

# Nonlinear Control...

The following parameters can be programmed in the **Nonlinear Control** dialog:

- › Active Transient Response (ATR) parameters to reduce undershoot or overshoot excursions during transient load events
- › Frequency Active Transient Response (FATR) parameters to improve transient response over output load frequency, especially for transient loads at beat frequency
- › Dynamic VID (DVID) parameters to optimize the VR's response to the SetVID\_Fast/Slow/Decay commands
- › Non-Linear parameters to gain more undershoot or overshoot margin at high load repetition frequency
- › Feed forward parameters to gain faster response during the specific cases listed below or variable case as below

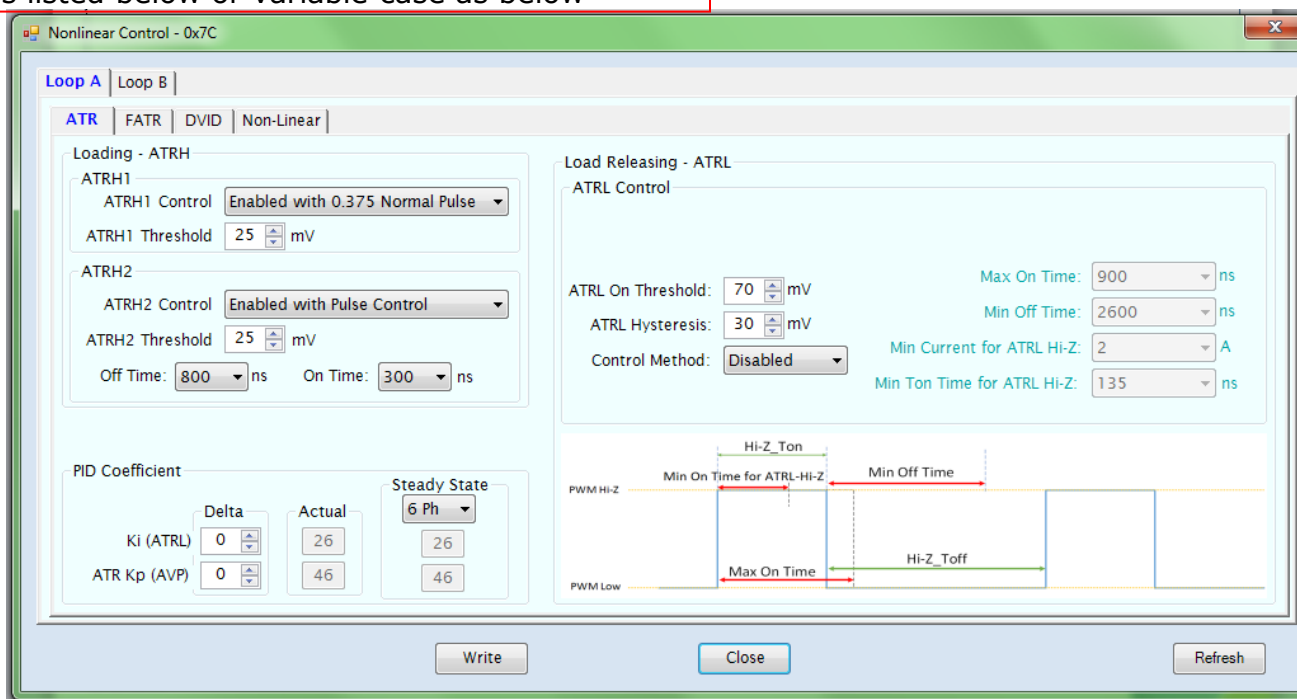
**Only enable the ATR functions if adjusting PID alone can not meet the undershoot and overshoot requirements**

–ATR control mechanisms are driven by comparators and programmable thresholds

–The response is non-linear and may add jitter at the output

– The thresholds should be at least 5mV (typically 10mV) wider than the measured steady state ripple voltage

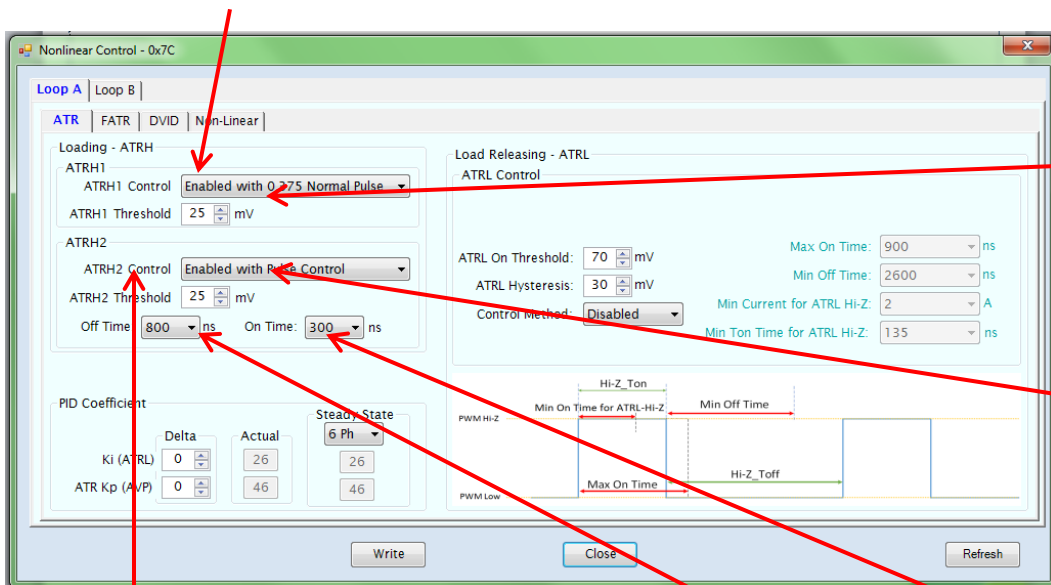
– If ATR has to be enable, the PID should be made less aggressive □ start by adjusting Kd and Kfp terms



# Nonlinear Control... ATR

## ATRH1 Control

- Use to program the strength of the ATRH1 control
- A wider pulse width corresponds to a stronger ATRH1 control
- Disable: No ATRH1 control
- Enabled with 0.50/0.375/0.25/0.125 Normal Pulse: ATRH1 control is enabled. The normal pulse width is decided by the feedback loop control and ATRH1 will be fired in 0.50/0.375/0.25/0.125 normal pulse width
- Recommended starting point is 0.25 of normal pulse if ATRH1 is needed. Stronger ATRH control reduces the undershoot of VOUT but will increase ring-back.



## ATRH2 Control

- Disabled: no ATRH2 control,
- Enabled with Pulse Control: ATRH2 pulse width is programmed by the Off Time and On Time

## Off Time

- Off time (PWM low duration) of the ATRH2 pulse when ATRH2 Control is set to Enabled with Pulse Control

## ATRH1 Threshold

- ATRH1 control threshold
- The smaller the threshold, the stronger the ATRH1 response because of the increased likelihood that ATRH1 will be triggered
- It is recommended that the threshold not be too close to the steady-state ripple size, otherwise ATRH pulses can be falsely fired during normal regulation. Select a threshold at least 10mV higher than measured VOUT switching ripple.

## ATRH2 Threshold

- ATRH2 control threshold
- Similar to ATRH1 Threshold
- Recommended to set > ATRH1 Threshold

## On Time

- On time (PWM high duration) of the ATRH2 pulse when ATRH2 Control is set to Enabled with Pulse Control
- Recommended settings:
  - If ATRH2 On time is too narrow, it could be swallowed by the driver and then provide little or no help in reducing undershoot
  - If ATRH2 On time is too large, it could saturate output inductor
  - Select ATRH2 pulse in the range of 100ns to 200ns and select a much longer Off time (>800ns) for robust ATRH2 behavior

# Nonlinear Control... ATR

## ATRL On Threshold

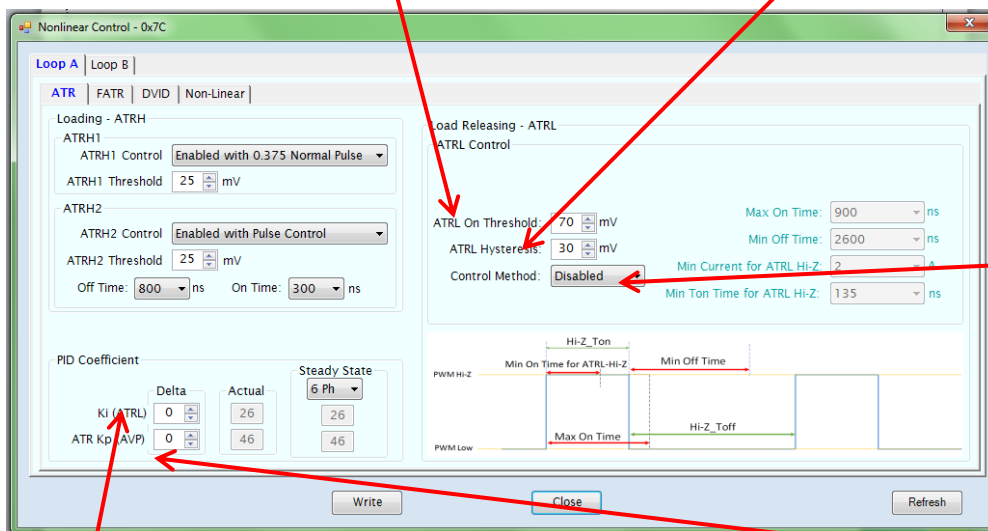
- ATRL will be engaged if the VOUT overshoot exceeds the target VOUT plus this threshold
- Recommended not to set smaller than the switching ripple size otherwise it will be falsely fired in the steady state

## ATRL On Hysteresis

- Prevents ATRL window chattering and hence stressing FET drivers
- Recommended value is 10mV

