MBA Fast Corrector Power Supply Development

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Byeong. Song*
Gary Sprau
Ju Wang

* No longer with APS

Outline

- Power supply requirement for the APS-U
- Technical requirement and challenges
- Choice of power circuit and regulation algorithm
- Prototype design
- Initial test results

Scope of APS-U Storage Ring Power Supplies

- 2082 power supplies for the APS-U magnets
  - Two large power supplies up to 1000A for L-bend (M1/M2) dipole magnets
  - One thousand 10 ppm stability-class and 230A unipolar DC power supplies for Q-bend (M3/M4) dipole, quadrupole, and sextupole magnets
  - 760 ±15A DC bipolar power supplies for trim/correction and skew quad coils
  - **320 ±15A bipolar power supplies for fast correctors**
- 400 power supply controllers
  - 200 Unipolar power supply controllers
  - 200 Bipolar power supply controllers
- Pre-installation test
  - All the power supplies and the power supply controllers will be 100% tested in a temperature-elevated environment before the installation starts

New SR requires 2082 power supplies and 400 power supply controllers.
All need to be pre-tested and ready before shutdown starts.

Fast Corrector PS Specifications and Parameters

Specifications/Design Paramters	Fast Corr PS	Exiting PS*	Unit
Maximun operating current	±13	±150	A
Maximun output voltage	40	40	V
Maximun output power	0.52	6	kW
Current stability (AC RMS)	TBD	300	ppm
Initial accuracy after installation	100		ppm
Magnet-to-magnet repeatability	100	700	ppm
Reproducibility after shutdown	10	600	ppm
Small-signal -3dB bandwidth	10		kHz
Current ripple	TBD	1000	ppm
Voltage ripple	TBD		ppm
Magnet inductance	16.5	3.48/4.28	mH

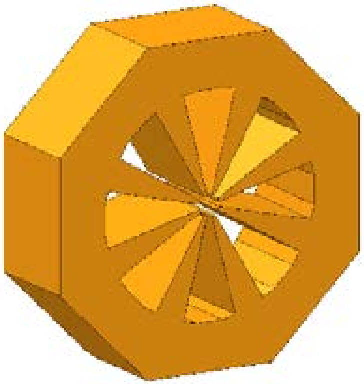
* Parameters from 1992 power supply design review

- Fast Communications Requirements
  - 22.6 kHz update rate
  - 10 μs latency

Challenges and Issues

- Fast corrector magnet is very inductive
  - 16.5 mH in the design by BNL
  - High impedance at 10 kHz

$$Z = \omega L = 2\pi f L = 2\pi \times 10000 \times 0.0165 = 1036.7\ \Omega$$

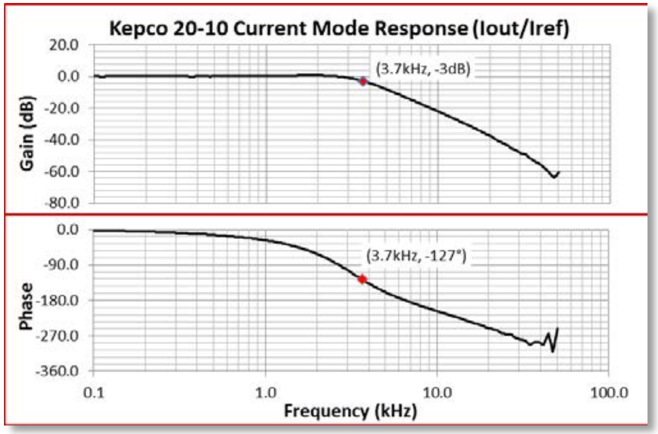


8 pole fast corrector magnet

  - For 130 mA (1% of full rating) peak-to-peak current at 10 kHz, required peak-to-peak voltage is

$$V = Z \times I = 1036.7 \times 0.13 = 134.7\ V$$

- No commercial bipolar power supplies meet this requirement



Example:

Kepco 20-10 (±20V, ±10A) linear power supply

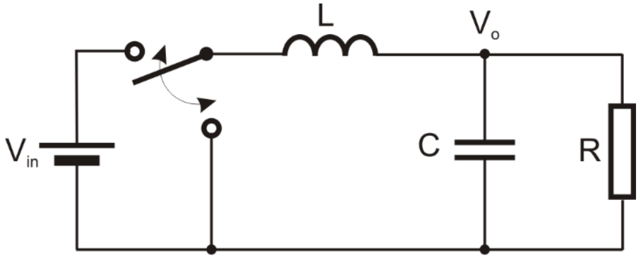
With a 10 mH load, -3dB at 3.7 kHz

R&D Goals

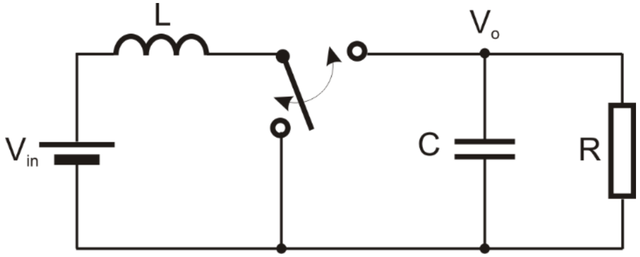
- Choose appropriate power supply circuit topology
- Choose appropriate hardware for the power circuit
- Design control loop
- Stay within constrains
  - Use existing 40V DC bus
- Deliver a 75 mA peak-to-peak current at 10 kHz
- Keep the design simple for reliability

Some of Basic Power Circuits

- Switching mode power supplies
  - Buck converters
    - Simple topology
    - Output voltage less than input voltage
    - Output can be unipolar or bipolar
    - All APS storage ring power converters are buck converters
  - Boost converter
    - Simple topology
    - Output voltage greater than the input voltage
    - Unipolar output only
  - Buck-boost or Boost-buck converters,
    - Output voltage can be either higher or lower than the input
    - Output can be unipolar or bipolar



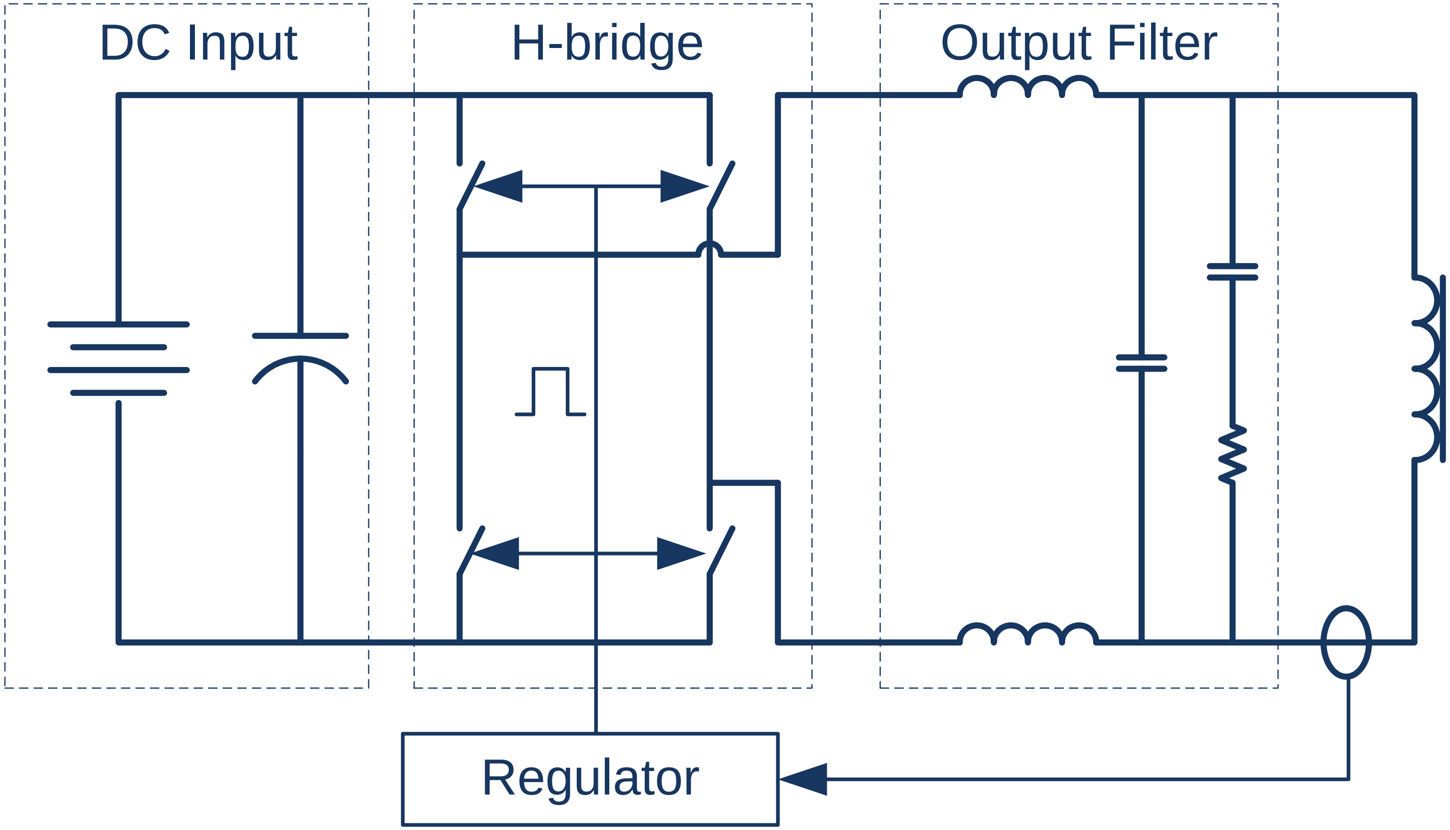
Buck Converter



Boost Converter

- Linear power amplifiers
  - Works like operational amplifiers
  - High bandwidth, hundreds kHz
  - High power consumption, good for AC, not good for DC

Proposed Circuit for Bipolar Power Supply



- An H-bridge with four semiconductor switches
- Bipolar output
- Output voltage ≤ input voltage – a buck converter
- Output filter to reduce ripple voltage and ripple current

