Overview FOD methods

Update on decay method for slotted FOD

WPC1903 September 2019

FOD methods for Qi

Version	Impedance measurement Before power transfer Disconnected load	*Advantages* *Disadvantages* *Not during power transfer* *Excludes uncertainty of load* *Indirect relation to FO power*	Power measurement During power transfer Connected load	*Advantages* *Disadvantages* *During power transfer* *Uncertainty of load* *Direct relation to FO power*
V1.0			**Rectified power**	*Simple implementation* *Uncertainty of internal losses not considered*
V1.1			**Power loss** **Ploss = PTx - PRx** Rx→Tx: received power	*Internal power losses included* *Synced measurements* *Insufficient resolution for >5W*
V1.2	**Q factor** Rx→Tx: ref Q factor	*Tx design differences* *Influence of Rx distance*	**Calibrated power loss** Rx→Tx: received power + type Calibration at start of power transfer	*Relative values → better resolution* *Calibration depends on FO absence before power transfer*
V1.3 draft	**Q factor +** **F resonance** Rx→Tx: ref Q factor Rx→Tx: ref f factor	*Combined info* *Enhanced protocol support* *EFOD: Porting to reference* *Influence of Rx distance*	**Calibrated power loss multipoint** at start and during power to include multiple loads	*Better resolution over whole power range* *Increased risk:* *calibration while FO is present*

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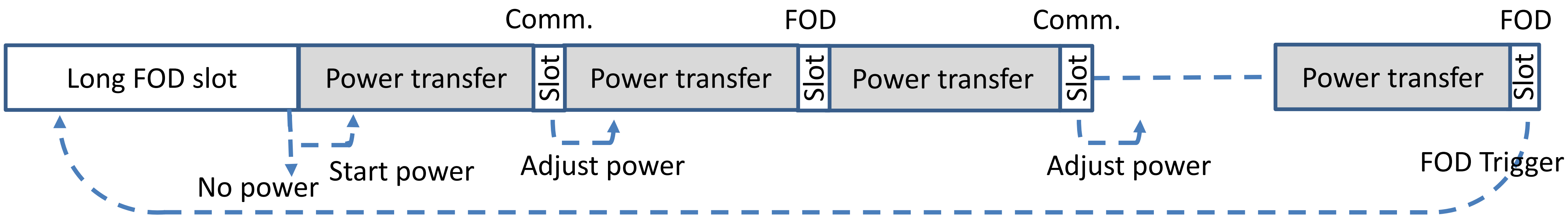
Take-aways from Qi FOD methods

- Q factor method before power transfer
  - more accurate than power loss
  - uncertainty of load is excluded
- Power loss method during power transfer
  - Uncertainty reduction by calibration
  - Dependent on FOD before power transfer
- Protocol enhancements in v1.3 draft
  - Reference resonance shift in addition to Reference Q factor
  - Multipoint calibration for power loss
  - Protocol enhancements Re-start at FOD

- Further improvements of pre-power methods addressed by EFOD taskforce
  - Porting of measurements by Tx design to reference Tx
  - Combination Q-factor and resonance shift
  - Currently not described in draft v1.3

- Insufficient resolution / no prove for safe power > 15W
- No compensation for different positioning of Rx (XY + Z)

Slotted FOD (2017, May 5)



- Long FOD & Comm. slot (load disconnected)
  - Prepare for FOD (Rx communicates boundaries)
  - Find optimal parameters for FOD measurement and store them
  - Apply stored parameters and take multiple measurements
  - Compare measurements to boundaries
  - Determine safe maximum field (which could be zero)
- Power transfer (load connected) – e.g. 100ms
  - Apply safe power signal
- Short FOD Slot (load disconnected) – e.g. 1ms
  - Apply stored parameters for fast FOD
  - At FOD trigger (e.g. by exceeding threshold multiple times) → Long FOD slot
    - Note: position change of device may also cause FOD trigger
- Short Comm. slot (load disconnected) – e.g. 1ms
  - Communicate control information to adjust power
- Flexible use of short slots, e.g.
  - Alternating FOD, Communication
  - Combined FOD + communication in single slot

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Medium power proposals for FOD

All proposals with disconnected load to exclude uncertainty of load

Method	**PTx only** before Rx placement	**PTx+PRx** **Long slot ~100ms** “Before” power transfer	*Advantages* *Disadvantages*	**PTx+PRx** **Short slot <1ms** “During” power transfer	*Advantages* *Disadvantages*
	No influence of Rx	Absolute measurements considering influence of Rx	*High accuracy* *Multiple parameters* *Long interruption of power transfer*	Relative measurements in given constellation	*Calibration depends on FO absence in long slot* *Short interruption of power transfer*
Q factor frequency domain	Expected Q factor of Tx	**Q curve** Rx→Tx: frequency dependent Q curve Calibration to references	*Accurate method* *Compensation for distance* *Allows variation Tx and Rx coils* *Indirect relation to FO power*	**Q factor** for single frequency determined during long slot	*Interruption 1ms* *Need to swap to predetermined frequency*
Decay time domain	*Not proposed yet*	**Decay curve** *Not proposed yet*	*Allows for fixed frequency design* *TBD*	**ΔDecay** Multipoint calibration (new)	*Interruption 100us* *No predetermined setting*
Power loss	*Expected power loss in Tx*	**Power loss** (disconnected load) Rx→Tx: $R_{friendly} + U_{Rxcoil}$	*Direct relation to FO power* *Compensation for distance / offset* *Complex compensation*	**ΔPower loss** (disconnected load) for single setting determined during long slot	*Interruption 1ms* *Need to swap to predetermined setting*