## Control Method

- Disabled: Disable ATRL
- Hi-Z/Low side on: FET turns on when ATRL window is active
- Recommended to be in Hi-Z if ATRL needs to be enabled
- When both high side FET and low side FET are off, the positive current will go through the low side body diode
- Compared to the path through low side FET, the low side body diode will cause a larger voltage drop across the low side FET and be able to reduce the positive inductor current sooner, thereby more effectively reduce the overshoot



## Ki (ATRL)

- Delta: This will reduce Ki when the ATRL window is active regardless of ATRL function is enabled/disabled. When the ATRL window is active, less Verr will be accumulated by the integrator which allows the average VOUT to be shifted up during high frequency transients that relieves some stress on meeting the undershoot specifications.
- Actual: Calculated value based on the Delta and Steady State
- Steady State: Steady state Ki value for the 1Ph, 2Ph, or MaxPh

## ATR Kp (AVP)\*

- Delta: Kp(avp) index when ATR is detected
- Actual: Calculated value based on the Delta and Steady State
- Steady State: Steady state Ki value for the 1Ph, 2Ph, or MaxPh

# Nonlinear Control... ATR

## Control Method

- Disabled: Disable ATRL
- Hi-Z/Low side on: FET turns on when ATRL window is active
- Recommended to be in Hi-Z if ATRL needs to be enabled

## Max Off Time

- Maximum PWM Hi-Z duration in ATRL Hi-Z control mode when the ATRL window is active

## Min Off Time

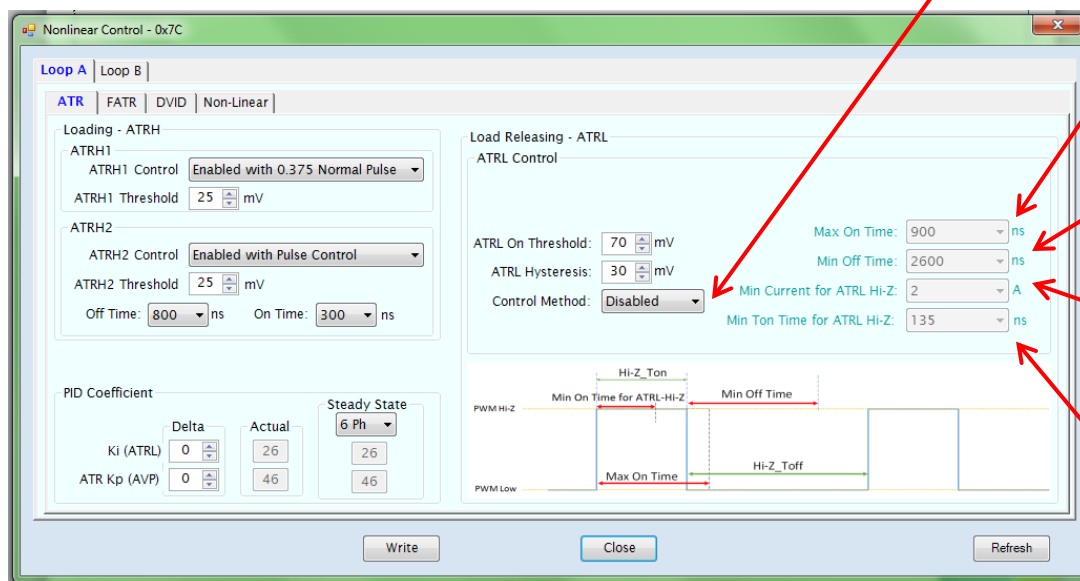
- Minimum PWM low duration in ATRL Hi-Z control mode when the ATRL window is active

## Min Current for ATRL Hi-Z

- Minimum current in ATRL Hi-Z control mode when the ATRL window is active. If the current (per phase) is lower the setting here, the ATRL control mode will become “Low Side ON” See next page for more details

## Min Ton Time for ATRL Hi-Z

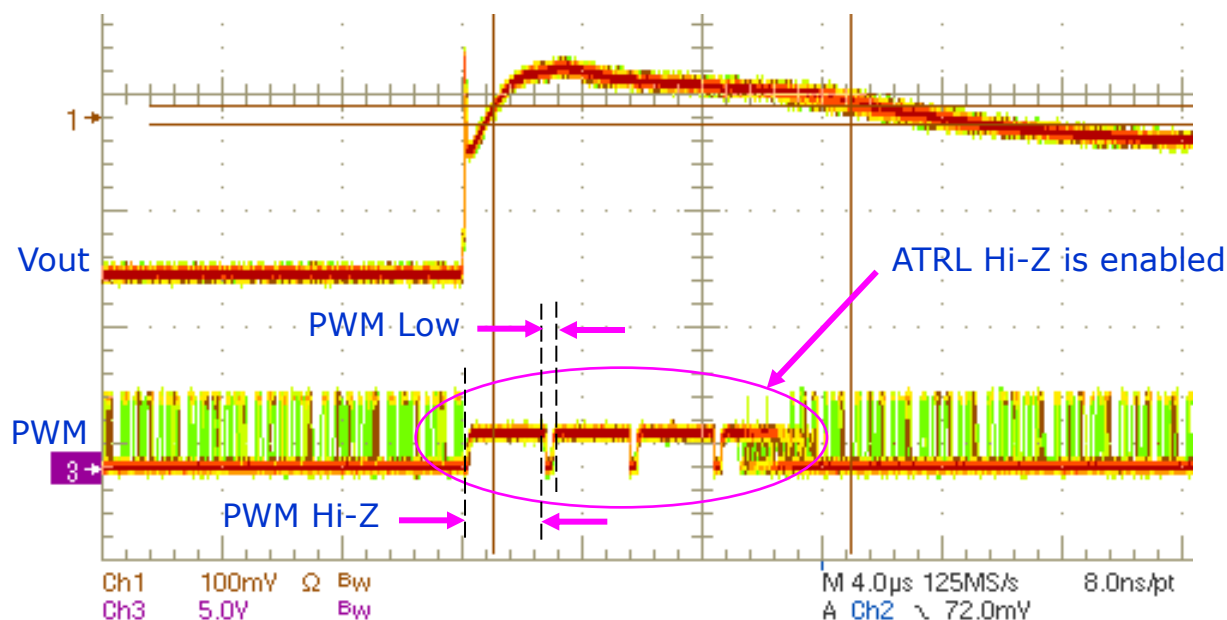
- Minimum PWM Hi-Z duration in ATRL Hi-Z control mode when the ATRL window is active



# Nonlinear Control... ATR

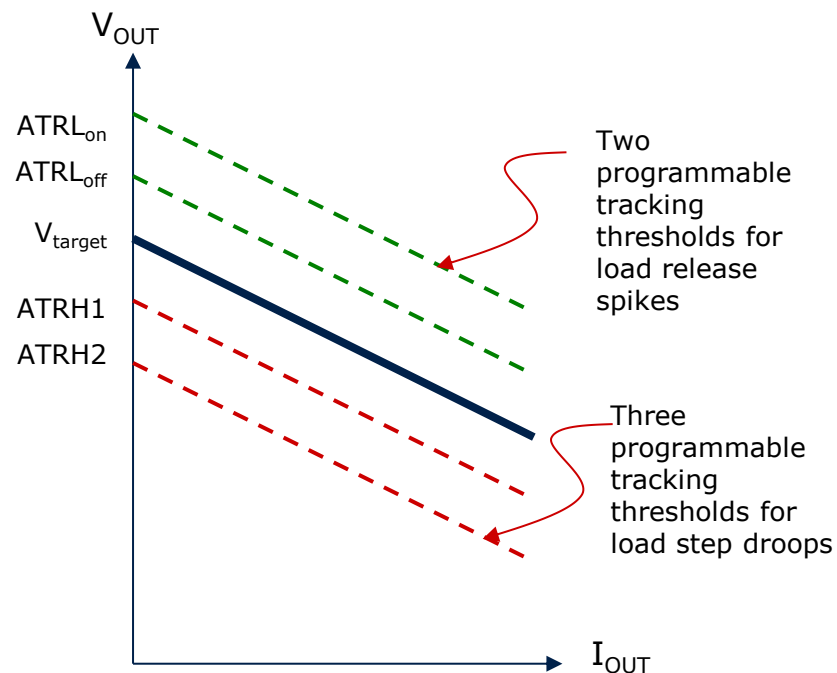
## › **Min Current for ATRL Hi-Z**

- › –When the phase current is lower than the setting specified here, the ATRL behavior will be changed from Hi-Z to LSFET on
- › –Minimum positive inductor required to sustain Hi-Z state during ATRL
- › –When the inductor current falls below this threshold, the low side FET will turn on to continuously discharge the output cap