Semiconductor Switches

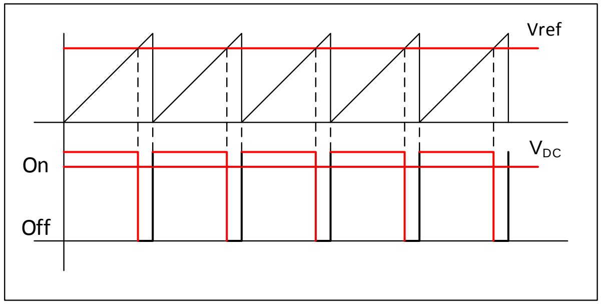
- Discrete MOSFET switches
  - Small size
  - Low conduction resistance
  - Low cost
- Switching (class D) amplifiers
  - Full bridge package
  - Built-in PWM generator
  - Built-in gate drive circuit
  - Built-in protection circuit
  - High conduction losses
  - High cost

Example:
IRFB 4610, 100V, 73A,
11 mΩ on resistance
TO-220 package
Less than $2.50 per MOSFET

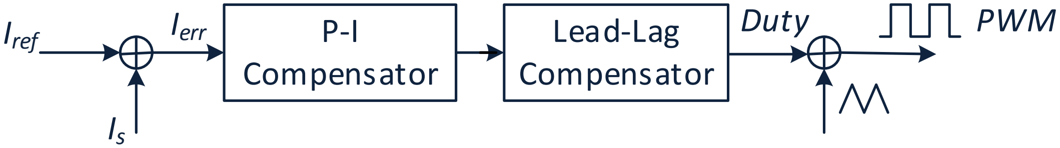
Example:
APEX SA12, 200V, 15A,
400 mΩ on resistance
200 kHz built-in PWM
$400 - $600 per unit

In comparison, existing SR corrector power supplies uses two IGBTs, each rated 600V, 300A, and cost ~ $200

Power Supply Regulator Design

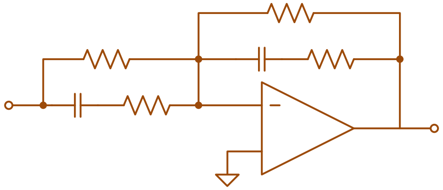


- Pulse width modulation (PWM) methods
  - A reference signal is compared with a periodic signal
  - Switches under control is turned on or off according to the comparison result
  - There are many PWM methods available
  - The simplest uses sawtooth or triangular waveforms
  - The power supply output voltage is proportional to the switch on time during the cycle, a.k.a. duty cycle or duty ratio
- Closed feedback loop for the current regulation
  - Proportional and integral (P-I) compensator
  - Lead-lag compensator to improve high frequency performance



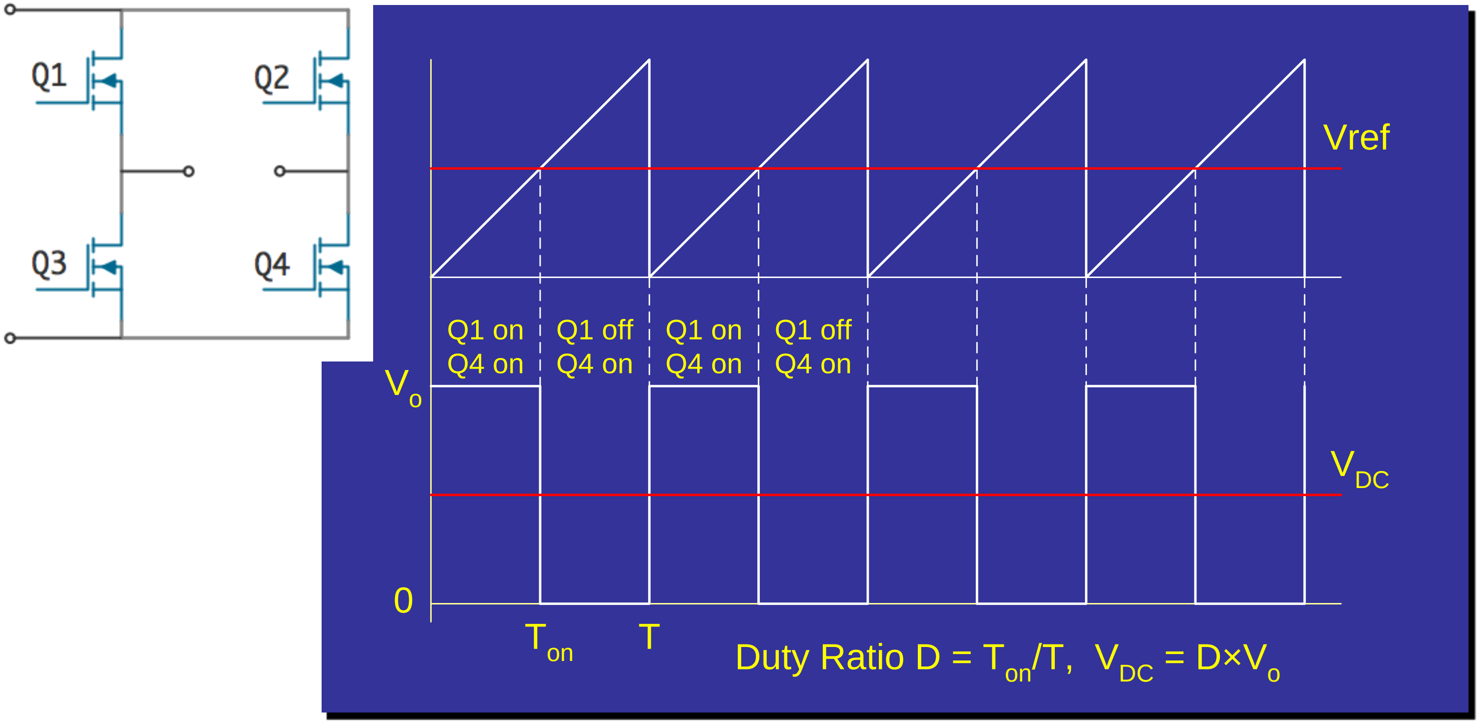
$$\frac{Y}{X}=\frac{(s+z_1)(s+z_2)}{(s+p_1)(s+p_2)}$$

$$|p_1|>|z_1|>|z_2|>|p_2|$$



Lead-lag compensator

Sawtooth PWM

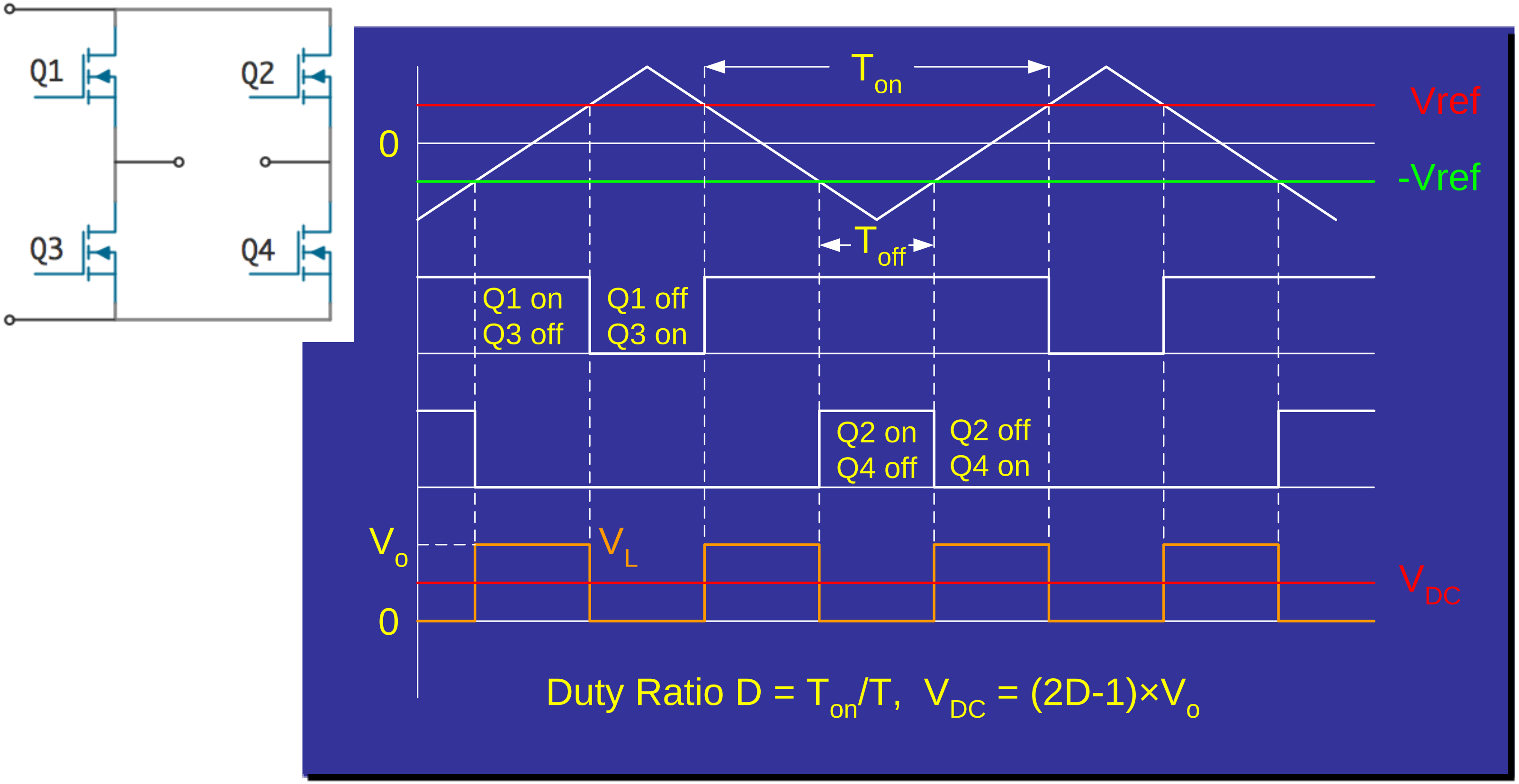


Duty Ratio $D = T_{on}/T$, $V_{DC} = D \times V_o$

Switch Q1 or Q2 is modulated to regulate the output while switch Q3 or Q4 is held on to control the polarity

- Only two switches are used for a given output polarity
- Very simple and easy to implement
- Does not work well for very small duty ratio or around zero for bipolar output
- Used in the storage ring quad, sext, and original corrector power converters

