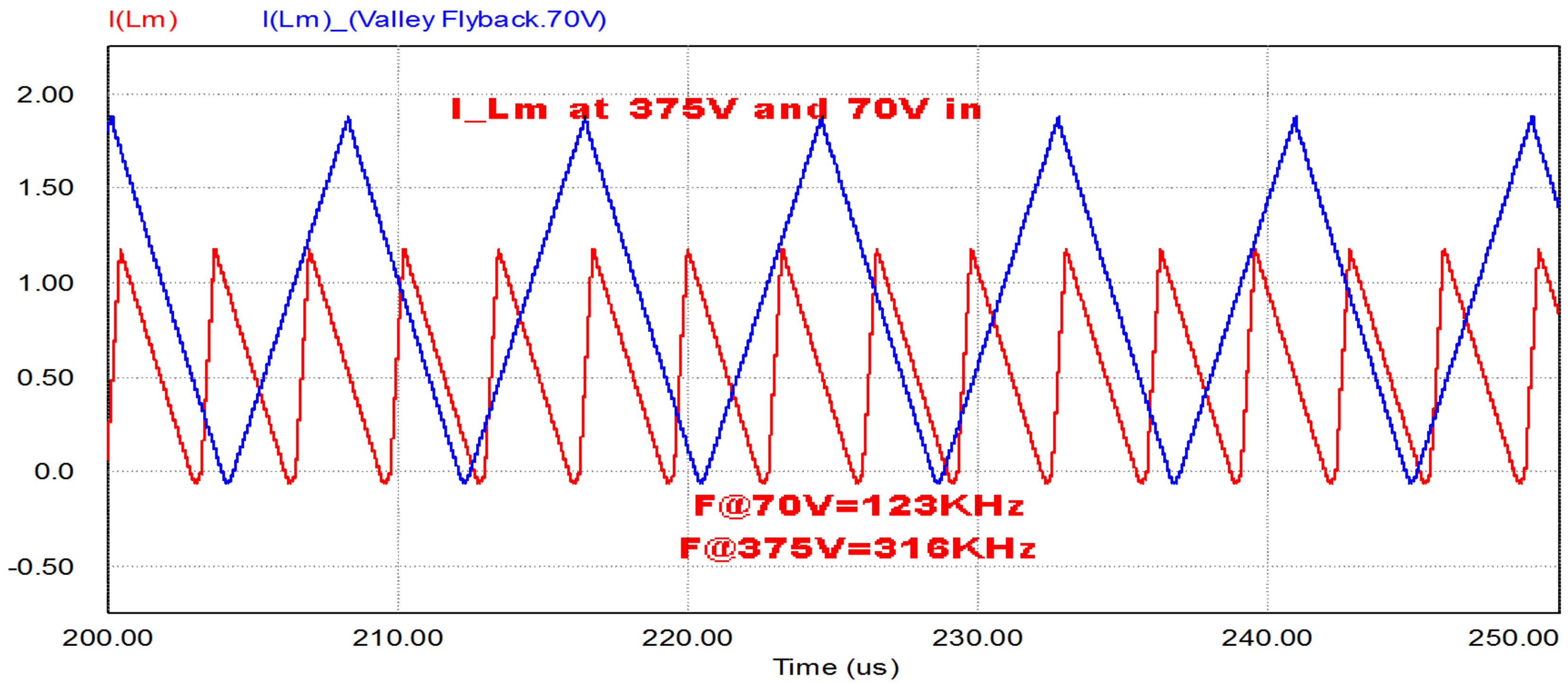


Vclamp/N*Vout

Effect of the input voltage range on power density of Flyback TM converters

- How does the input voltage range affect the power density and/or the efficiency of a FB transformer?
- Investigate the effect of input voltage range on loss of Flyback transformers
- To verify, design a TM Flyback converter optimized to deliver a power P at a frequency F and an input voltage Vin.
- Examine the effect of reducing the input voltage Vin by a factor Kv