# Nonlinear Control: ATR Overview

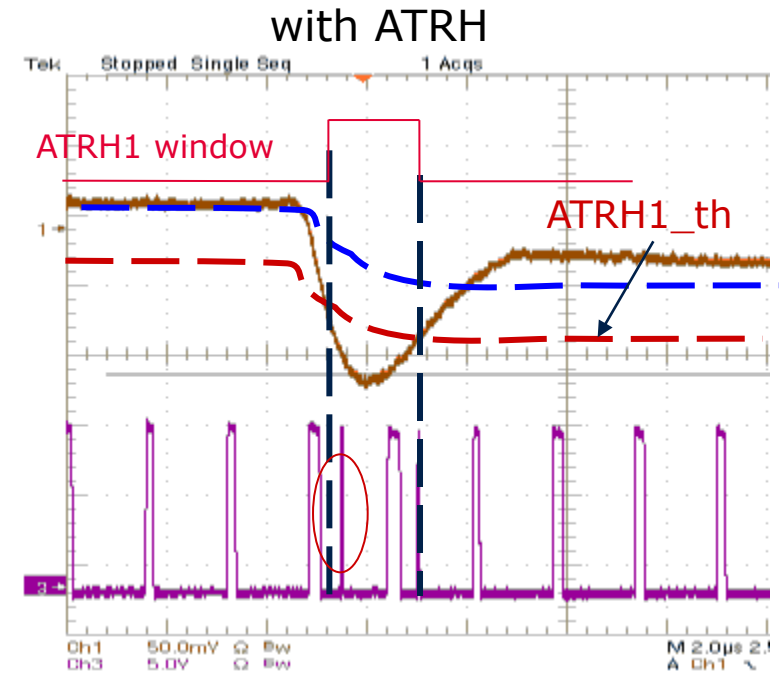
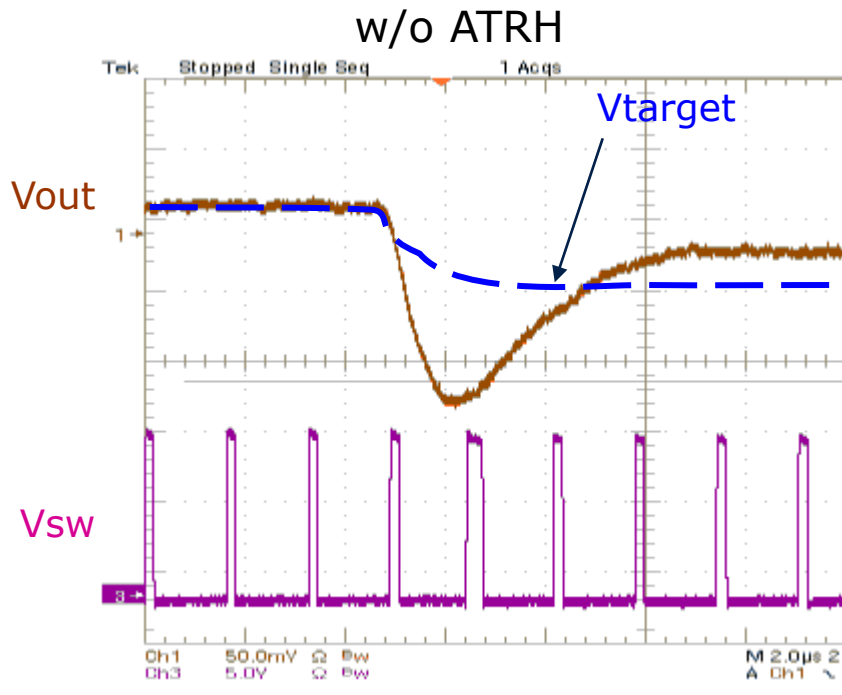
- › Active Transient Response (ATR) is used to reduce undershoot or overshoot excursions during transient load events
  - **ATRH**: Actively inserts additional pulses (PWM **H**igh pulses) on each phase to minimize undershoot during load step conditions
  - **ATRL**: Actively turns on the low side FET(s) (PWM **L**ow pulses) or forces PWM into tri-state so that the inductor current can go through the low side body diode during load release conditions
- › **ATRH** threshold: ATRH will be fired when the droop caused by the load step is above the programmed threshold
  - ATRH1/2 programmable thresholds
- › **ATRL** threshold: ATRL will be fired when either of the 2 programmable tracking thresholds are entered during load release spikes
  - ATRLon
  - ATRLoff = ATRLon Hysteresis



- › ATRH – undershoot detector
  - Use during positive load steps to enable the additional PWM pulses on top of the regular scheduled PWM pulses controlled by the PID
    - This adds pulses to one or more phases to reduce the  $V_{OUT}$  undershoot
  - When  $V_{OUT}$  is below the ATRH threshold, the corresponding ATRH window will be activated
  - The firing of ATRH pulses between phases are “scheduled” to prevent inductor saturation
    - The pulse width of the ATRH pulses is controlled by a combination of the PID and the programmable on/off time durations

# Nonlinear Control: ATRH

- › When the load undergoes a positive step (increased load current),  $V_{OUT}$  droops
- › When  $V_{OUT} < ATRH\_th$ , the controller will fire extra PWM pulses to reduce undershoot
  - The  $ATRH\_th$  is equal to target voltage minus ATRH threshold



# Nonlinear Control: ATRL

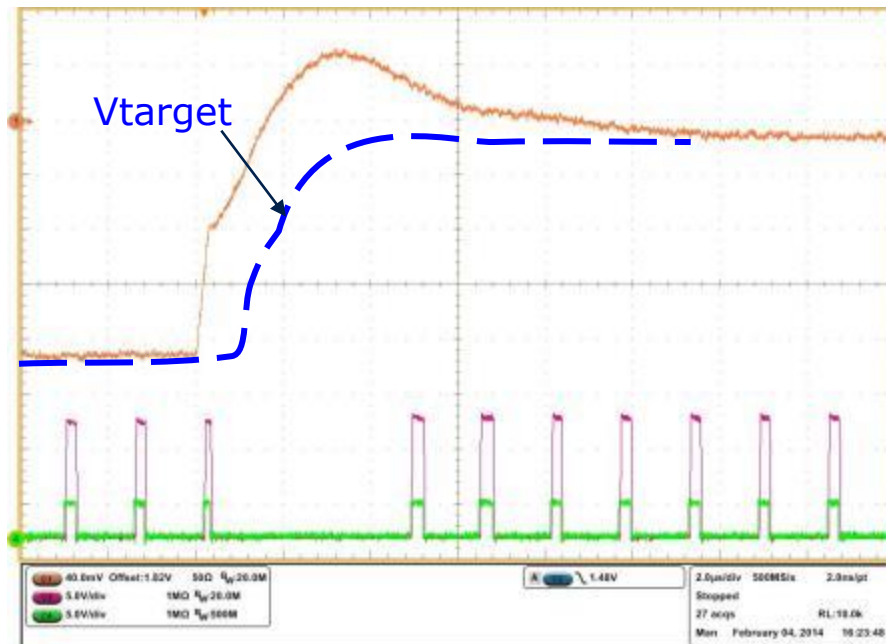


- › ATRL – overshoot detector
  - Use during negative load step (load current release) to quickly bring the PWM outputs to a Hi-Z or Low state (depending on what the programmed action is)
    - This turns off the power stage or turns on the low side FET to reduce the  $V_{OUT}$  overshoot
  - When  $V_{OUT}$  is above the ATRLon threshold, the ATRL window will be activated and deactivates once  $V_{OUT}$  drops below ATRLoff threshold

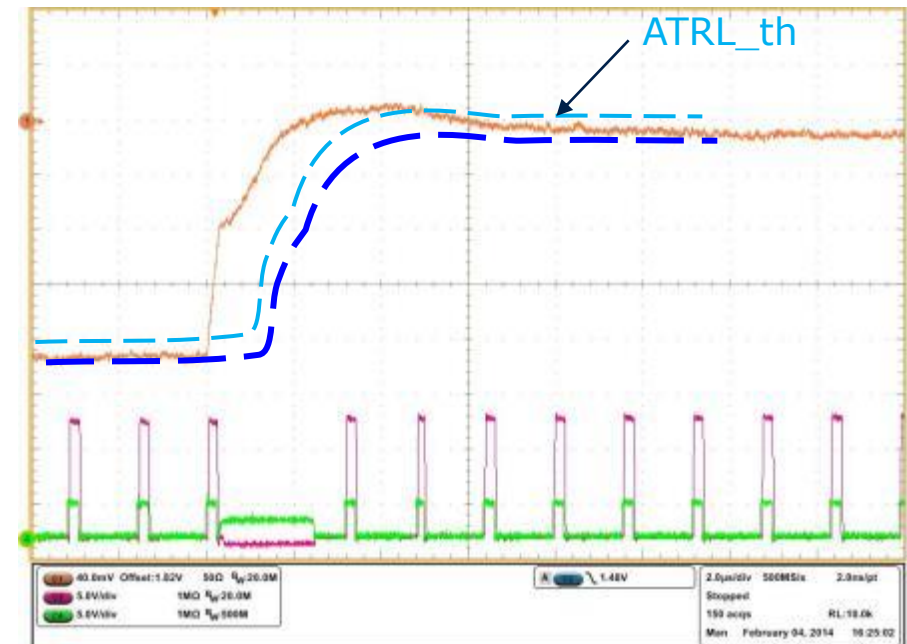
# Nonlinear Control: ATRL

- › When the load is released,  $V_{OUT}$  overshoots due to excess energy in the inductor being transferred to the output capacitors
- › When  $V_{OUT} > ATRL\_th$ , firing a **PWM Hi-Z or Low** pulse will attempt to dissipate some excess energy to reduce overshoot
  - $ATRL\_th$  is target voltage plus ATRL on threshold

w/o ATRL



with ATRL



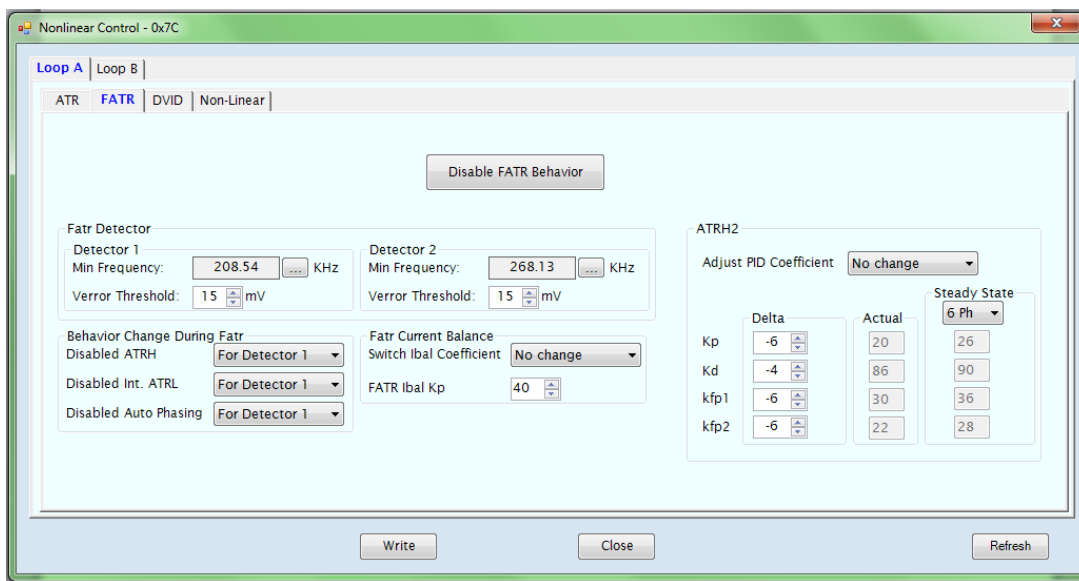
# Nonlinear Control: ATR Recommendations