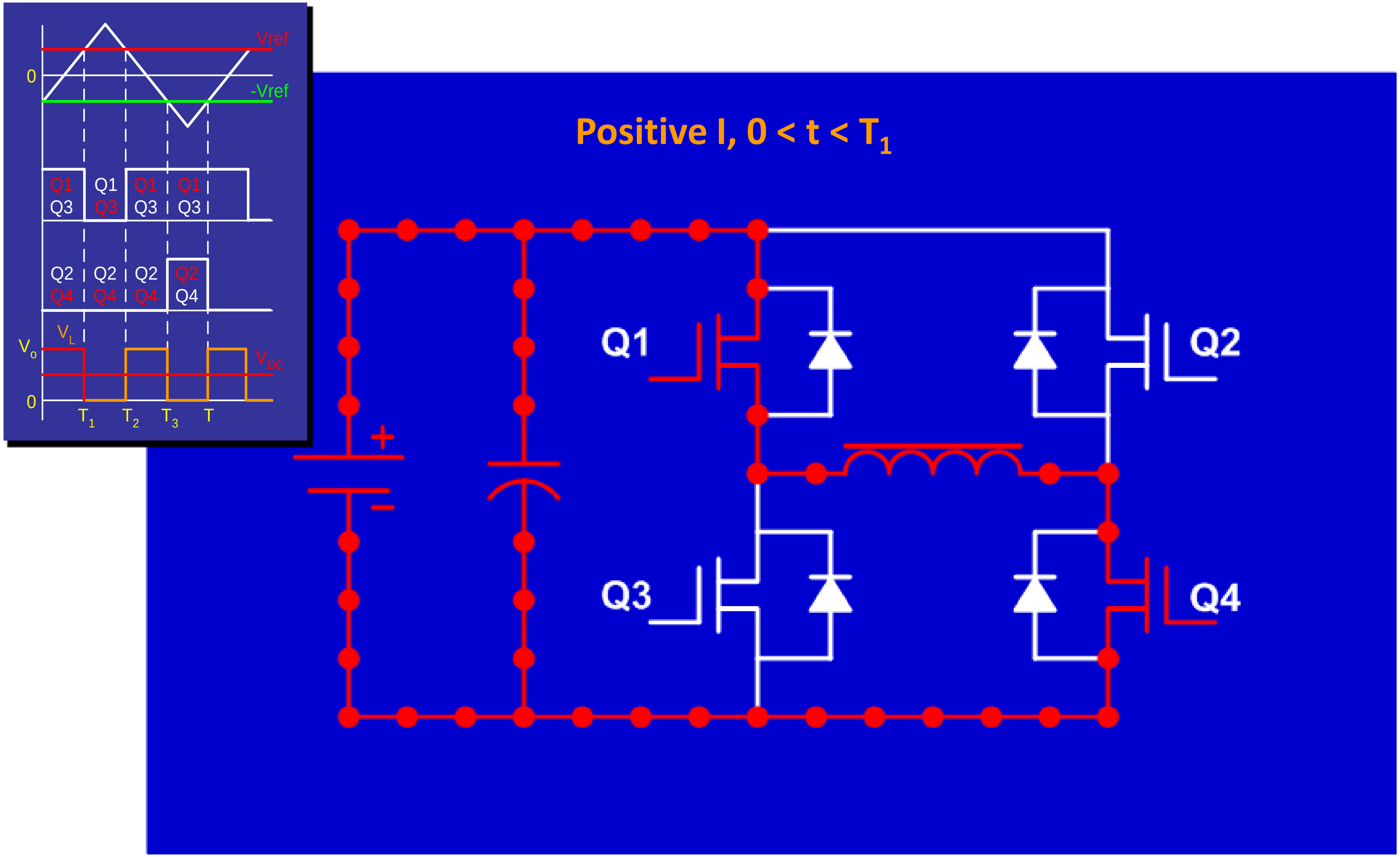
Unipolar PWM – choice for the design



Duty Ratio $D = T_{on}/T$, $V_{DC} = (2D-1)\times V_o$

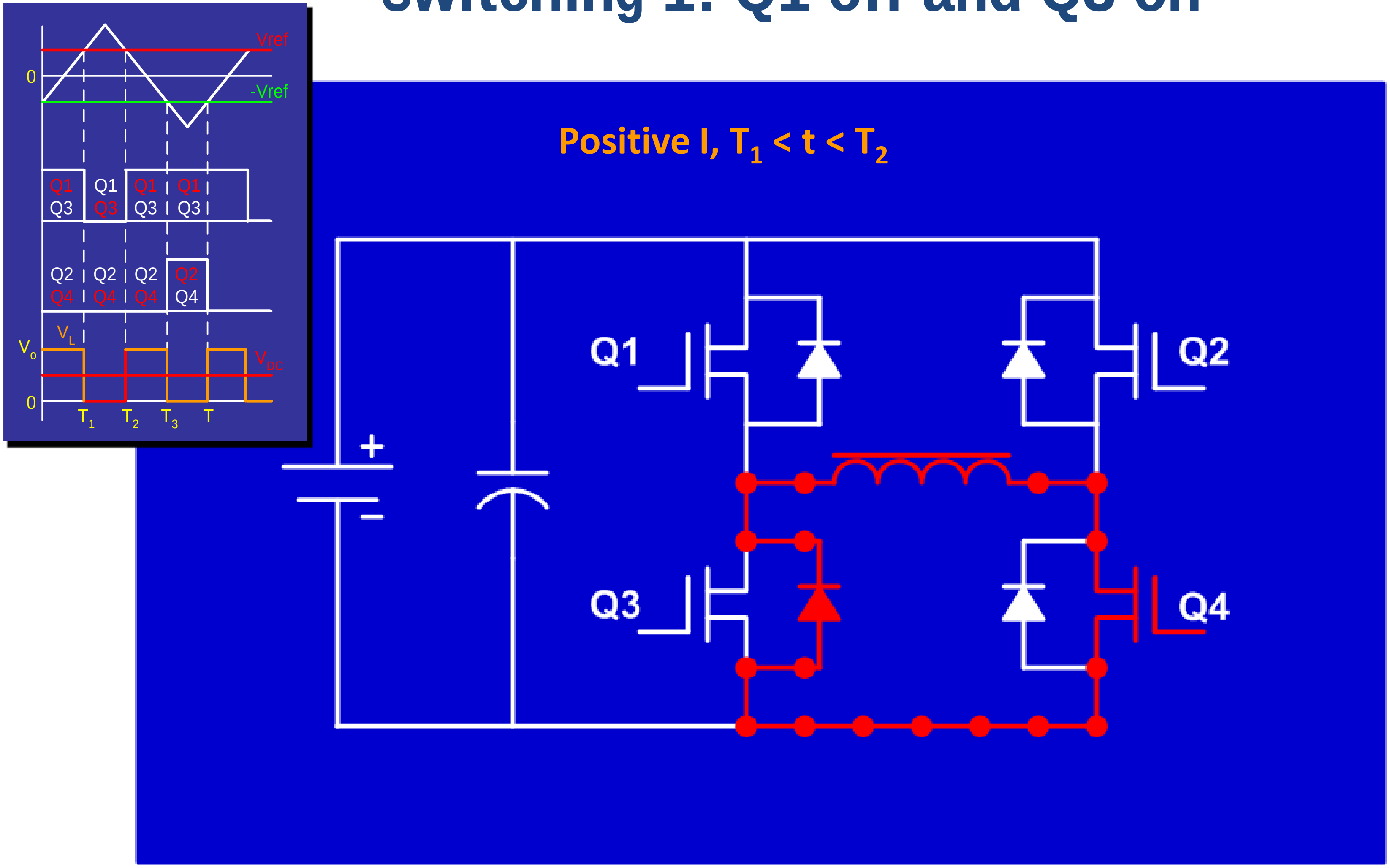
- V_{DC} can be positive or negative
- Ripple frequency is twice the PWM frequency
- Zero output at D = 0.5
- Smooth transition around zero