Mag Current at Vin=375V and 70V input



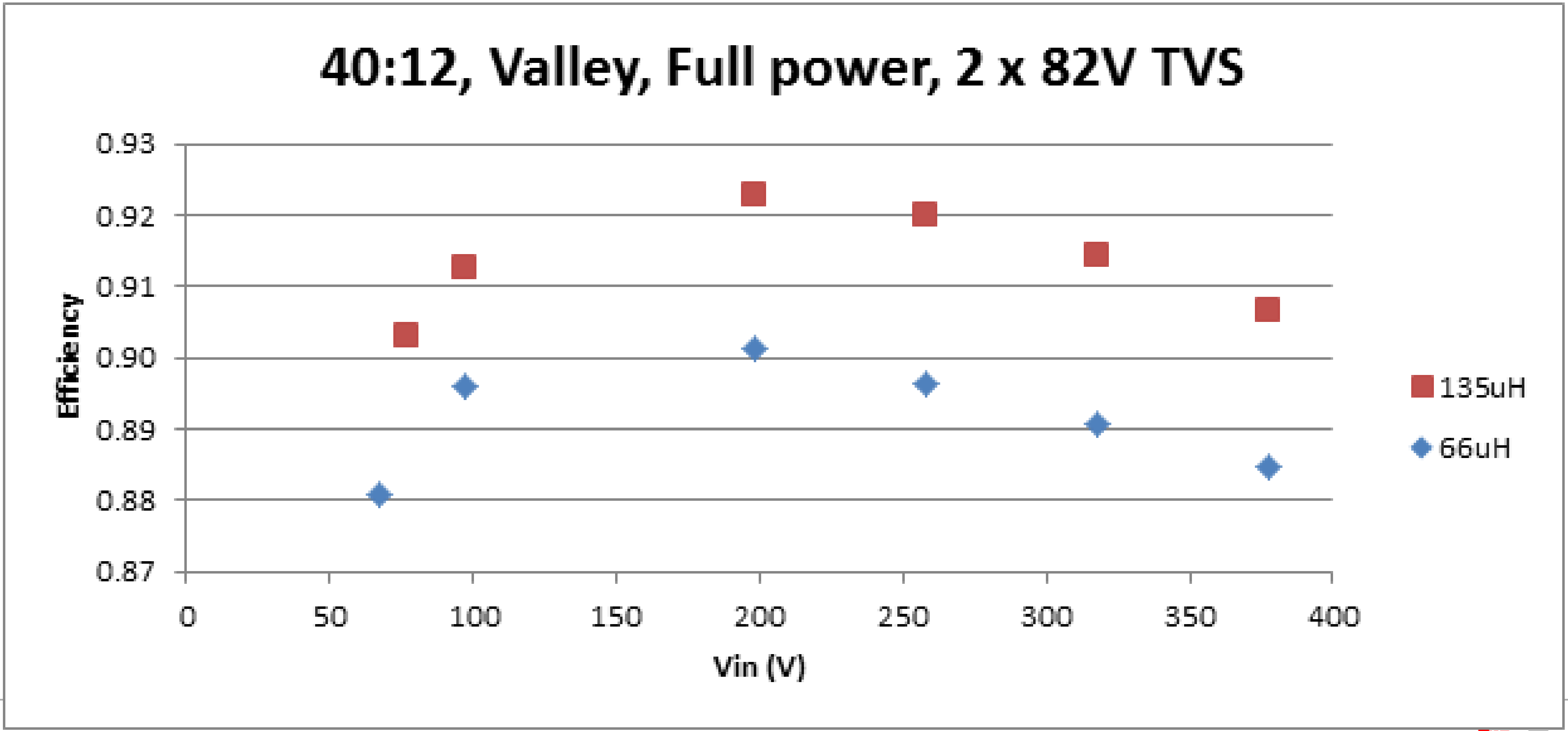
- Frequency decreases, peak current must increase to maintain same output power
- Energy storage in the transformer (=size) must increase
- Output cap must increase

Analysis result

- **The volume of a TM transformer designed to deliver a power P at 375V has to be increased by a factor of 2.361 to deliver the same power at 70V!!!**
  - CCM is only slightly better: Starting in TM at high line, the volume of a TM transformer will increase by a factor 2.044
- The output cap will increase by a factor of between 2 and 3 (depending if selection dominated by capacitance or ESR)
  - Much smaller increase for CCM (frequency is fixed)
- The effect on other topologies will also be significant
- Reducing the dynamic range of the input voltage is very beneficial for density and/or efficiency improvement
  - **That's a justification for two stage conversion and the phenomenal power density of "DC transformers"!**

Verification: High L_{mag} vs. Low L_{mag}

- Valley Switched Flyback Transformer designed to work at 70V<Vin<375V has been re-gapped for operation over 200V<Vin<375V range
- **Significant efficiency improvement: 2% - that is 35% reduction in total loss!**



Appendix

Ferroxcube Power Ferrites Core Loss Calculator

Recommended literature & further reading

FERROXCUBE
A YAGEO COMPANY

$$Pv = Cm \times f^{x} \times B^{y} \times (Ct_2 \times T^2 - Ct_1 \times T + Ct)$$

(f in Hz, B in T, T in deg C)