- › Only enable the ATR functions if adjusting PID alone can not meet the undershoot and overshoot requirements
  - ATR control mechanisms are driven by comparators and programmable thresholds
  - The response is non-linear and may add jitter at the output
- › The thresholds should be at least 5mV (typically 10mV) wider than the measured steady state ripple voltage
- › If ATR has to be enable, the PID should be made less aggressive → start by adjusting Kd and Kfp terms

# Nonlinear Control...FATR

- ›FATR can improve transient response over output load frequency, especially for transient loads at beat frequency.
- ›FATR is made up of 3 independent load frequency detectors and adjustment controls that activate when the target load frequencies are detected.
- ›Only enable FATR if adjusting PID and ATR together still cannot meet the undershoot and overshoot requirements.
- ›Recommended FATR settings are the default settings when FATR is required.
- ›Recommended FATR settings for manual optimization of the FATR settings
  - Step 1: Determine the oscillation frequency
  - Step 2: Determine the cause of the oscillation
    - If it is due to ATR, disable ATR at a frequency that is slightly below the frequency determined in step 1
    - If it is due to an aggressive PID, lower the bandwidth at a frequency that is slightly below the frequency determined in step 1
    - If it is due to current balance, increase the current balance Kp coefficient at frequencies above one-fifth of the switching frequency



# Nonlinear Control...FATR

## Min. Freq. (Detector 1 and 2)

- Minimum load transient frequency for Detector 1 and 2
- A frequency above the specified frequency and an amplitude above Verror Threshold will execute FATR settings.

## Disable FATR Behavior / Restore FATR Behavior

- Button will toggle the text each time it is clicked
- Selection boxes below will display “No Change” in terms of FATR behavior when disabled

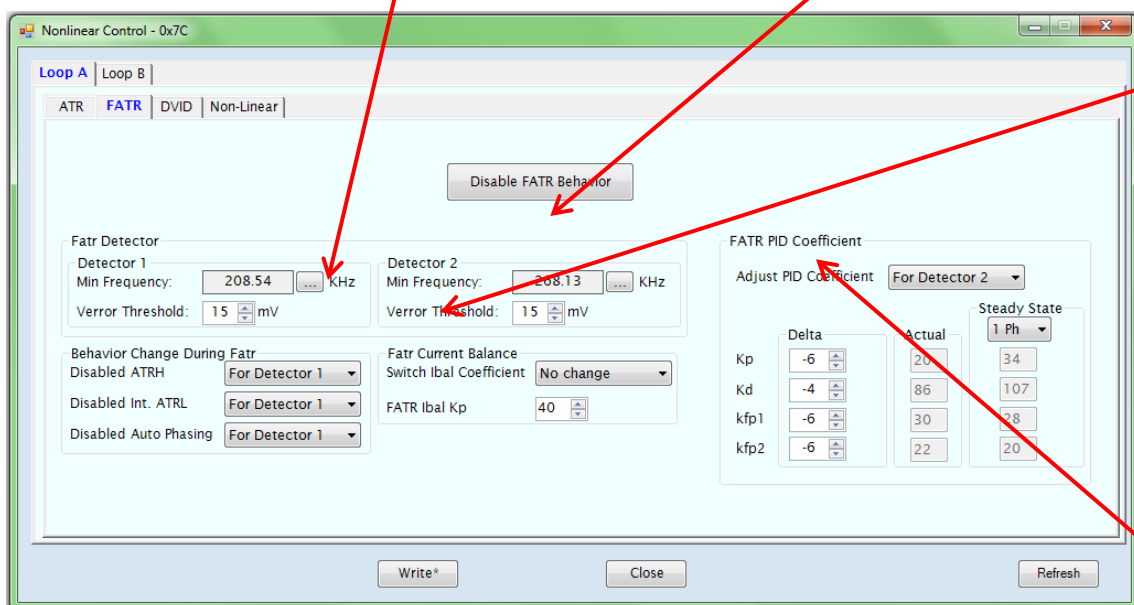
## Error Threshold (Detector 1 and 2)

- Defines the window which the controller counts the number of crossings above and below the Verror threshold over time to determine the load repetition frequency
- Verror threshold should be greater than the output ripple voltage to avoid false detection.



## FATR Current Balance

- The recommended setting is to adjust the current balance parameter Kp (**FATR Ibal. Kp**) to  $\geq 40$  at and above one-fifth of the switching frequency to mitigate circulating current



# Nonlinear Control...FATR

**Behavior Change During FATR:** select the desired behavior for various Non-Linear features when the load frequency is above the FATR setting

- *No Change*: no behavior change
- *For Detector 1 or 2*: behavior change based on the detector value selected

## FATR Current Balance

- The recommended setting is to adjust the current balance parameter Kp (**FATR Ibal. Kp**) to  $\geq 40$  at and above one-fifth of the switching frequency to mitigate circulating current

## FATR PID Coefficient

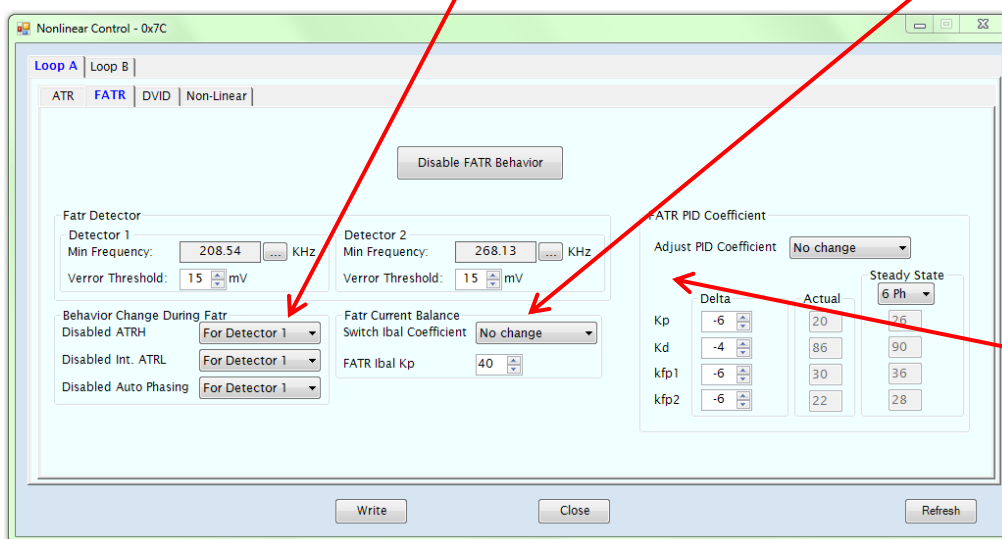
- Reducing the PID coefficients during load transient will help stabilize the system

### – Adjust PID Coefficient

- adjust PID coefficient based on the detector selected

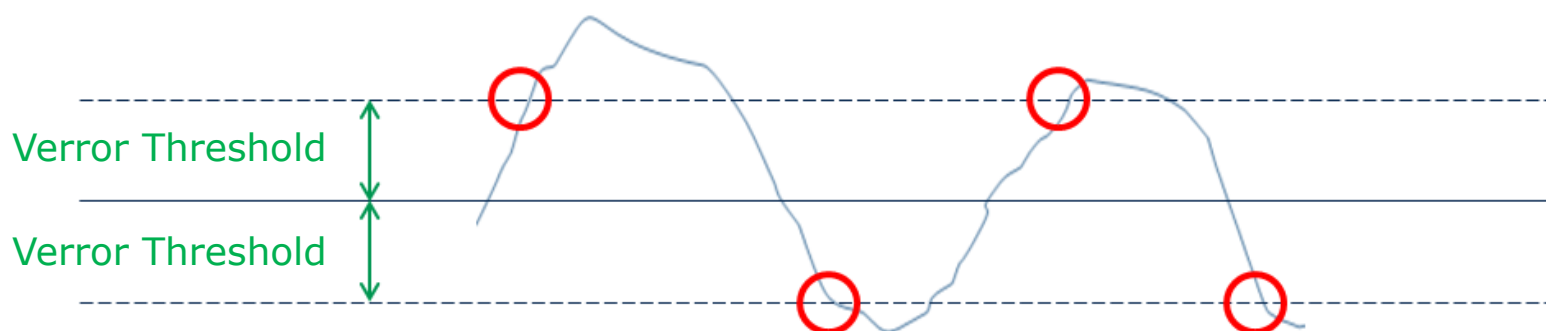
### – Kp/Kd/Kfp

- **Delta**: allows user to set PID coefficient changes
- **Actual**: Calculated value based on the Delta and Steady State
- **Steady State**: Steady state values for the 1Ph, 2Ph, or MaxPh