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From Bosch proposals

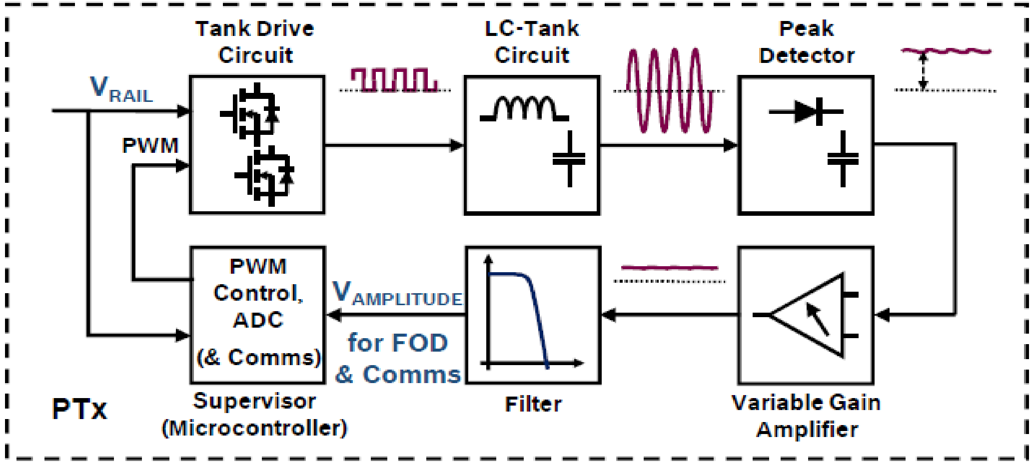
FOD via Q-Factor Measurement at Resonant Frequency

At the transmitter (PTx), while power is **not** being transferred…

- Q-Factor (k_Q) is calculated as the ratio of the peak tank circuit voltage ($V_{AMPLITUDE}$) versus the the exciting voltage (V_{RAIL}):

$$k_Q = V_{AMPLITUDE} / V_{RAIL} \qquad \ldots(1)$$

- A maximum k_Q found within the expected frequency range together with the corresponding frequency, represent the resonant frequency parameters (k_{Q_RES} , F_{RES}) of the system.



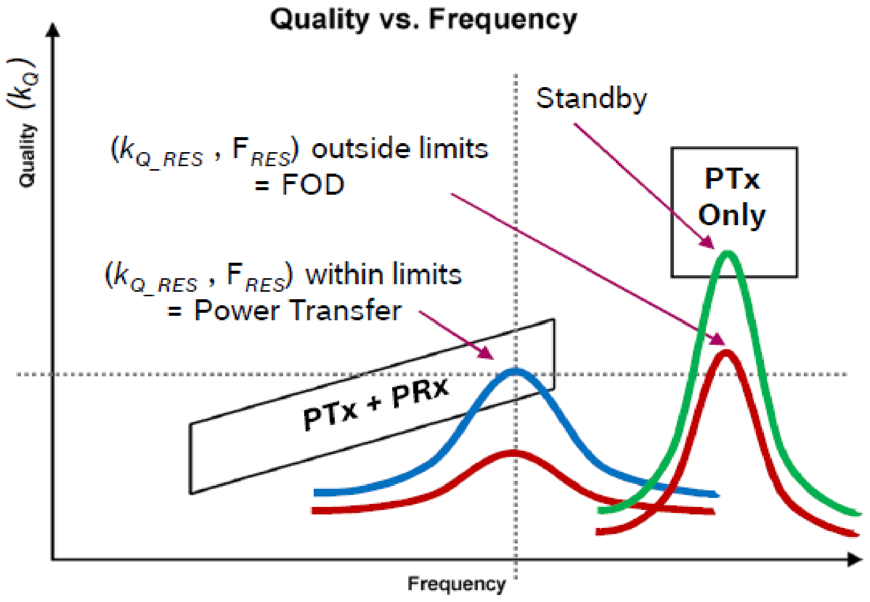
From Bosch proposals

Quality and Frequency Limits - Look-up-Table comparison

- The measured resonance frequency parameters (k_{Q_RES} , F_{RES}) are compared to predefined limits for a given transmitter and also for combinations of transmitter+receiver
- Changes in k_{Q_RES} and F_{RES} over time indicate changes in the system:
  - FO present
  - Change in PRx vs PTx alignment (Z, or in X or Y)

If (k_{Q_RES} , F_{RES}) are ..