Switching sequence: assume Q1 and Q4 on initially



Positive I, $0 < t < T_1$

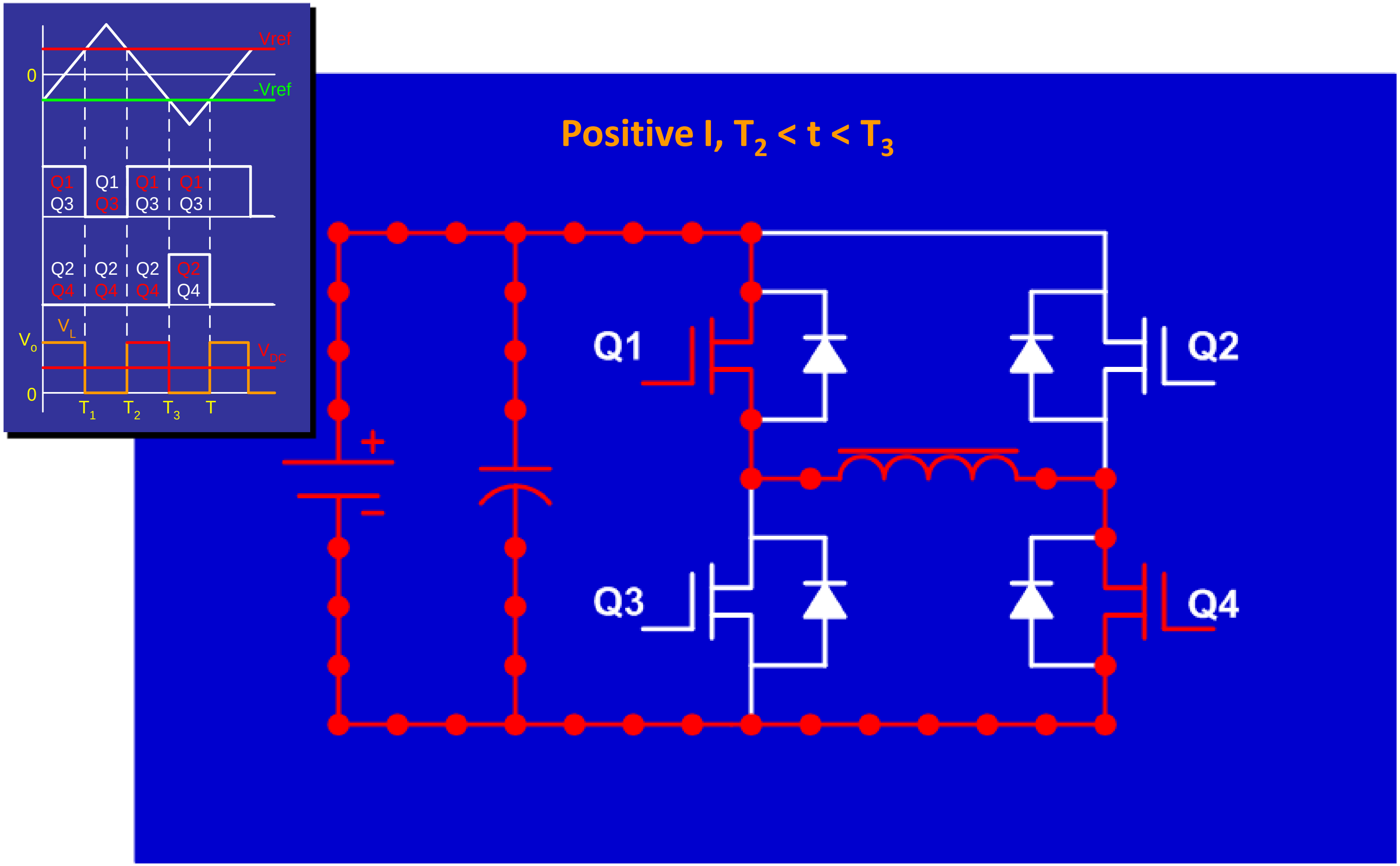
Switching 1: Q1 off and Q3 on



Positive I, $T_1 < t < T_2$

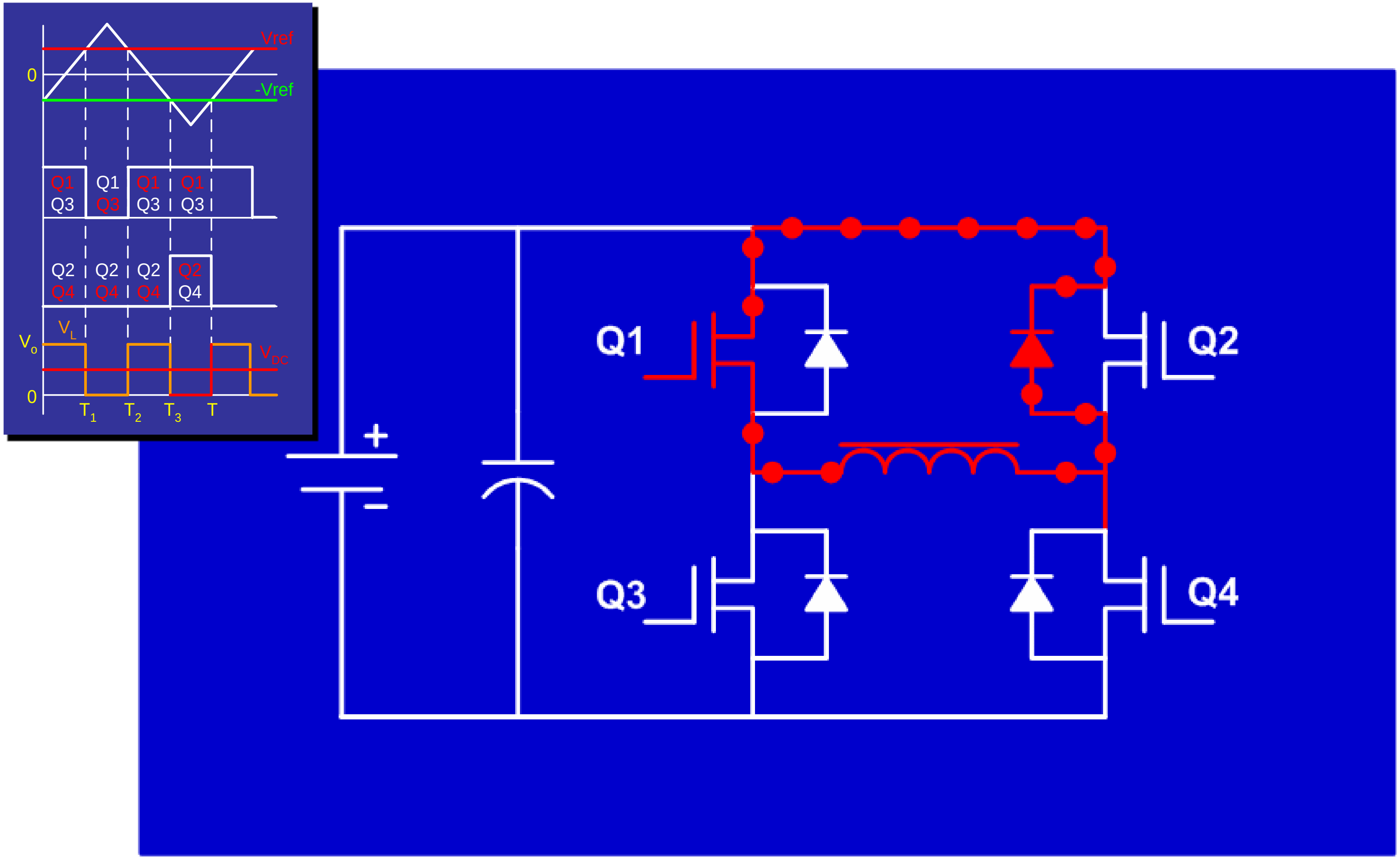
Q3 does not need to be gated on. But, with MOSFETs, gate-on may result in lower conduction losses.