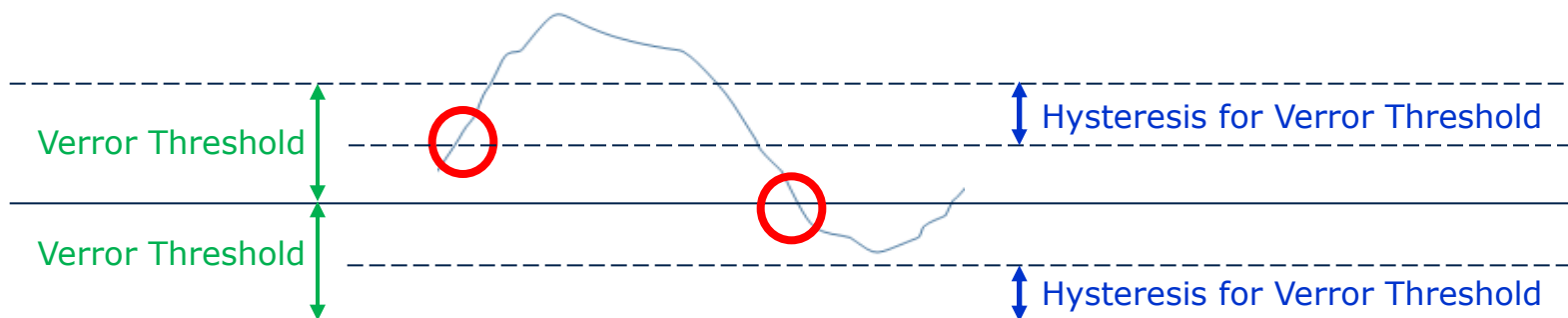
## Error Threshold (Detector 1/2 )

- Defines the window which the controller counts the number of crossings above and below the Verror threshold over time to determine the load repetition frequency
- Verror threshold should be greater than the output ripple voltage to avoid false detection



## Hysteresis for Verror Threshold

- Once the load repetition frequency has been detected, the hysteresis threshold reduces the threshold necessary to stay at the detected frequency



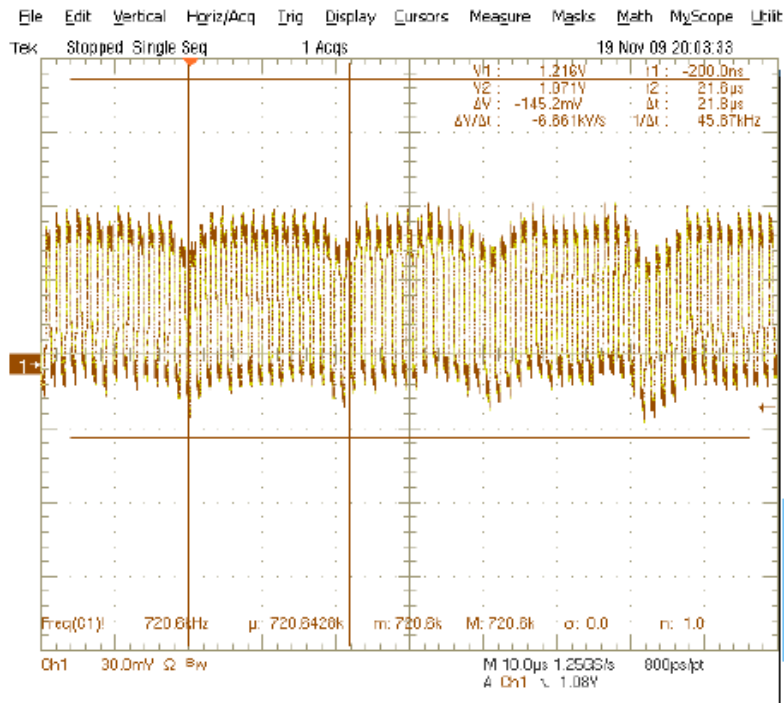
**Behavior Change During FATR:** select the desired behavior for various Non-Linear features when the load frequency is above the FATR setting

- *No Change*: no behavior change
- *For Detector 1/2/3*: behavior change based on the detector value selected
- ATRH Disabled Rate
  - Rate that applies to both entering and exiting the behavior
  - Recommended settings is Slew

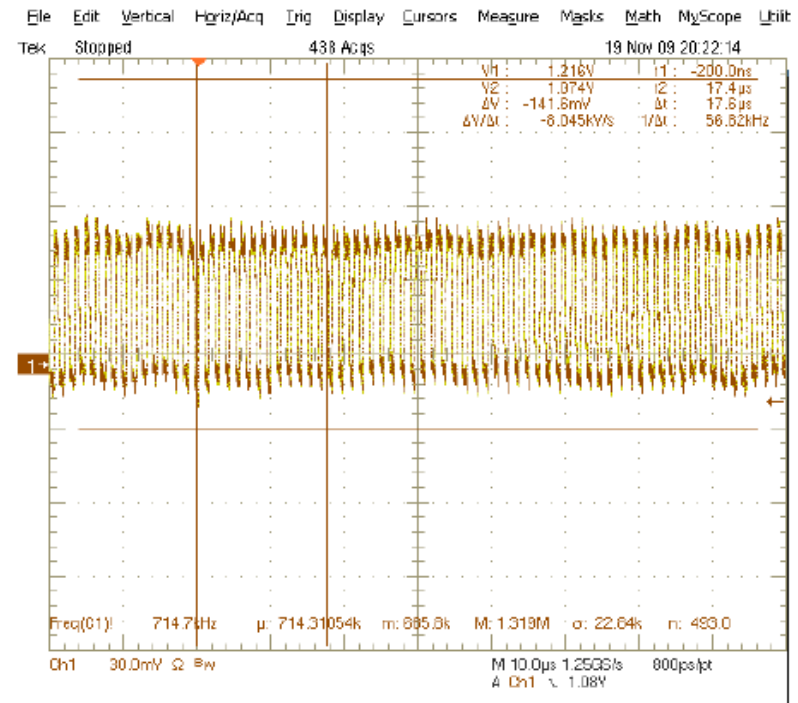
# Nonlinear Control: FATR Design Example

- › Observation:  $V_{OUT}$  oscillation at load frequencies above 700kHz
- › Optimization: Reduce PID in FATR PID Coefficient for load frequencies > 700kHz

*FATR disabled*



*FATR enabled*



## VOUT Waveform Comparison

# Nonlinear Control...DVID

Dynamic VID (DVID) parameters to optimize the VR's response to the SetVID\_Fast/Slow/Decay commands

The screenshot shows the 'Nonlinear Control - 0x7C' window with the 'DVID' tab selected. The interface includes tabs for 'Loop A', 'Loop B', 'ATR', 'FATR', 'DVID', and 'Non-Linear'. The 'DVID' tab contains several parameter groups:

- SR Parameters:** SR-Fast: 10 mV/μs, SR-Slow: 5.00 mV/μs. A 'Default DVID Setting' button is present.
- ESR Compensation Index:** 170.
- Advanced Settings:** A checkbox that is checked.
- DVID Compensation for Positive Step - Overshoot Suppression:**
  - Current Comp Gain: -0.250
  - ESR Voltage Gain Adj: 0.000
- DVID Compensation for Negative Step - Undershoot Suppression:**
  - Current Comp Gain: 0.500
  - ESR Voltage Gain Adj: 0.875
- DVID Compensation for Positive Step:**
  - Duration for Voffset: 0.00 μs
  - Voffset: 0.00 mV
- DVID Compensation for Negative Step:**
  - Duration for Voffset: 10.08 ns
  - Voffset: 8.75 mV
- Misc:**
  - Voffset for Decay Operation: 0 mV
  - Power State After Decay: Same as Before Decay

At the bottom of the window are buttons for 'Write', 'Close', and 'Refresh'.

# Nonlinear Control...DVID

## Default DVID Settings

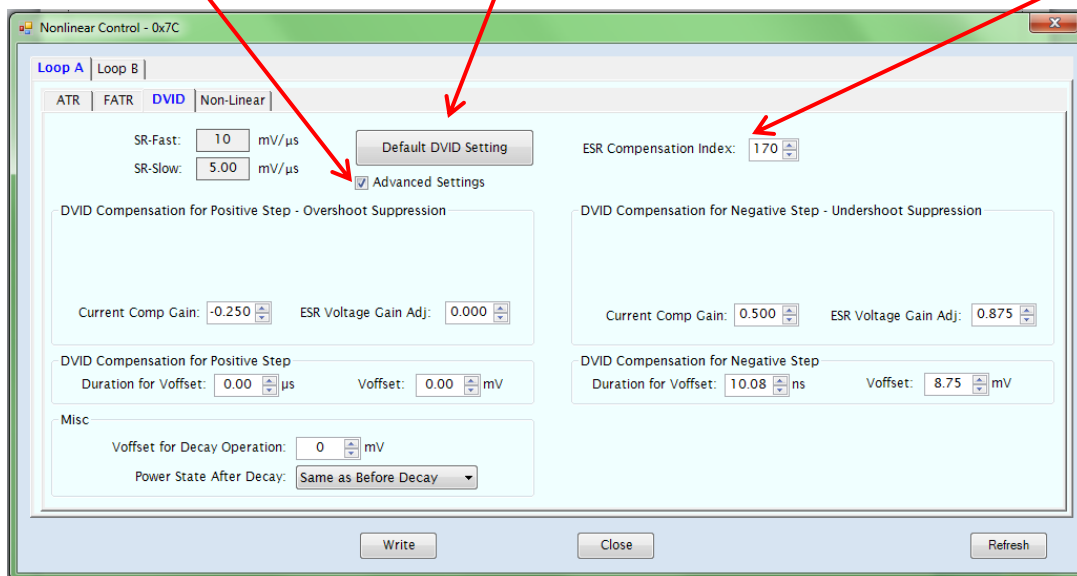
- Calculates and sets the ESR Compensation Index based on the user-specified parameters in the Feedback Loop/Output Model dialog
- Sets all other parameters (including advanced setting parameters) to their default values

## Show Advanced Settings

- Enables DVID advance settings when selected

## ESR Compensation Index

- Calculates the voltage offset caused by the ESR of the output capacitors during DVID slewing
- Is inversely proportional to the  $C_{out} * ESR$  time constant (**Cannot equal 0!**)
- Decrease and re-adjust the DVID Compensation slider bars (when Advance setting box is not marked)
- If fast response is needed or ring back follows the overshoot
- Lowering this value forces the target voltage to ramp up/down faster that makes the response more aggressive and bigger overshoot if the sliders stay in the same position
- Increase and re-adjust the DVID Compensation slider bars when Advance setting box is not marked
- If there is a need to weaken the compensation



**Note:** The normal range for **ESR Compensation Index** is ~40 to ~130. Values below 40 often result in a very aggressive response and the ones bigger than 130 end up very small improvements.