- Within PTx+PRx region limits → Power transfer can proceed (preceeded by PRx – PTx communications)
- Within PTx region limits → Standby
- Outside limits → FOD is present



From joint Philips Bosch proposal @WPC 1901

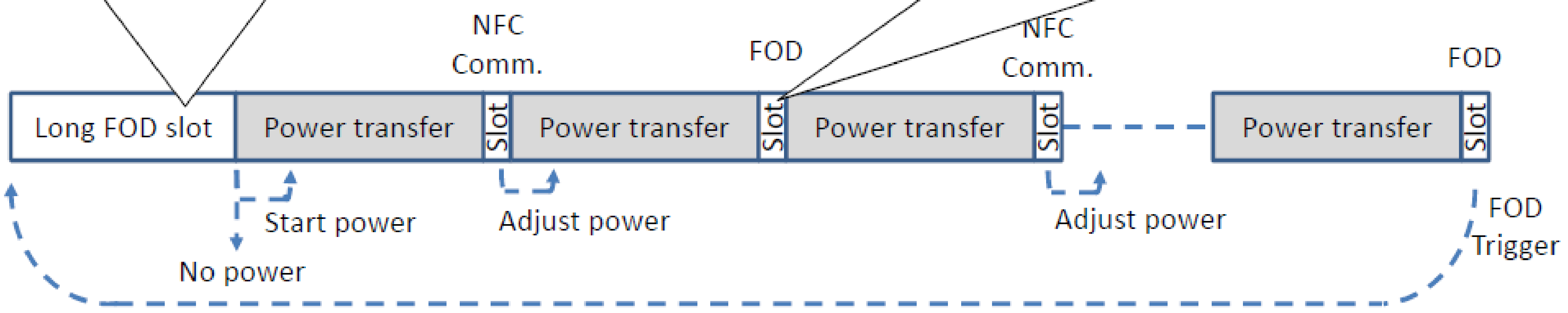
Q-Factor FOD method in long slot / short slot scheme

Long FOD slot (load disconnected)

- Prepare for FOD (Rx communicates reference values)
- Find PTx resonant frequency (F_{RES}) and measure K_{Q_RES}, V_{peak_RES}
- Compare measurements to boundaries
- Store F_{RES} , V_{peak_RES} and inverter settings (voltage /duty cycle) for use during short power slots.

Short FOD slot (load disconnected)

- Apply stored parameters for fast FOD (F_{RES} , inverter voltage / duty cycle)
- Measure V_{peak} and compare with reference level from long slot
- At FOD trigger => Long FOD slot
  (FOD triggers when V_{peak} deviates > 3% from V_{peak_RES})



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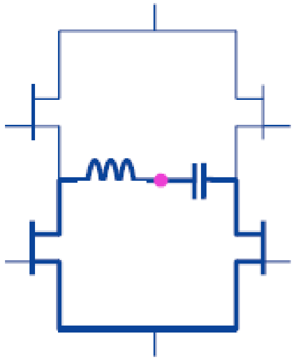
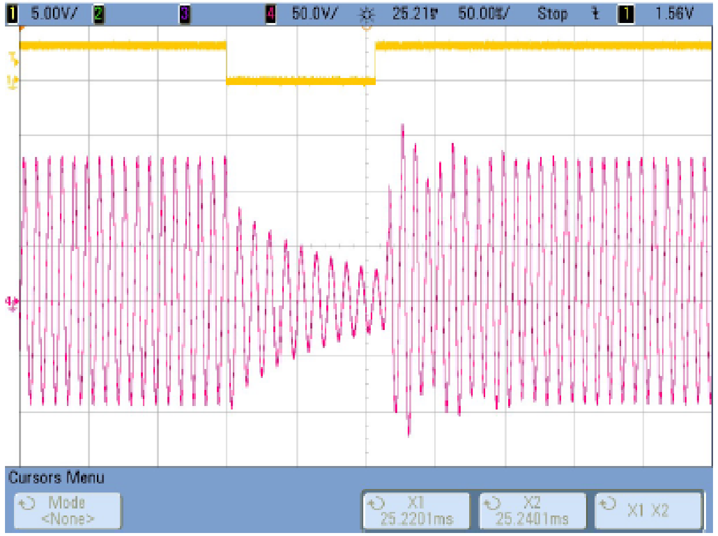
From Philips proposal @WPC 1902

Short slot approach (1/2)



- Short-circuit the resonant tank with the low-side H-bridge switches
- Signal will decay under the influence of:
  - PTx system resistance
  - Friendly metal
  - Foreign objects
- Load basically ‘disconnected’ because the rectifier in the PRx is no longer conducting
  - Valid when: DC bus voltage > voltage induced in PRx coil
  - No influence of PRx coil current on PTx signal decay
- Short FOD slot duration: 100 μs during initial testing