Switching 2: Q1 on and Q3 off

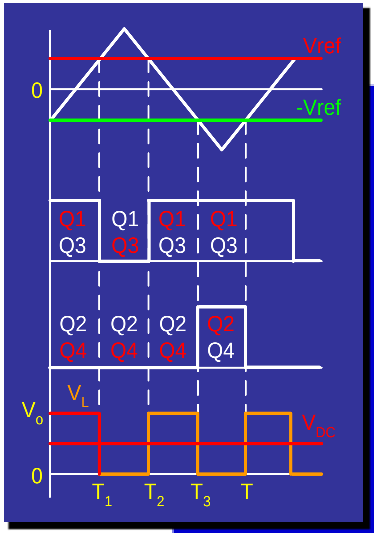


Positive I, $T_2 < t < T_3$

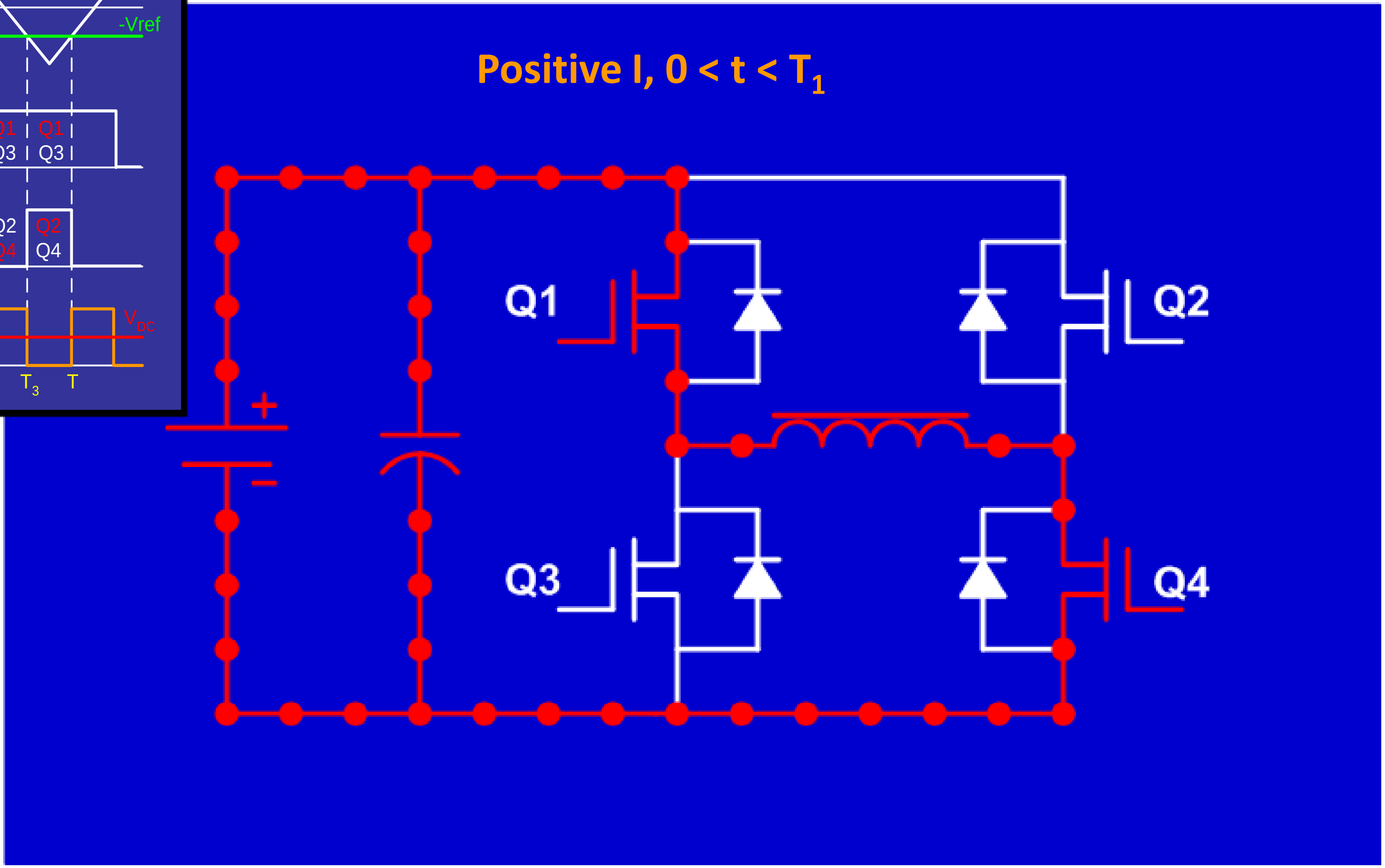
Switching 3: Q4 off and Q2 on



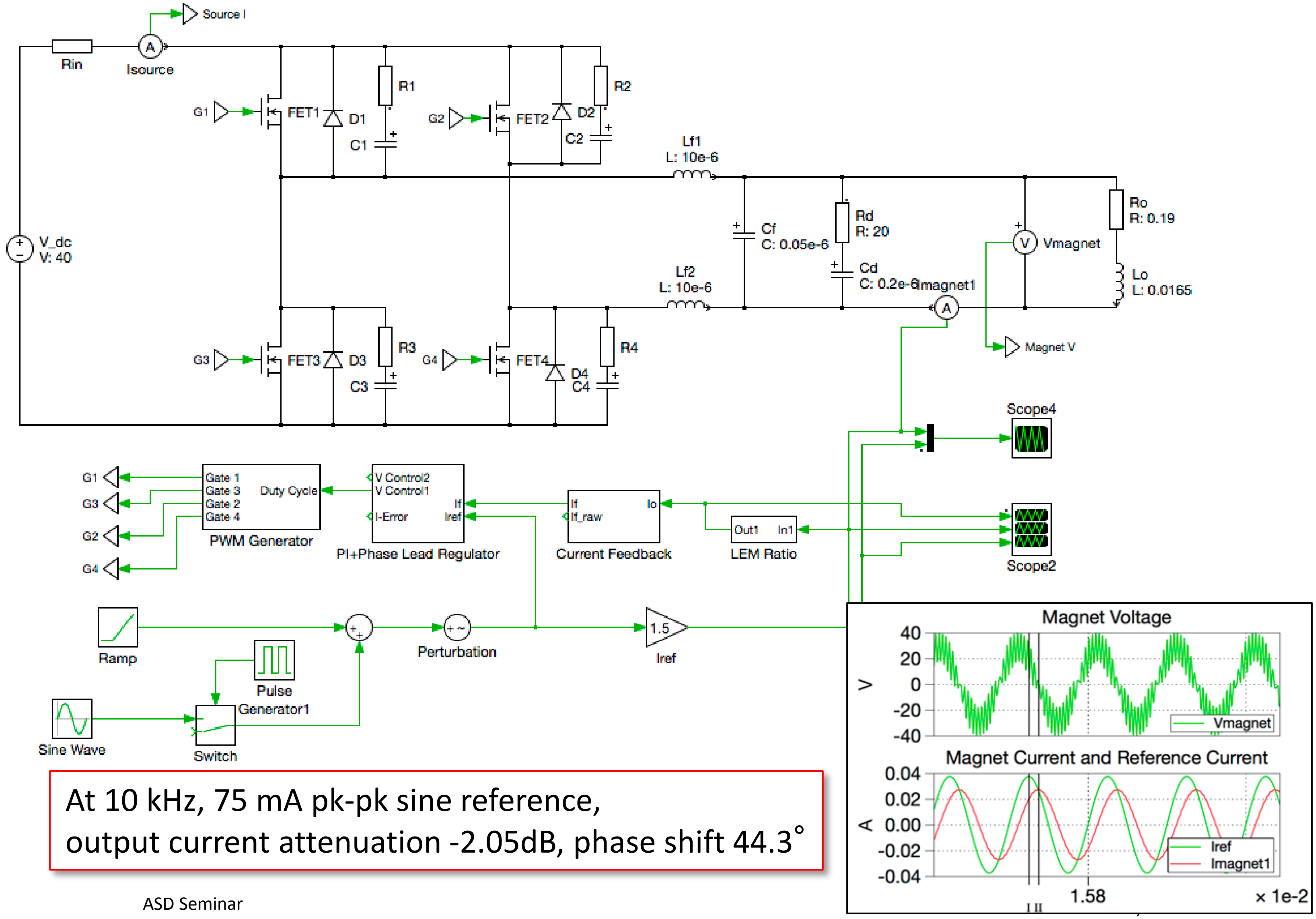
Switching 4: Q4 on and Q2 off, back to initial condition



Positive I, $0 < t < T_1$

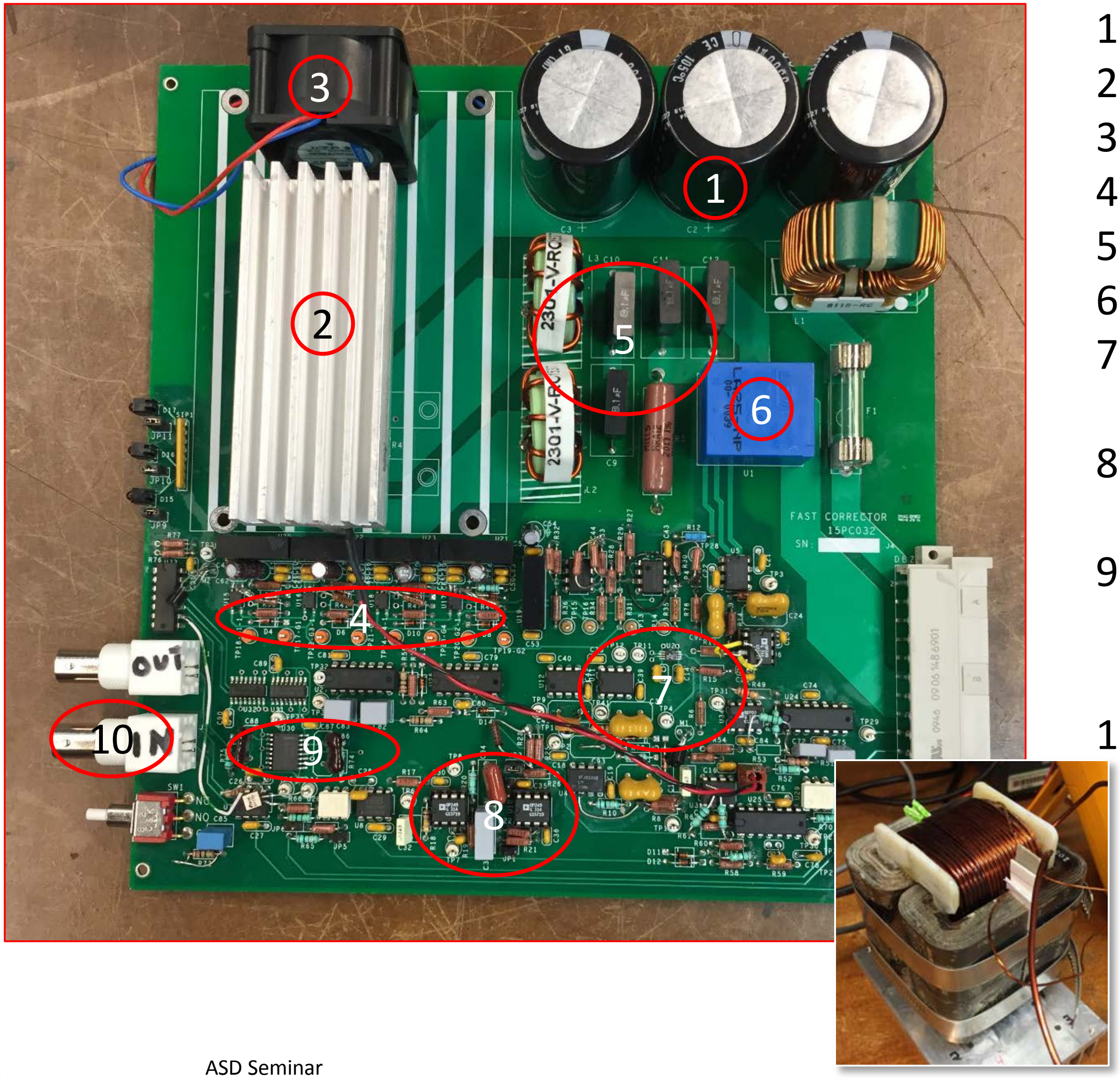


Simulation with PLECS (piecewise linear electrical circuit simulation)



At 10 kHz, 75 mA pk-pk sine reference,
output current attenuation -2.05dB, phase shift 44.3°