# Nonlinear Control...DVID

## DVID Compensation slider bars

–Use to adjust Current Comp. Gain and ESR Voltage Gain Adjust in positive or negative step

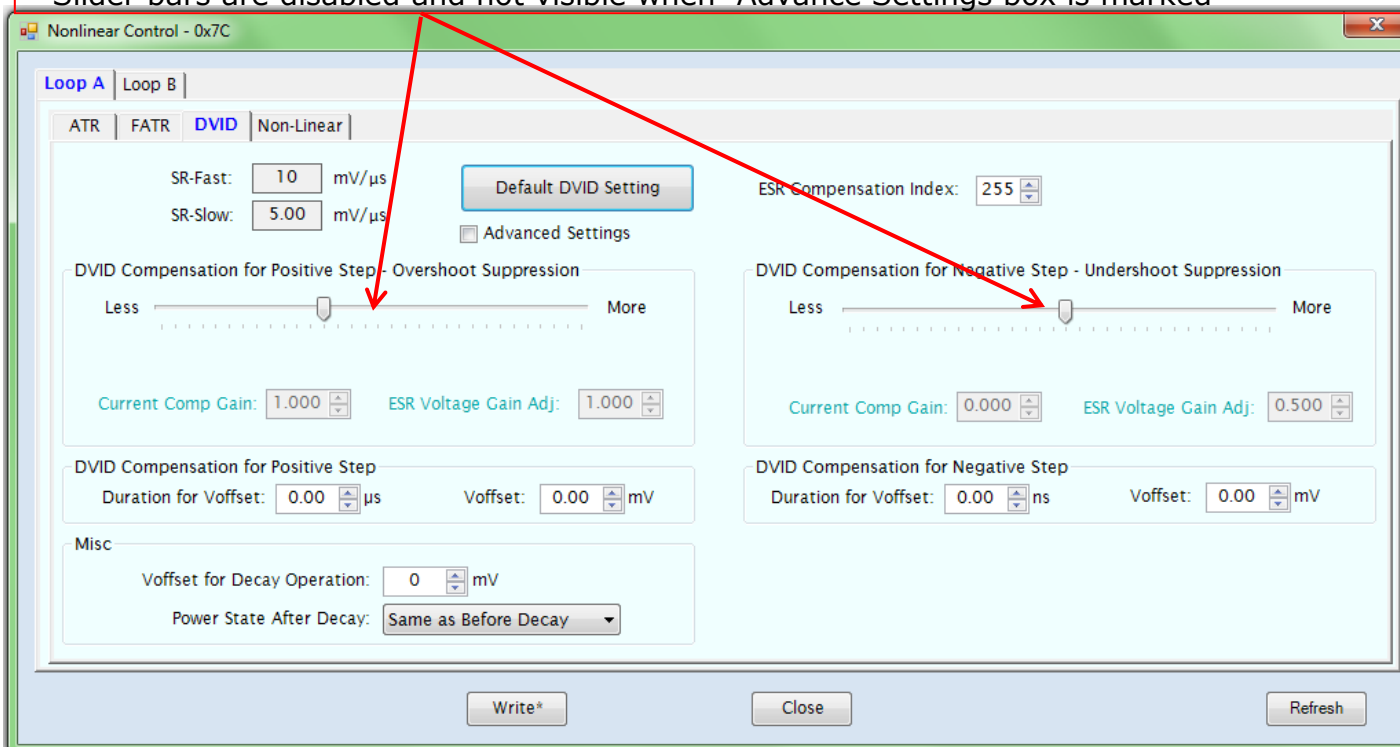
–Positive Step – Overshoot Suppression

- If the DVID response is slow, move the slider to the right to make it faster at the expense of a higher overshoot
- If the DVID response is very aggressive, move the slider to the left to make it slower and have more overshoot suppression

–Negative Step – Undershoot Suppression

- If a slower response and with less undershoot is desired, move the slider to the left (smaller index)
- Move the slider to the right or left to obtain the desired response

–Slider bars are disabled and not visible when Advance Settings box is marked



# Nonlinear Control...DVID

## Current Comp. Gain

–Use to compensate the voltage offset caused by the load-line effect on the output capacitor charging or discharging current during DVID slewing

–Directly proportional to load-line and inversely proportional to ESR

–Positive Step – Overshoot Suppression

•Usually  $\geq 1$  because faster response is desired

– Negative Step – Overshoot Suppression

•Usually  $\leq 0$  because response should be slowed down to prevent any undershoot, therefore it is suggested to be not fully compensated

## ESR Voltage Gain Adj

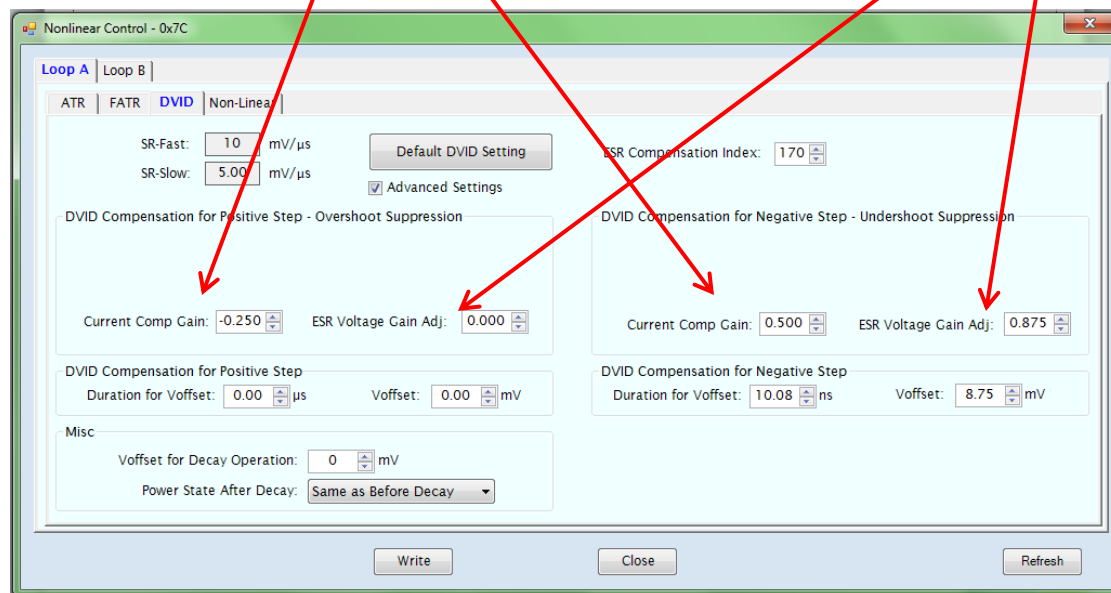
–Used to compensate voltage offset caused by the output capacitors' ESR during DVID slewing

–Positive Step – Overshoot Suppression

•Usually set to 1

–Negative Step – Undershoot Suppression

•Usually set less than Positive Step – Overshoot Suppression value



## Duration for Voffset

–Time where the Voffset will be applied after the ramp completion

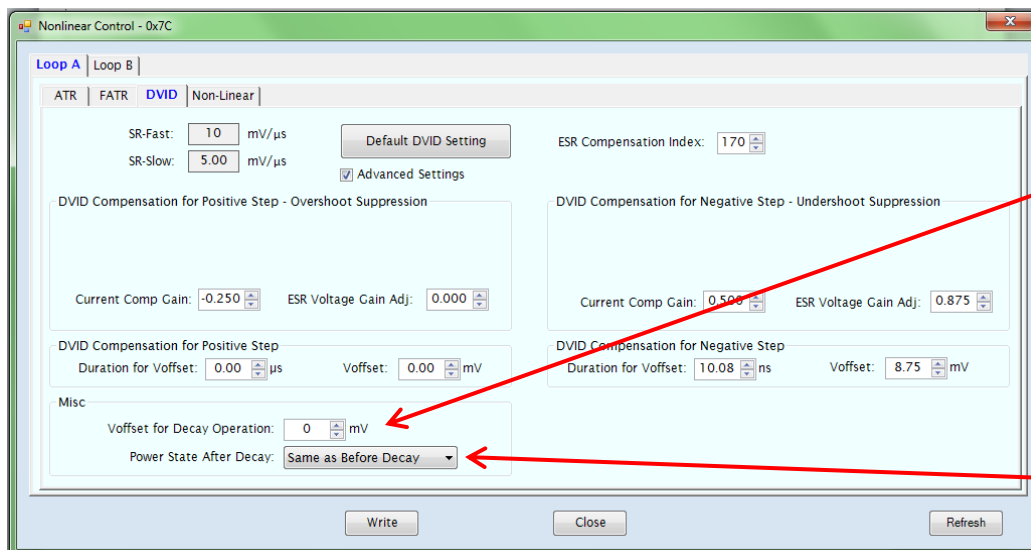
–Independent settings for Positive and Negative Step