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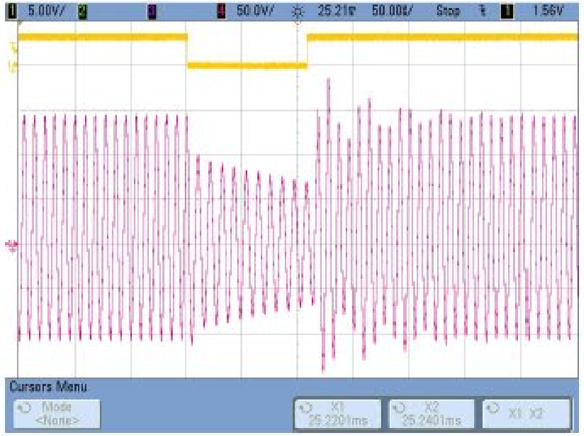
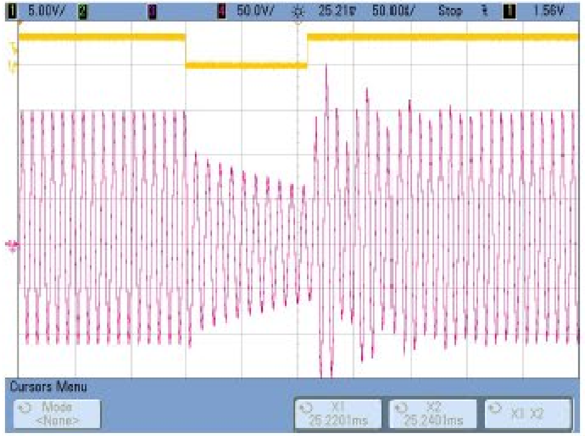
From Philips proposal @WPC 1902

Short slot approach (2/2)

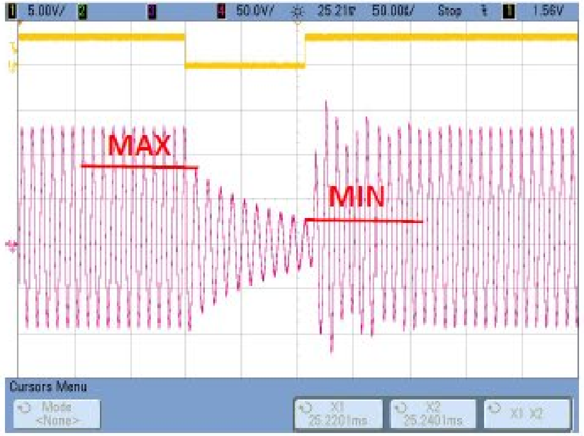
- Measure the decay of PTx resonant tank voltage during a short FOD slot
- Improve accuracy by averaging over multiple short FOD slots
- Compare average decay against threshold



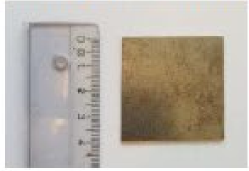
No FO



Small coin as FO



Piece of copper sheet as FO



Update Decay method

- Ensure to measure at time that load is disconnected
  - Start decay measurement after 2 cycles

- Calibration
  - Decay depends on operating point
  - Apply (auto)calibration for multiple operating points

- Calculations
  - Safe operation by limiting coil current
  - Related to ESR offset (ΔR) of resonance tank
  - to limit potential power dissipation in FOD