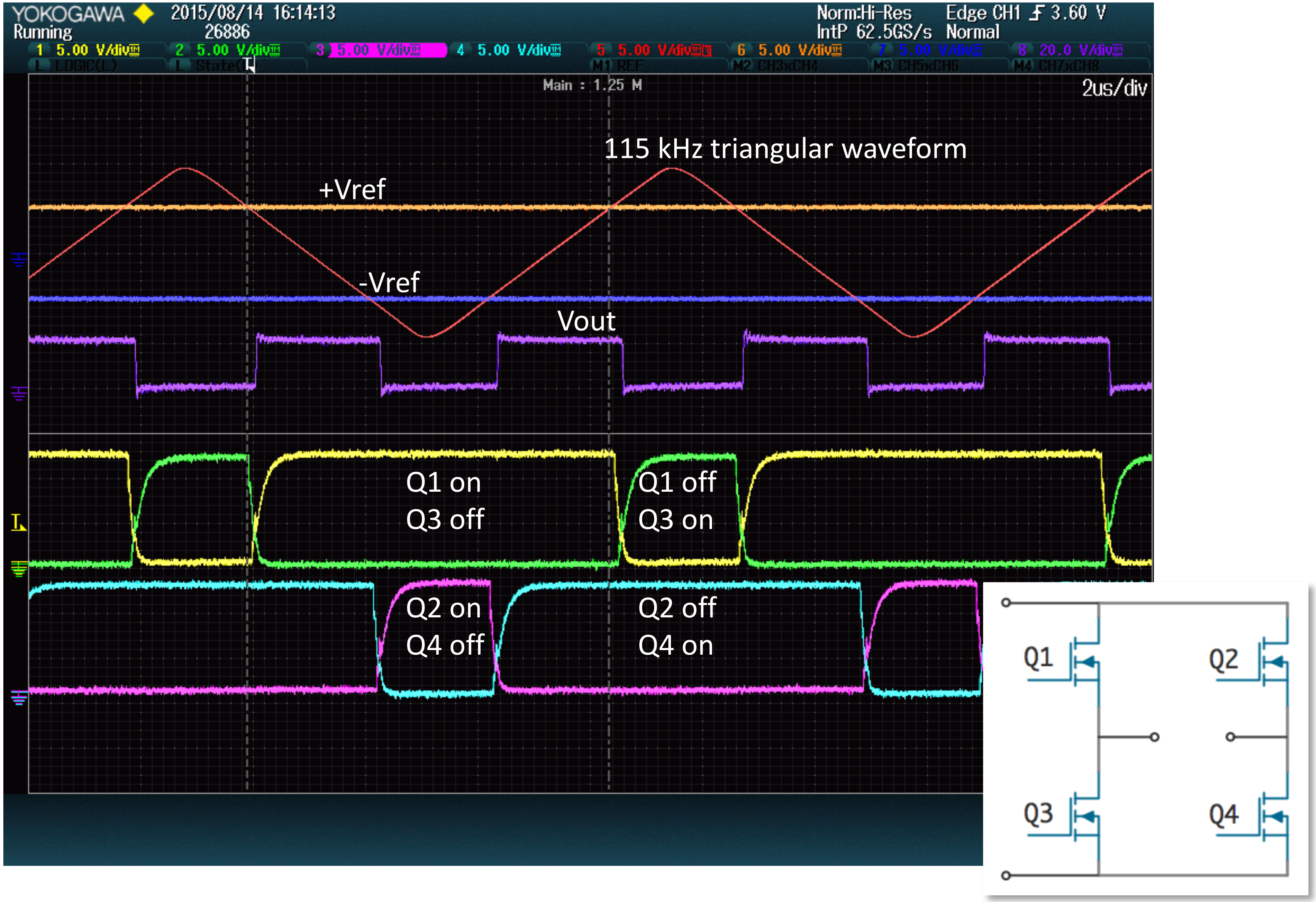
First Prototype



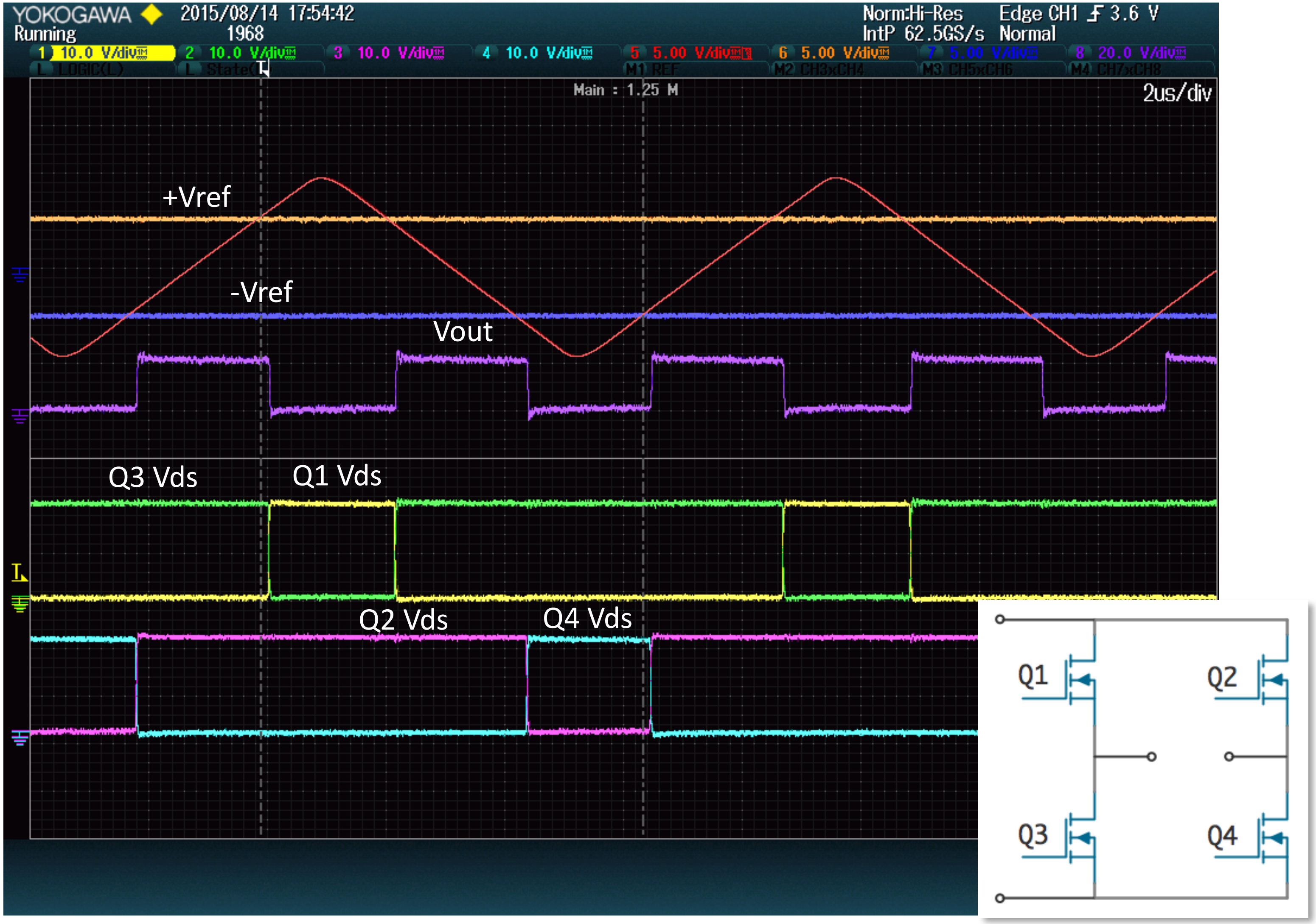
1. Input capacitor bank
2. MOSFET heat sink
3. Cooling fan
4. MOSFET gate drive circuit
5. Output filter
6. Current sensor, LEM
7. Triangular waveform generator
8. P-I and lead-lag compensators
9. Interlocks for over current and over temperature
10. Reference input

16.5 mH high frequency magnet

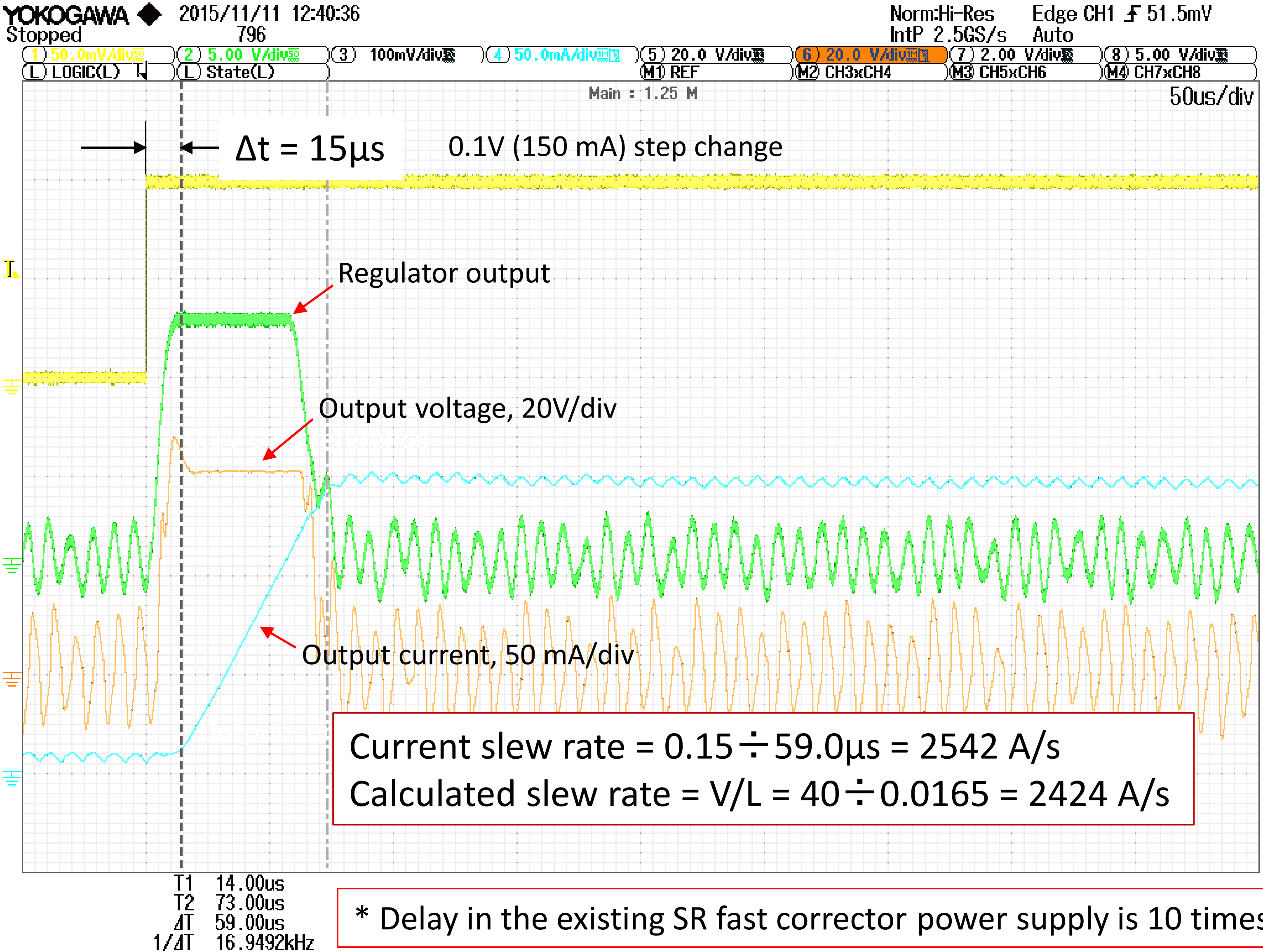
Initial Test Results – MOSFET Gate Signals