## Voffset

–Offset amplitude added after the ramp completion

–Independent settings for Positive and Negative Step

# Nonlinear Control...DVID



## Voffset for Decay Operation

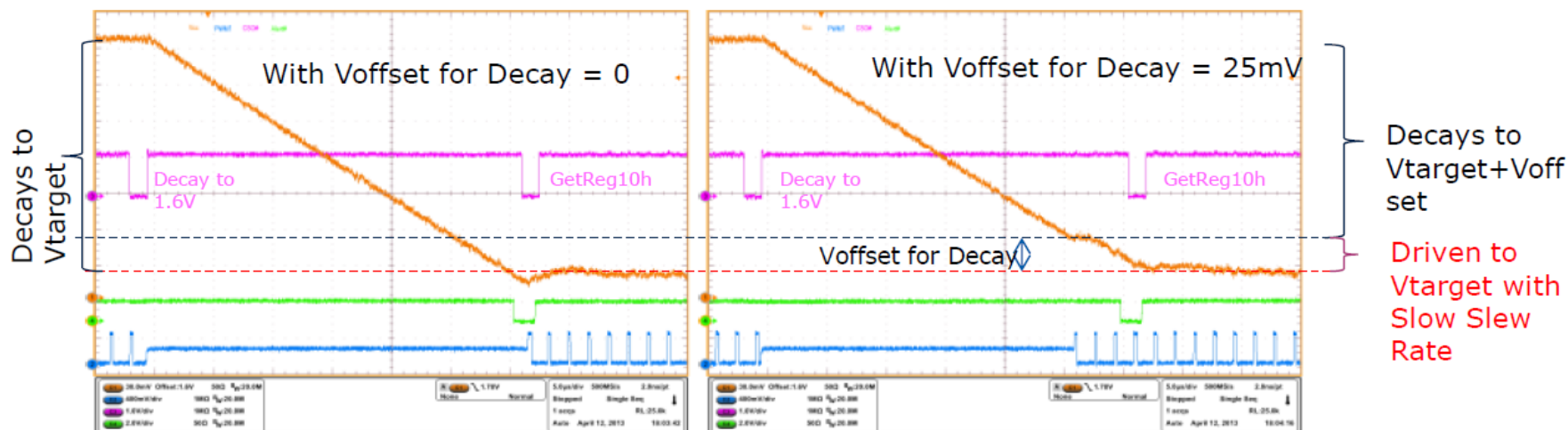
–After the VR reaches the  $V_{target} + V_{offset}$  through decay, the VR will actively drive  $V_{out}$  and continue to ramp to the  $V_{target}$  with the specified number of phases for PS2, at slow slew rate

–Recommended value is 25mV

## PowerState After Decay

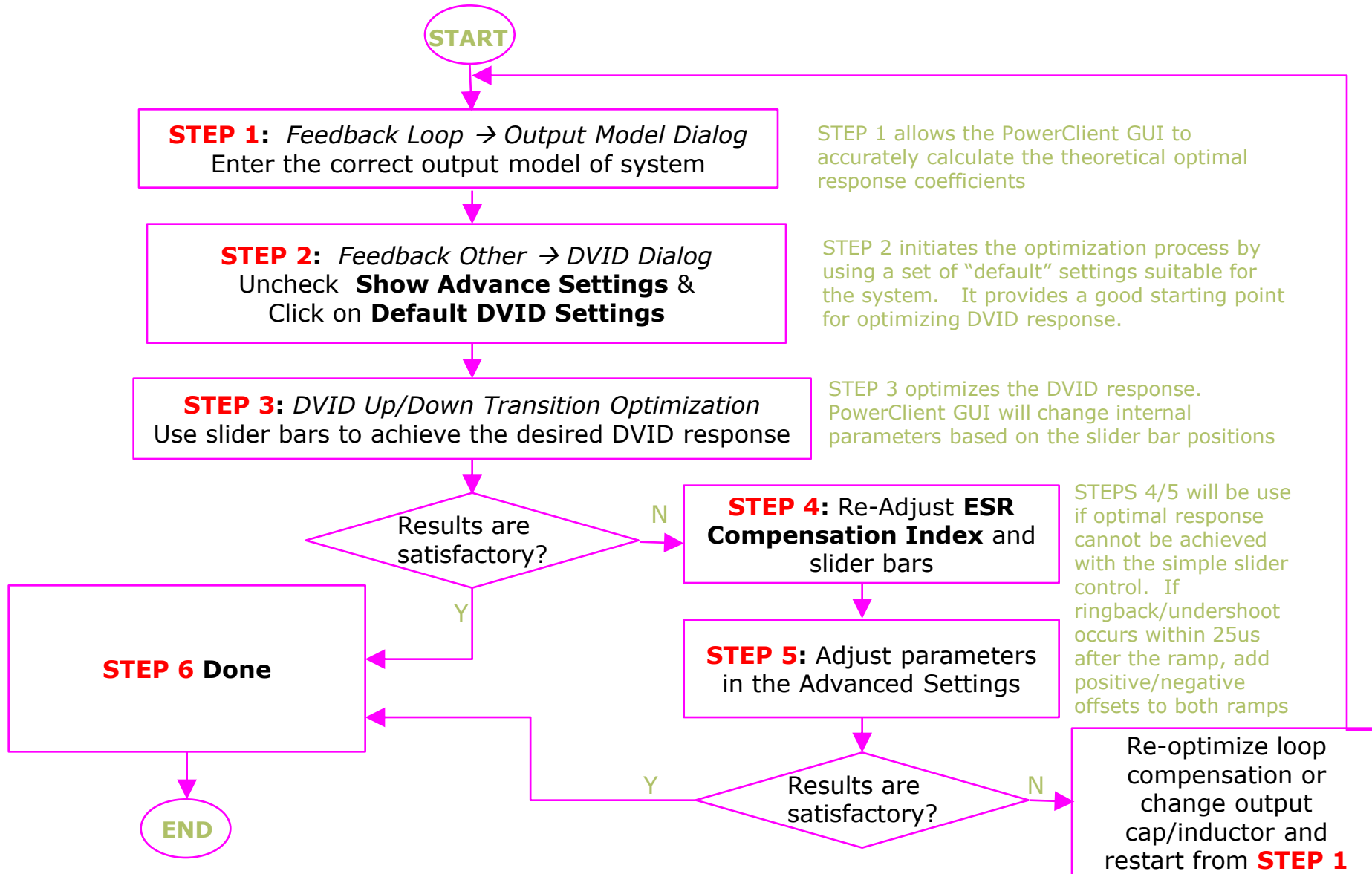
–Same as Before Decay – VR will keep the same PowerState after the decay as it had before decay. Normally for VR13 applications.

–PS2 – VR enters PS2 state after decay. Normally for IMVP8 applications.



# Nonlinear Control...

## DVID Optimization Procedure



# Nonlinear Control...

## DVID Optimization Procedure



- › If desired response cannot be achieved in **Step 5**
- › –Re-adjust PID coefficients in the Feedback Loop/Compensation tab dialog. The current response is not well optimized.
- › •An unstable system will cause undesired rings or oscillations
- › •A very slow system cannot meet DVID timing requirements
- › –Reduce output inductance or capacitance: Current introduced by very large output capacitance ( $C \cdot dv/dt$ ) is very difficult to compensate for.
- › •Extra current (energy stored in L) during a DVID up event will transfer to the output cap resulting in overshoot waveform
- › •Large overshoot will accumulate more error in the PID which the loop has to remove, resulting in slight undershoot

# Nonlinear Control... Non-linear

Non-Linear parameters to gain more undershoot or overshoot margin at high load repetition frequency.  
More explanation at end of this Nonlinear Control section.

Nonlinear Control - 0x7C

Loop A | Loop B

ATR | FATR | DVID | **Non-Linear**

Non-Linear Ki

	Delta	Actual	Steady State
Positive Error: 20 mV	Ki 4	30	26
Negative Error: -20 mV	Ki 0	26	26

Feed Forward

Feed Forward Ki: 18

Write Close Refresh

# Nonlinear Control... Non-linear

## Positive Verror:

–Verror threshold to activate Ki change specified in Delta Ki

## Delta Ki :

–Ki change applied to the original Ki when Positive or Negative Verror is met

## Actual:

–Calculates and displays the actual Ki when the changes in Delta are applied

## Steady State:

–Displays the original steady state Ki

## Feed Forward:

–a low pass filter to make it less sensitive to noise on Vin

## Negative Verror:

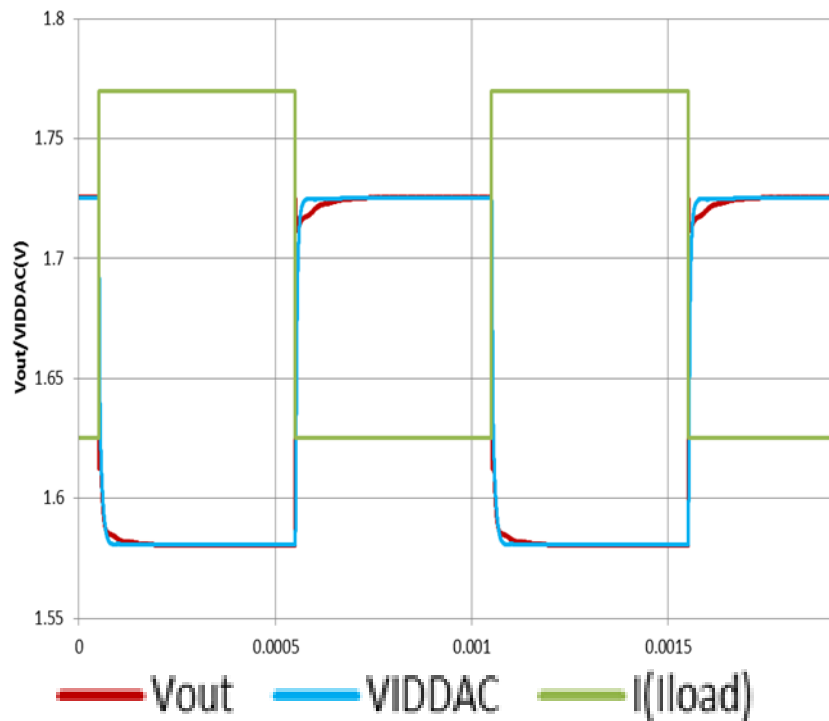
–Verror threshold to activate Ki change specified in Delta Ki