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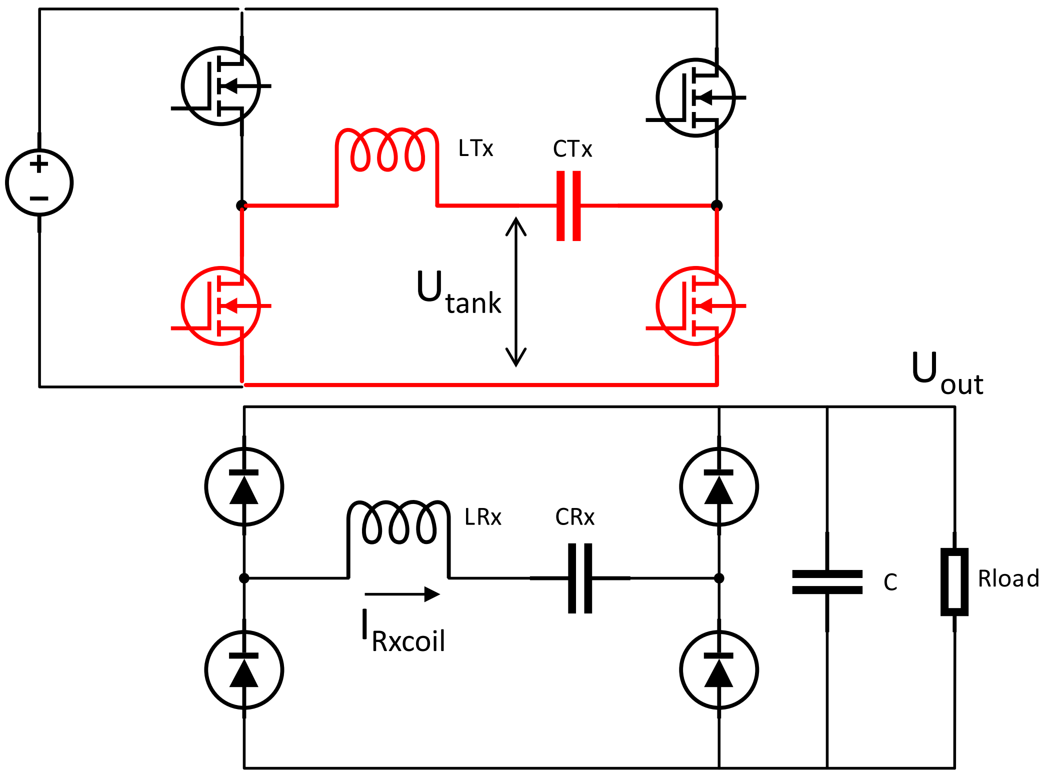
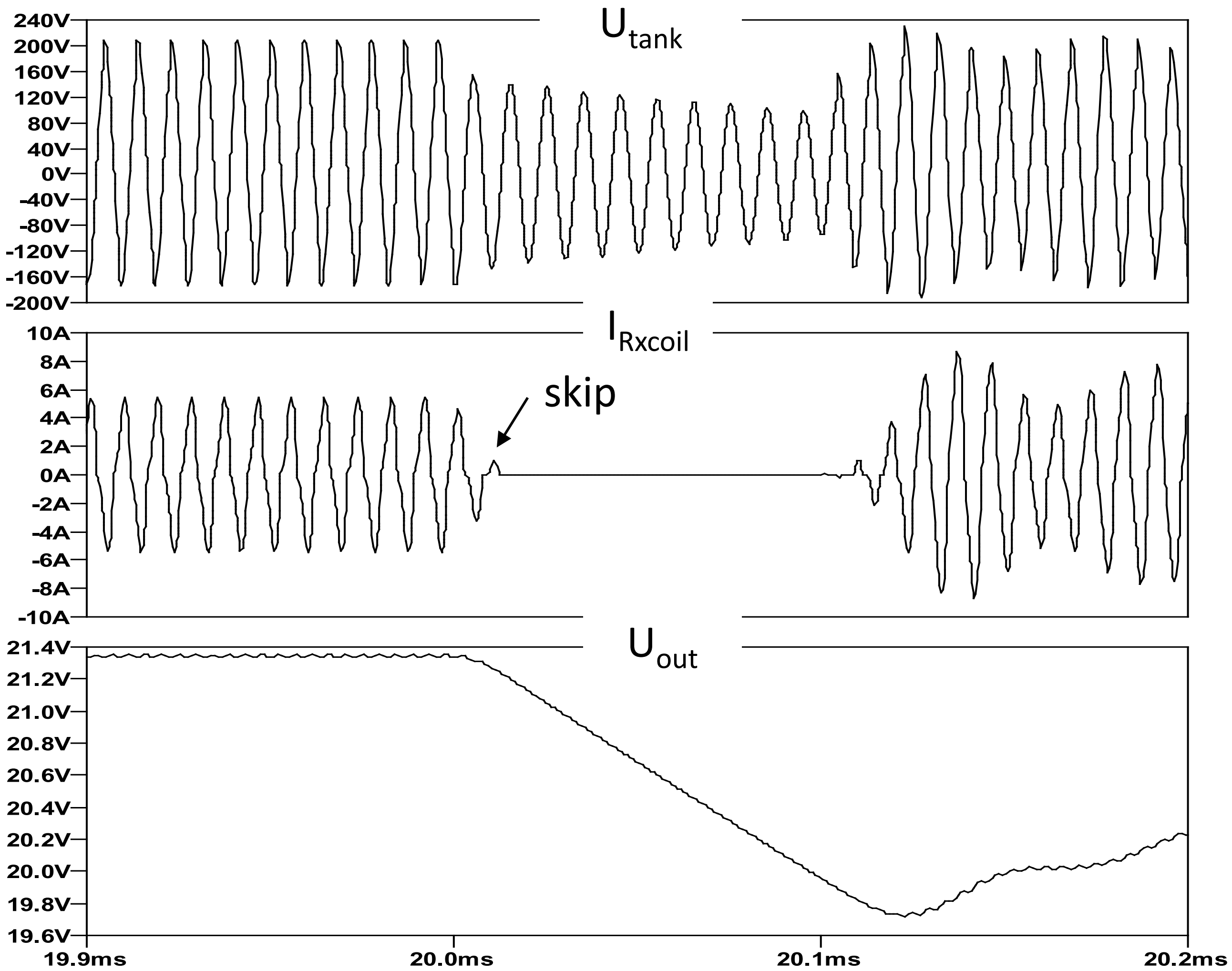
Decay method