Freq =	339,000	Hz
B =	0.100	T
T =	100	°C

Material	Freq min	Freq max	Cm	x_1	y_1	Ct2_1	Ct1_1	Ct_1	Freq chk			Pv (mw/cc)
3C30	20000	100000	7.13	1.42	3.02	0.000365	0.0665	4	1	0	1	0.00
	100000	200001	7.13	1.42	3.02	0.0004	0.068	3.8	1	0	1	0.00
3C34	20000	100000	5	1.42	3.02	0.000365	0.0665	4	1	0	1	0.00
	100000	200001	5	1.42	3.02	0.0004	0.068	3.8	1	0	1	0.00
3C81	10000	100001	7	1.4	2.5	0.000142	0.013	0.88	1	0	1	0.00
3C90	20000	200001	3.2	1.46	2.75	0.000165	0.031	2.45	1	0	1	0.00
3C91	10000	100000	3.5	1.4	2.5	0.000142	0.013	0.88	1	0	1	0.00
	100000	200000	3.5	1.4	2.5	0.000142	0.013	0.88	1	0	1	0.00
	200000	400001	3.33E-14	4.05	2.5	0.000142	0.013	0.88	1	1	2	2628.77
3C92	20000	100000	26.52000126	1.194999973	2.649999941	0.000267895	0.054329115	3.7539611	1	0	1	0.00
	100000	200000	0.349247262	1.589999964	2.67499994	0.000150599	0.030541568	2.548162342	1	0	1	0.00
	200000	400001	0.000119	2.24499995	2.66499994	0.000208173	0.04371632	3.289902504	1	1	2	669.65
3C93	20000	100000	14.88000071	1.249999972	2.399999946	8.00874E-05	0.023433827	2.542508482	1	0	1	0.00
	100000	200000	1.164810806	1.484999967	2.516186865	0.000123601	0.03483324	3.247310786	1	0	1	0.00
	200000	400001	0.034618541	1.794502476	2.5216425	0.000147064	0.042472053	3.776566357	1	1	2	874.23
3C94	20000	150000	3.530102481	1.419999968	2.884999936	0.000125359	0.022263625	1.972776047	1	0	1	0.00
	150000	400000	0.000588	2.124999953	2.70499994	0.000116598	0.023272995	2.1613195	1	1	2	654.71
	400000	400001	0.0000021	2.6	2.75	0.000165	0.031	2.45	0	1	1	0.00
3C95	20000	150000	92.16643453	1.045	2.44	4.62E-05	7.94E-03	1.332362959	1	0	1	0.00
	150000	300000	7.47E-03	1.955	3.07	6.06E-05	0.0126	1.654230769	1	0	1	0.00
	300000	400001	7.87E-04	2.055	2.535	9.55E-05	9.78E-03	1.022919887	1	1	2	531.51
3C96	20000	100000	5.120544636	1.33999997	2.66499994	0.000547543	0.110384636	6.563034122	1	0	1	0.00
	100000	200000	0.082700122	1.719999962	2.804999937	0.000183438	0.036614276	2.827045247	1	0	1	0.00
	200000	400001	0.0000917	2.21999995	2.464999945	0.000232691	0.047189773	3.39206666	1	1	2	594.86
3C97	20000	150000	42.36588301	1.16	2.8	6.35519E-05	0.01100719	1.465	1	0	1	0.00
	150000	300000	0.003448693	1.99	2.935	7.85219E-05	0.0136	1.575	1	0	1	0.00
	300000	400001	0.000449188	2.055	2.415	8.74899E-05	0.01403339	1.528	1	1	2	399.76
3F3	20000	100000	0.020005432	2.009999955	3.004999933	0.000104167	0.020833333	2.041666667	1	0	1	0.00
	100000	300000	0.605541056	1.509999966	2.399999946	0.000116701	0.023900302	2.223023277	1	0	1	0.00
	300000	500001	0.693612776	1.509999966	2.399999946	0.000086362	0.017134212	1.849801672	1	1	2	619.04
3F35	100000	499999	0.00683	1.43902	3.26718	0.0001614	0.0335167	2.7593536	1	1	2	342.47
	500000	799999	1.12499E-07	2.19515	2.71986	0.0001284	0.0210531	1.800507	0	1	1	0.00
	800000	1200000	2.23928E-10	2.61053	2.49772	0.0000817	0.0101073	1.1523273	0	1	1	0.00
3F36	100000	499999	0.00683	1.43902	3.26718	0.000083946	0.010783518	1.232717265	1	1	2	333.13
	500000	799999	1.12499E-07	2.19515	2.71986	8.92639E-05	0.011719438	1.28161335	0	1	1	0.00
	800000	1200000	2.23928E-10	2.61053	2.49772	6.11871E-05	0.006141983	1.010843873	0	1	1	0.00
3F4	500000	3000000	1932000000	3.20E-02	3.185474956	0.000095	0.011	1.15	0	1	1	0.00
	3000000	3000001	1680000000	3.20E-02	3.185474956	0.000034	0.0001	0.67	0	1	1	0.00
3F45	500000	1000000	0.003753067	1.94	2.775	0.000525253	0.104	6.147474747	0	1	1	0.00
	1000000	2000001	3.27561E-10	3.06	2.51	0.00045202	0.0716	3.63979798	0	1	1	0.00
4F1	3000000	5000000	19.525	1.37	2.425	9.01169E-05	0.01337335	1.436165854	0	1	1	0.00
	5000000	7500000	19.56258061	1.37	2.425	0.000149007	0.027	2.209933775	0	1	1	0.00
	7500000	10000001	21.3125	1.37	2.425	0.000237741	0.031001448	1.722733153	0	1	1	0.00