MOSFET Drain-Source Voltage – no shoot-through condition



Step Function Response



Δt = 15μs

0.1V (150 mA) step change

Regulator output

Output voltage, 20V/div

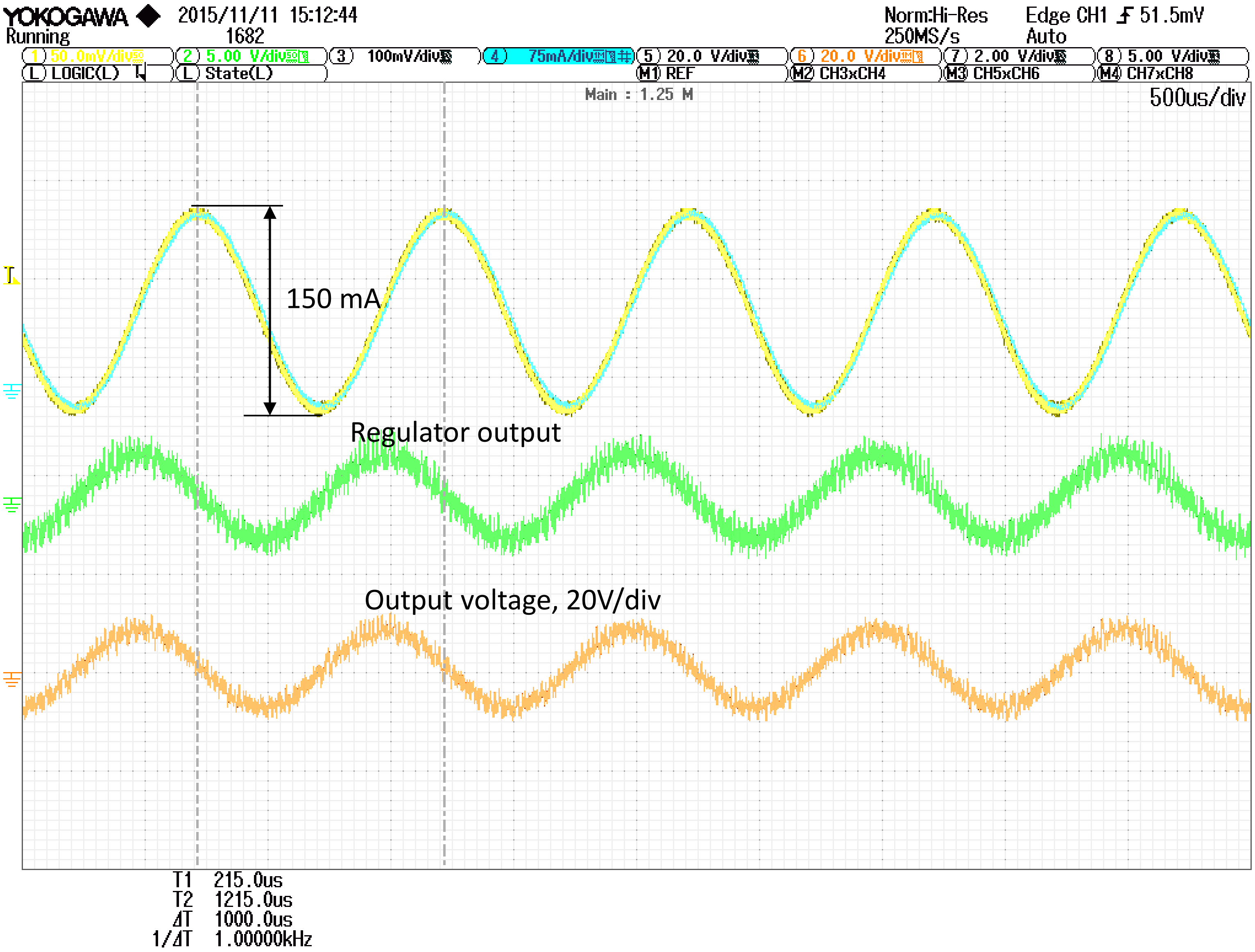
Output current, 50 mA/div

Current slew rate = 0.15÷59.0μs = 2542 A/s

Calculated slew rate = V/L = 40÷0.0165 = 2424 A/s

* Delay in the existing SR fast corrector power supply is 10 times longer

150 mA (1%) Peak-peak Reference at 1 kHz

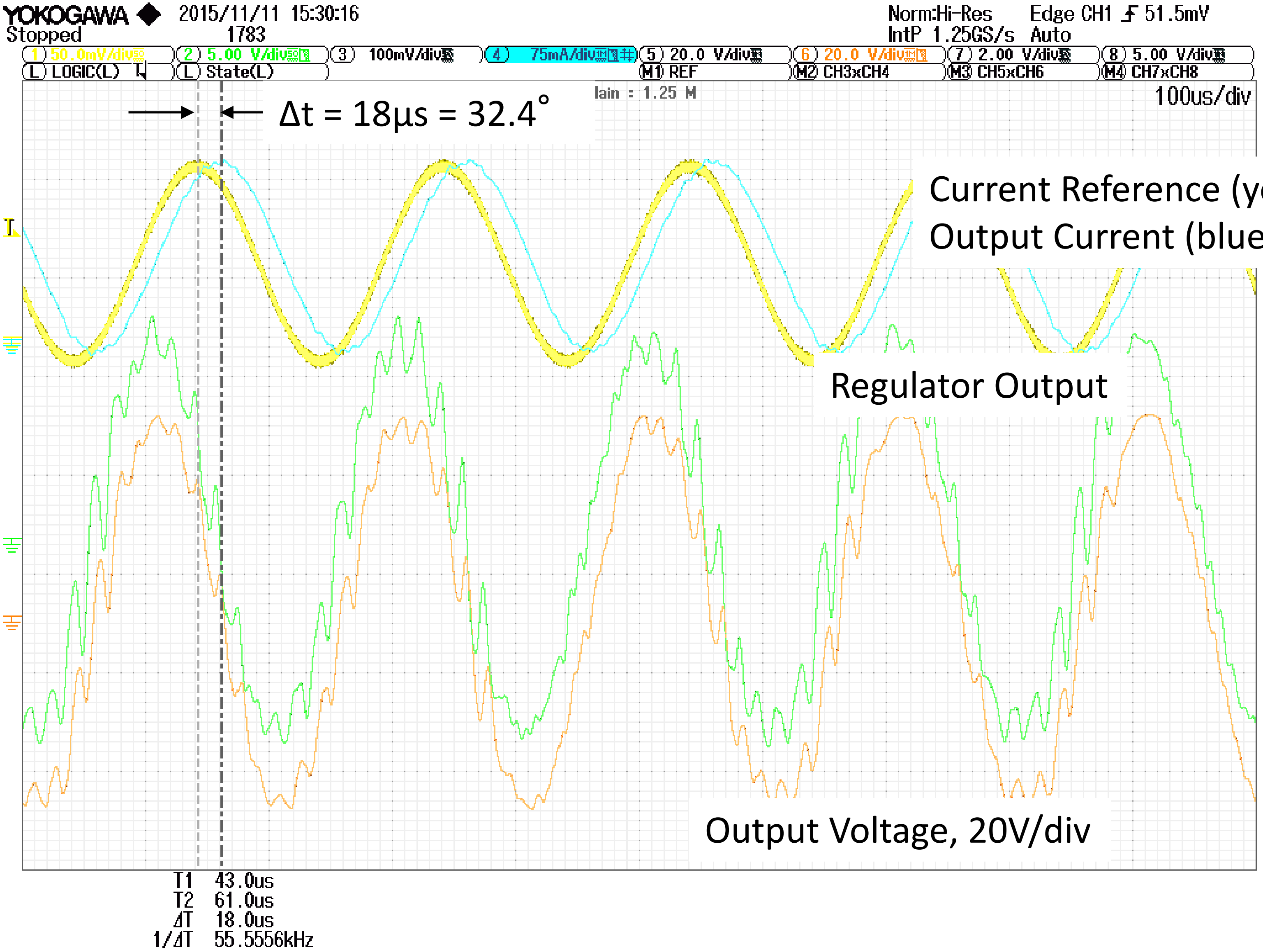


150 mA

Regulator output

Output voltage, 20V/div

150 mA (1%) Peak-peak Reference at 5 kHz



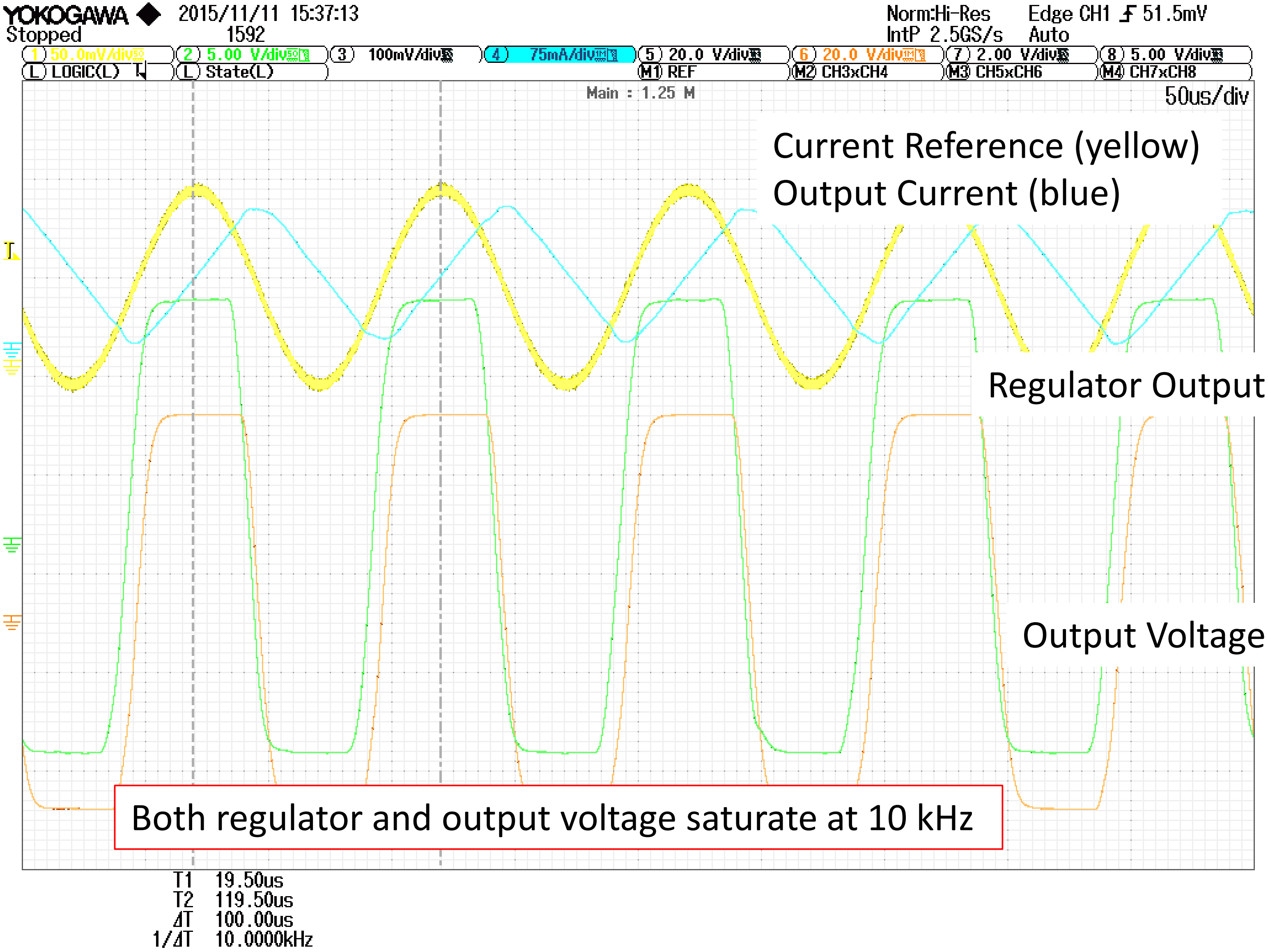
Δt = 18μs = 32.4°

Current Reference (yellow)
Output Current (blue)