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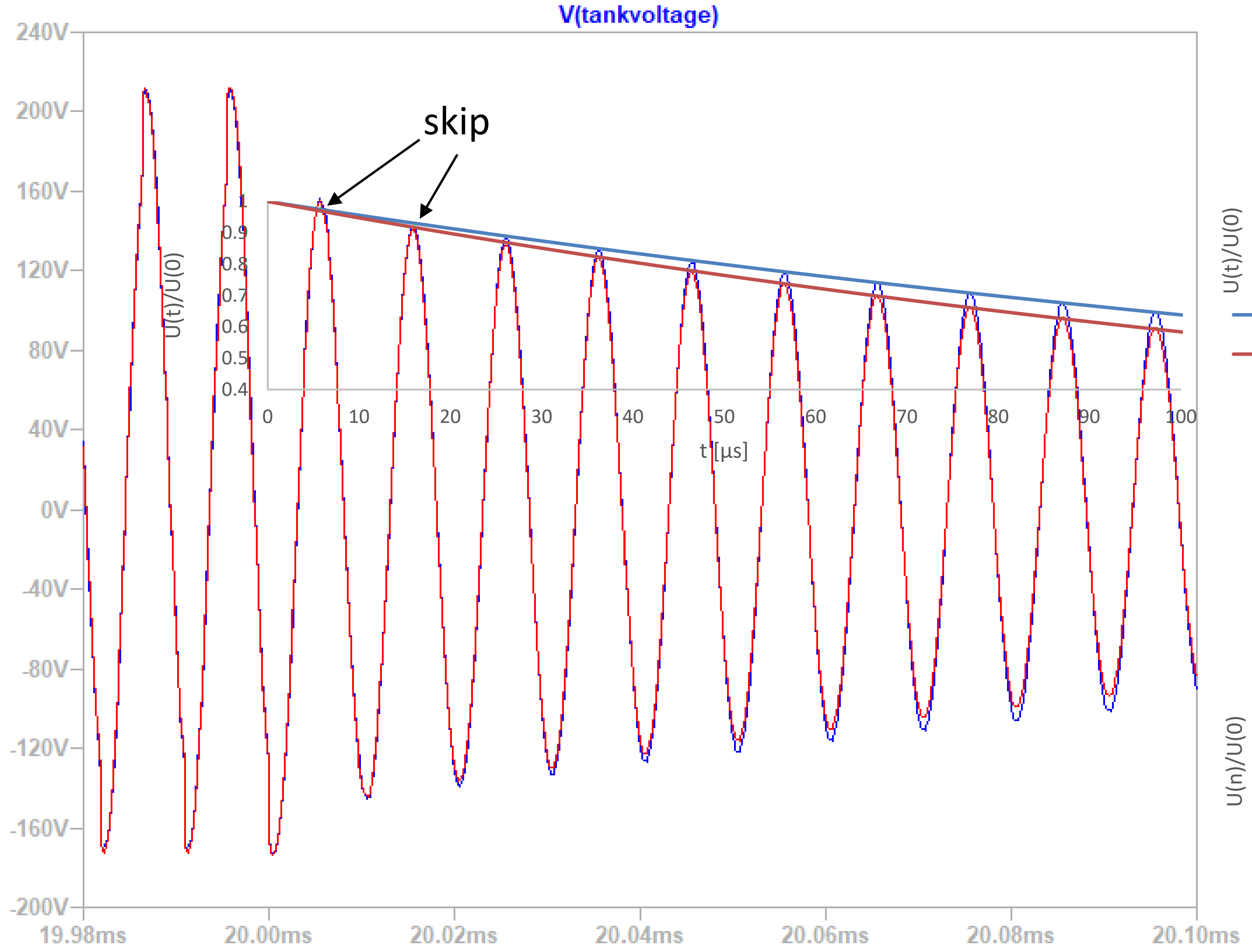
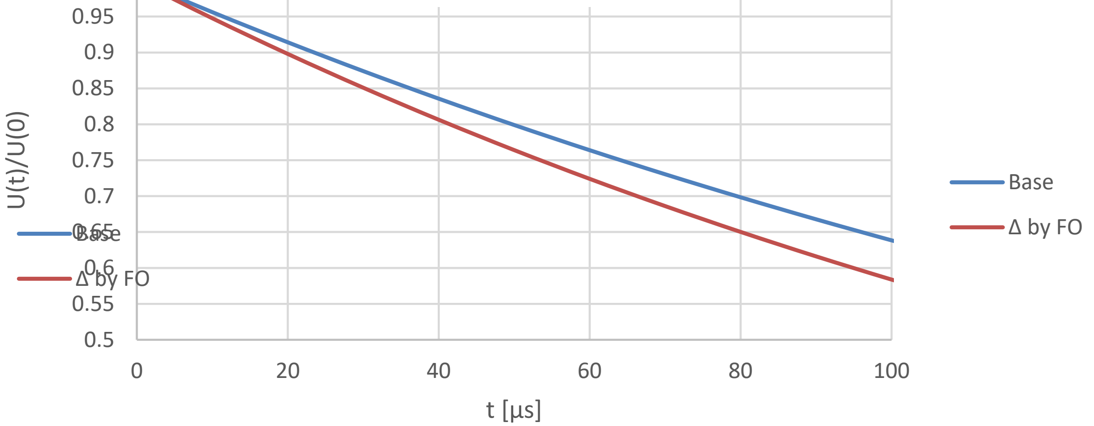
ΔDecay caused by FO