**Note:** Verror threshold should be larger than output ripple size to avoid false trigger

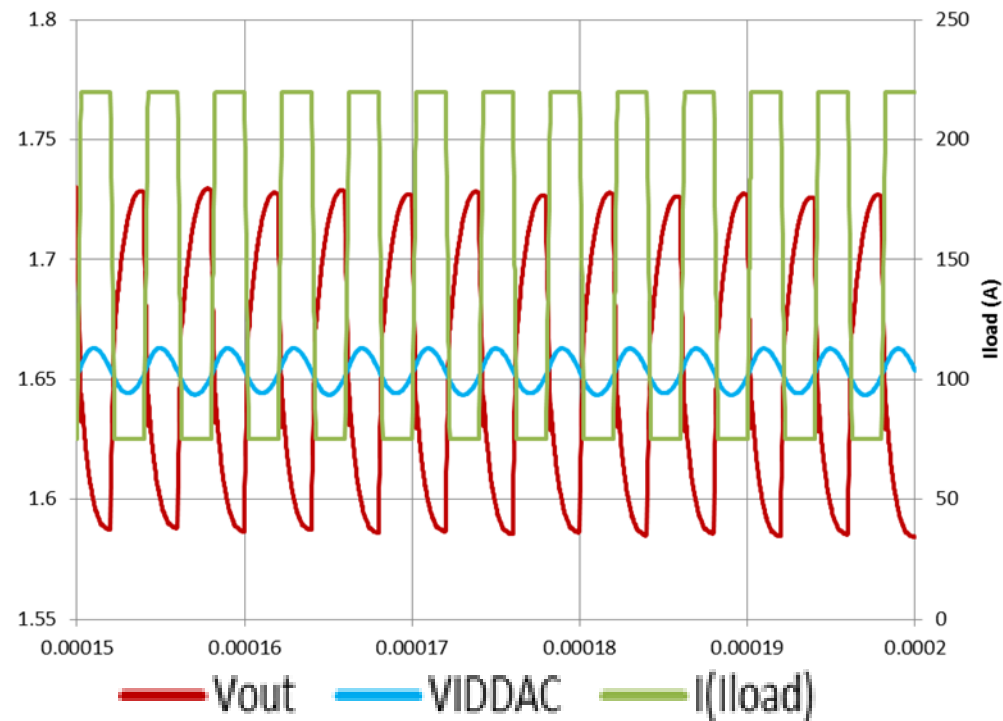
# Nonlinear Control: Non-Linear Background

- At high load repetition frequency,  $V_{OUT}$  cannot settle within one load cycle

1kHz Load Transient  
( $V_{OUT}$  is settled)



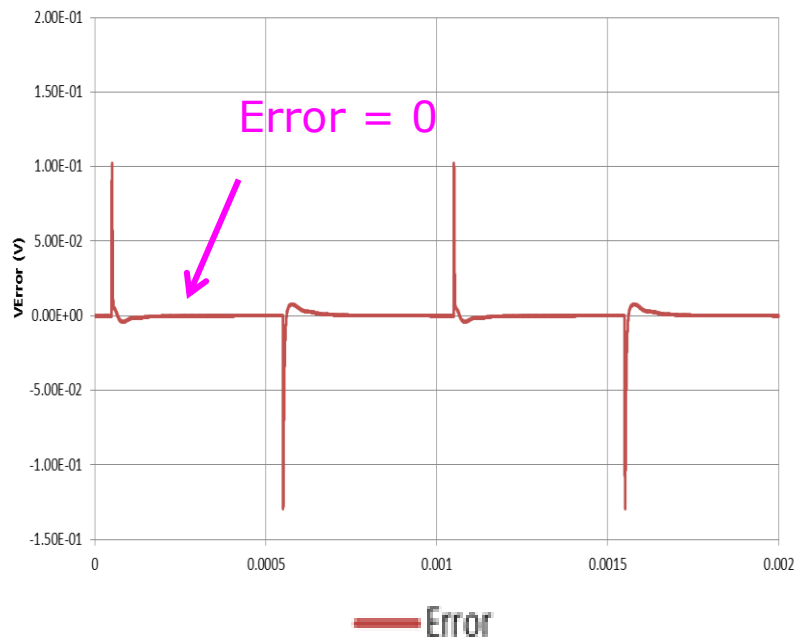
250kHz Load Transient  
( $V_{OUT}$  is not settled)



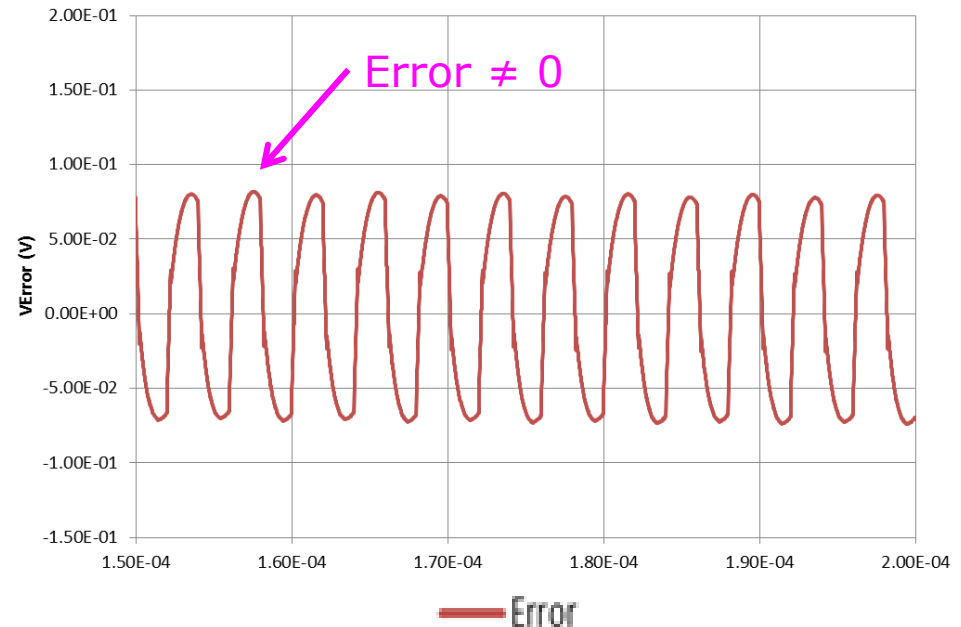
# Nonlinear Control: Non-Linear Background

- For high frequency transient response error cannot be reduced to 0 before next cycle of transient load occurs

VError at 1kHz Load Transient



VError at 250kHz Load Transient

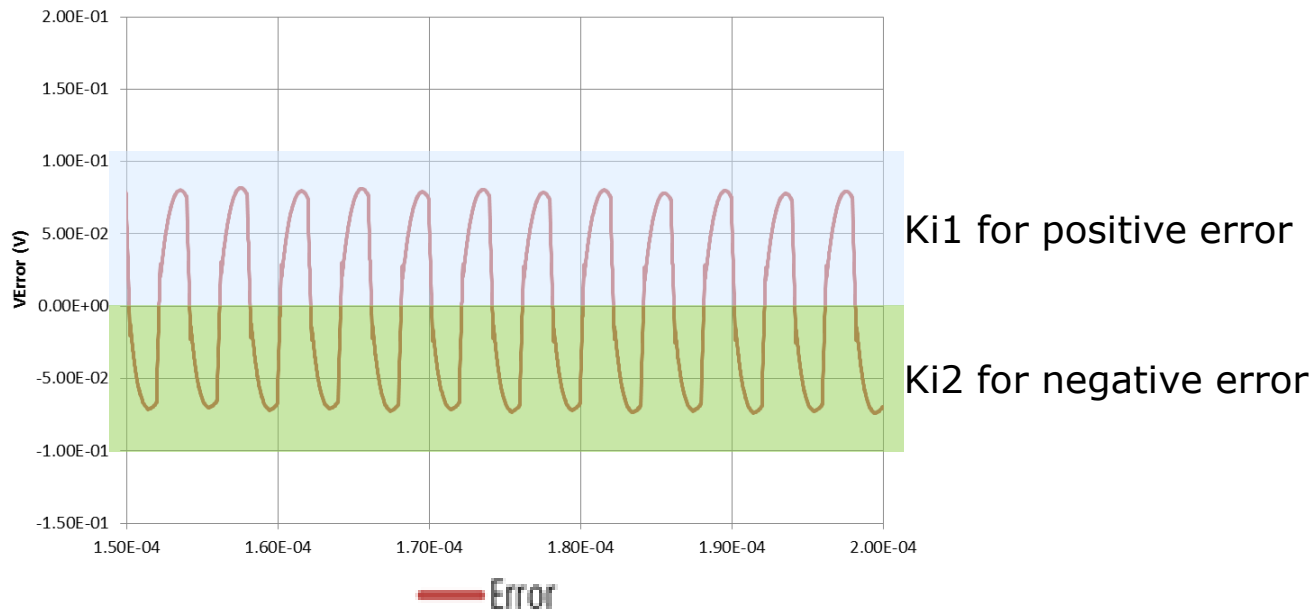


# Nonlinear Control: Non-Linear Background

- › Compensator I term is proportional to the integrated error

$$I \text{ term} = K_i * \int Error \, dt$$

- ›  $K_i$  for positive and negative Verror can be specified separately to influence the I term:
  - If  $K_{i1} > K_i(\text{original})$  AND  $K_{i2} \leq K_i(\text{original})$ ,  $V_{OUT}$  will be shifted up
  - If  $K_{i1} \leq K_i(\text{original})$  AND  $K_{i2} > K_i(\text{original})$ ,  $V_{OUT}$  will be shifted down



# Nonlinear Control: Non-Linear example

- › If more undershoot margin is needed, we can specify a positive  $K_i$  to shift  $V_{OUT}$  up

Non-Linear  $K_i$

Positive Verror:	20 mV	$K_i$	4
Negative Verror:	-20 mV	$K_i$	0

Delta

$K_i$	0
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