Regulator Output

Output Voltage, 20V/div

150 mA (1%) Peak-peak Reference at 10 kHz



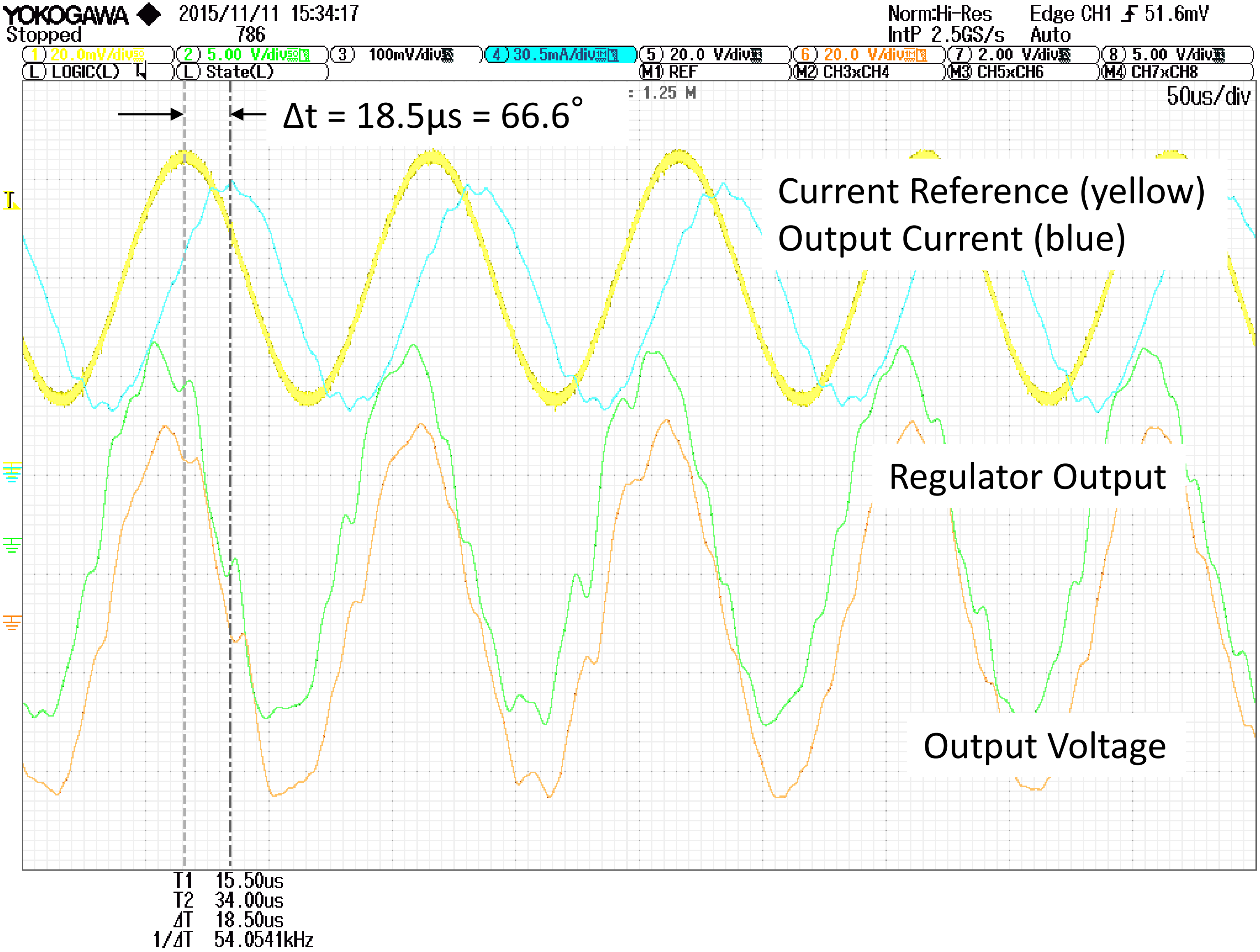
Current Reference (yellow)
Output Current (blue)

Regulator Output

Output Voltage

Both regulator and output voltage saturate at 10 kHz

75 mA (0.5%) Peak-peak Reference at 10 kHz



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YOKOGAWA ◆  2015/11/11 15:34:17                    Norm:Hi-Res     Edge CH1 ⨍ 51.6mV
Stopped          786                               IntP  2.5GS/s   Auto
1 20.0mV/div  2 5.00 V/div  3 100mV/div  4 30.5mA/div  5 20.0 V/div  6 20.0 V/div  7 2.00 V/div  8 5.00 V/div
L LOGIC(L)    L State(L)                             M1 REF        M2 CH3xCH4    M3 CH5xCH6    M4 CH7xCH8
                                         : 1.25 M                                              50us/div
      T1   15.50us
      T2   34.00us
      ΔT   18.50us
    1/ΔT   54.0541kHz
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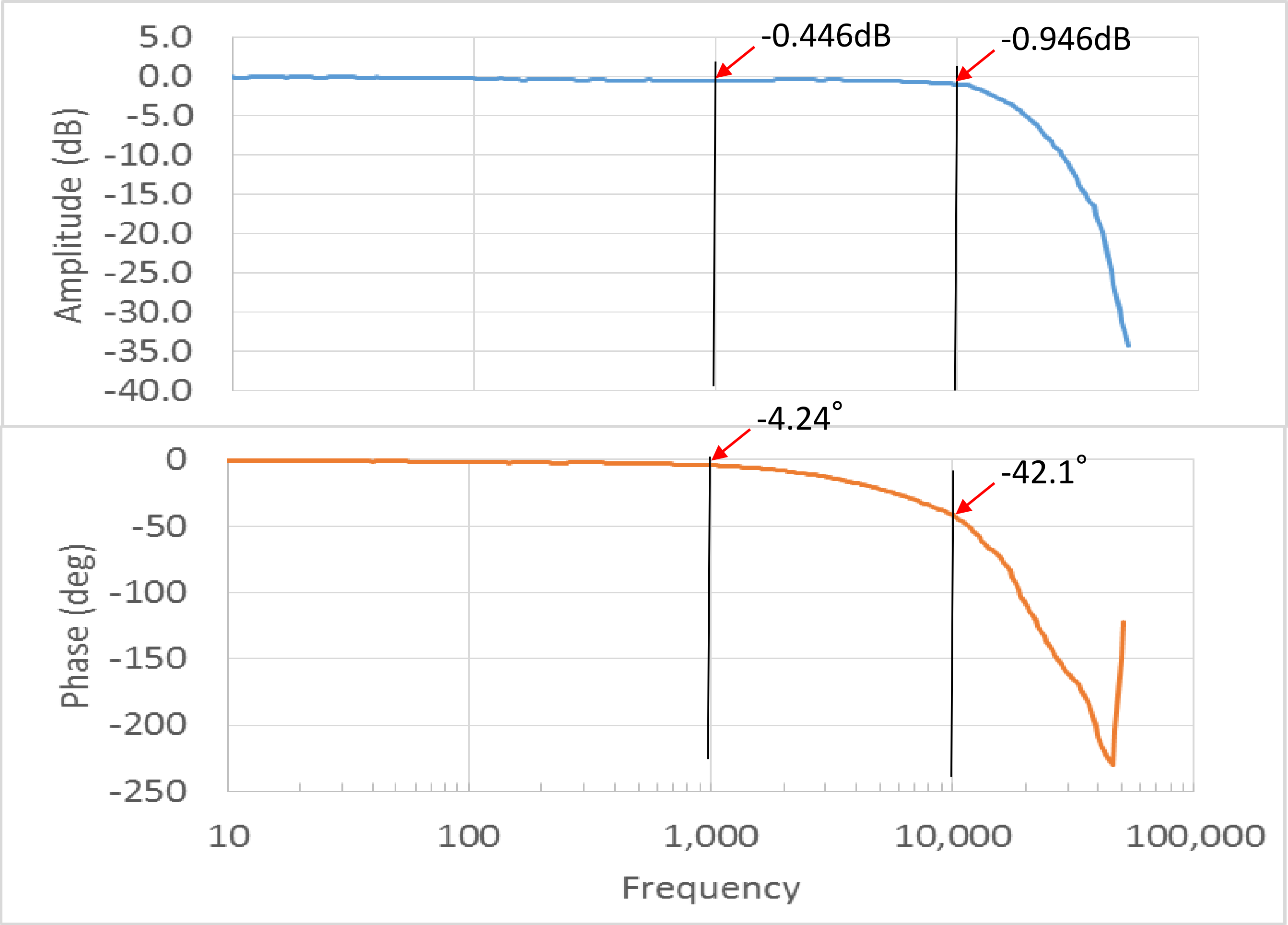
Δt = 18.5μs = 66.6°

Current Reference (yellow)
Output Current (blue)

Regulator Output

Output Voltage

Frequency Response (24.8981 mVpk, zero offset drive)



Test equipment: Dynamic signal analyzer HP35670A
24.8981 mVpk = 37.35 mApk, ~1 μrad bend

Summary

- A prototype MOSFET-based fast bipolar power supply is developed
- Achieved 10 kHz bandwidth for a 0.5% small signal
- Prototype is under redesign to
  - Reduce switching noise in the circuit
  - Clean up the mistakes
- Retune control loop parameters for real magnet, which is a laminated magnet and may have a very different characteristic at high frequency

Questions?