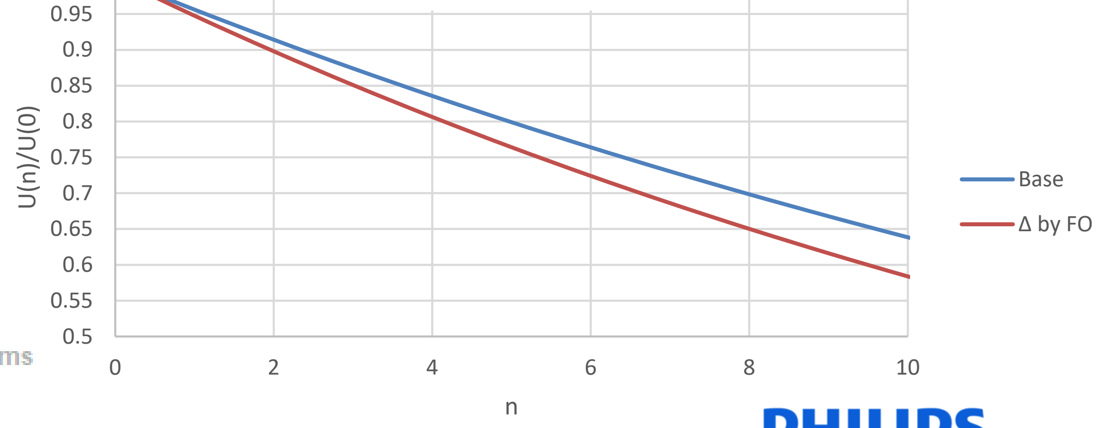
Example: L=28µH, f=100kHz, R=250mΩ, ΔR (R_{FO})=50mΩ, Q=70, ΔQ=11.7



$$\frac{U(t)}{U(0)} = e^{-\frac{\omega}{2Q}t}$$



$$\frac{U(t)}{U(0)} = e^{-2\pi^2 RC\frac{n}{\lambda}}$$



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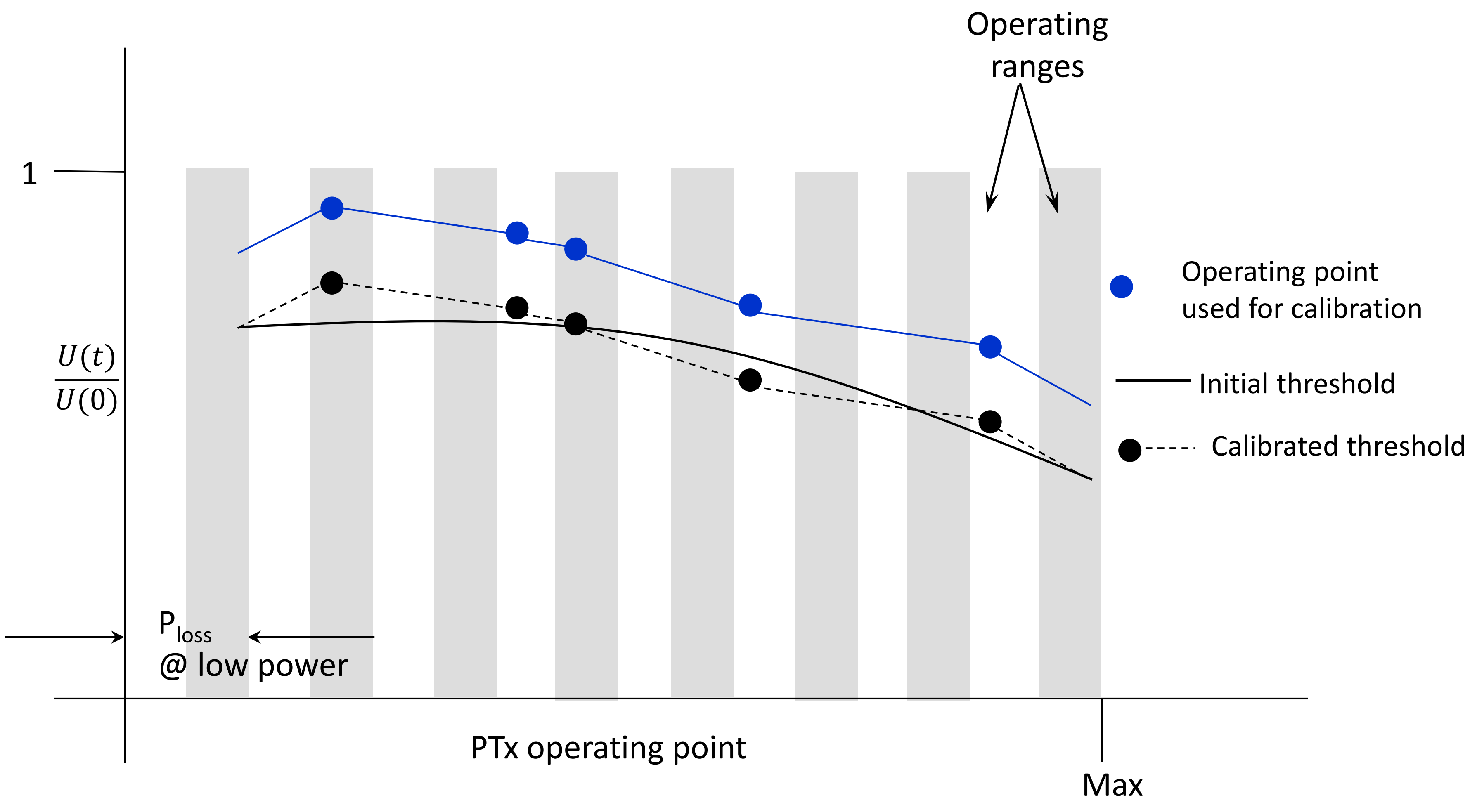
Multipoint calibration for Δdecay



Trigger for calibration at:

- start of power transfer
- change of operating range

- FOD trigger if

  Measured $\frac{U(t)}{U(0)}$ < Threshold

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Calculations

Decay: $\frac{U(t)}{U(0)} = e^{-\frac{\omega}{2Q}t}$

with $Q = \frac{1}{\omega RC}$ $\frac{U(t)}{U(0)} = e^{-\frac{\omega^2 RC}{2}t}$

Over n cycles: $t = n\lambda$ $\frac{U(t)}{U(0)} = e^{-\frac{\pi}{Q}n}$

with $Q = \frac{\lambda}{2\pi RC}$ $\frac{U(t)}{U(0)} = e^{-2\pi^2 RC\frac{n}{\lambda}}$

$U(0)$	Resonance tank Voltage at start of decay measurement
$U(t)$	Resonance tank Voltage at time t
t	time from start of decay measurement
Q	Q factor
f	resonance frequency $f = \omega/2\pi$
λ	wavelength = period of a resonance cycle $\lambda = 2\pi/\omega$
n	number of wavelengths for decay measurement
C	capacitor of resonance circuit
R	ESR of resonance circuit
R_{FO}	ΔR caused by FO
I	rms current in Tx coil

For fixed *C*, *R* can be calculated:

With measured *f* and *Q:* $R = \frac{1}{2\pi f QC}$

With configured *n* and measured *λ*: $R = \frac{-\lambda}{2\pi^2 nC} \ln\left(\frac{U(t)}{U(0)}\right)$

Safe operation:

Limit primary coil current by estimation of P_{FO}

$$P_{FO} = I^2 R_{FO} = I^2 \Delta R \rightarrow \boldsymbol{I^2 \leq \frac{P_{FOmax}}{\Delta R}}$$

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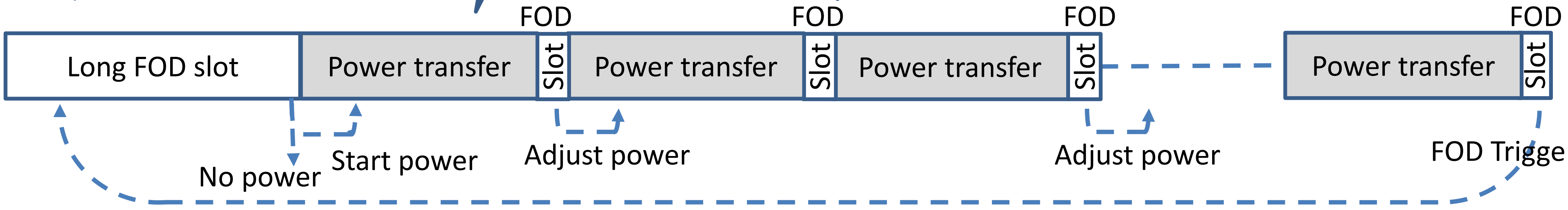
Slotted FOD for Δdecay in short slots

Long Slot
- E.g. Q curve method
- Determine safe maximum field
  - $I^2 \leq \frac{P_{FOmax}}{\Delta R}$

Power transfer
- Apply safe maximum field

Short Slot, decay method
- Wait for 2 cycles
- Measure decay: $\frac{U(t)}{U(0)}$ over time = t or $n\lambda$
- Average decay (e.g. over 75 slots in 2 seconds)
- FOD trigger: Average decay-value < threshold



Conclusions

- Proposals for medium power
  - Learnings from Qi
    - Measure at disconnected load
    - Calibrate power loss
    - Add more parameters
  - Accurate FOD in long slot
    - Multiple parameters: e.g. Q, f, U_{Rxcoil}, etc.
    - Compensate for different offset and distance positions
    - Calibration routines to compensate for design variations
  - FOD in short slot
    - Predefined settings, e.g. frequency and/or
    - Calibrated relative measurements, e.g. Δdecay

- Multiple methods enables
  - Design freedom
  - Increased reliability
  - Smart combinations, e.g.
    - Accurate Q curve method in long slot
    - Fast Δdecay method in short slot

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Todo

- Upgrade Decay method for long slot
  - Compensate for position of Rx coil on Tx coil
    - Additional parameters (resonance wavelength)
  - Influence of component temperature
    - Long slot may require cool down-period
    - Measure R_{on} of MOSFETS

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