Capability Curve-Based Generator Protection Minimizes Generator Stress and Maintains Power System Stability

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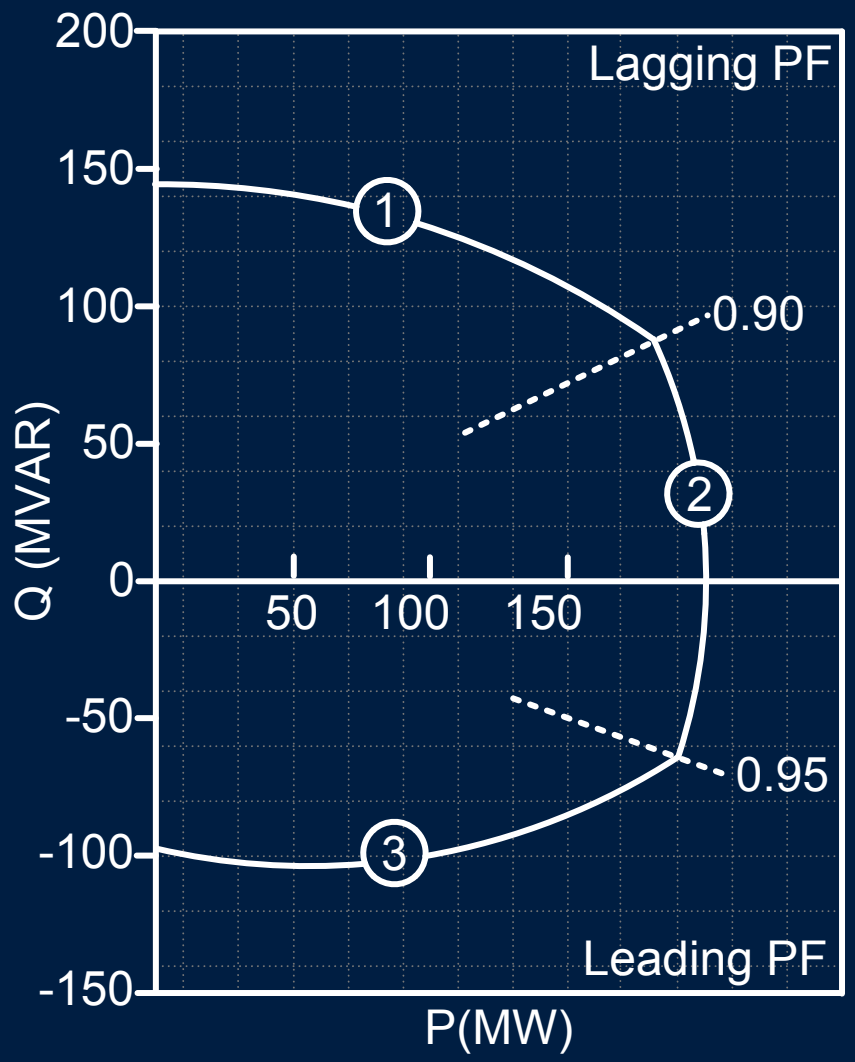
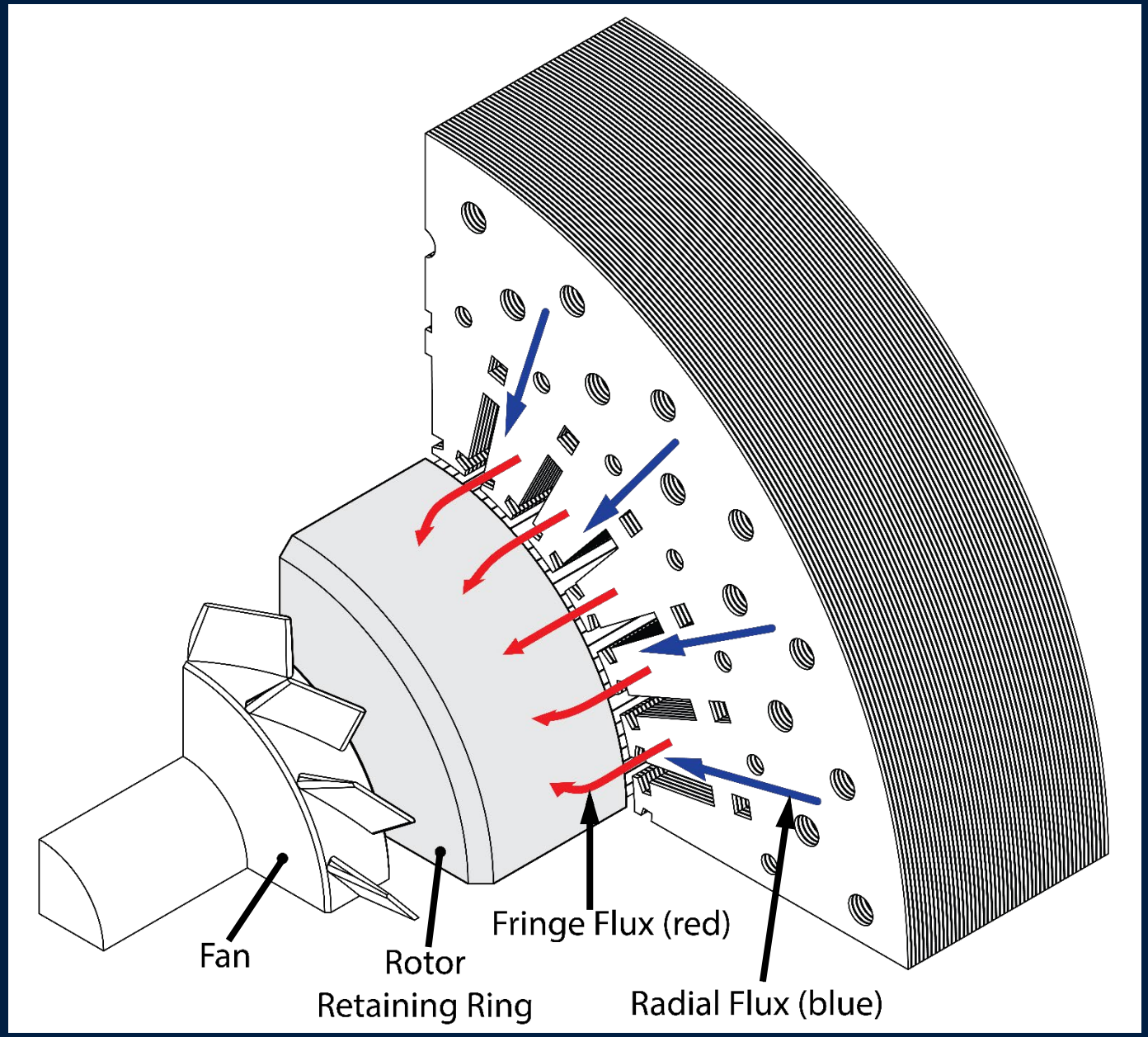
Generator Capability Curve

1. I^2R rotor heating
2. I^2R stator heating
3. End-iron heating for a round rotor or stability for a salient-pole generator



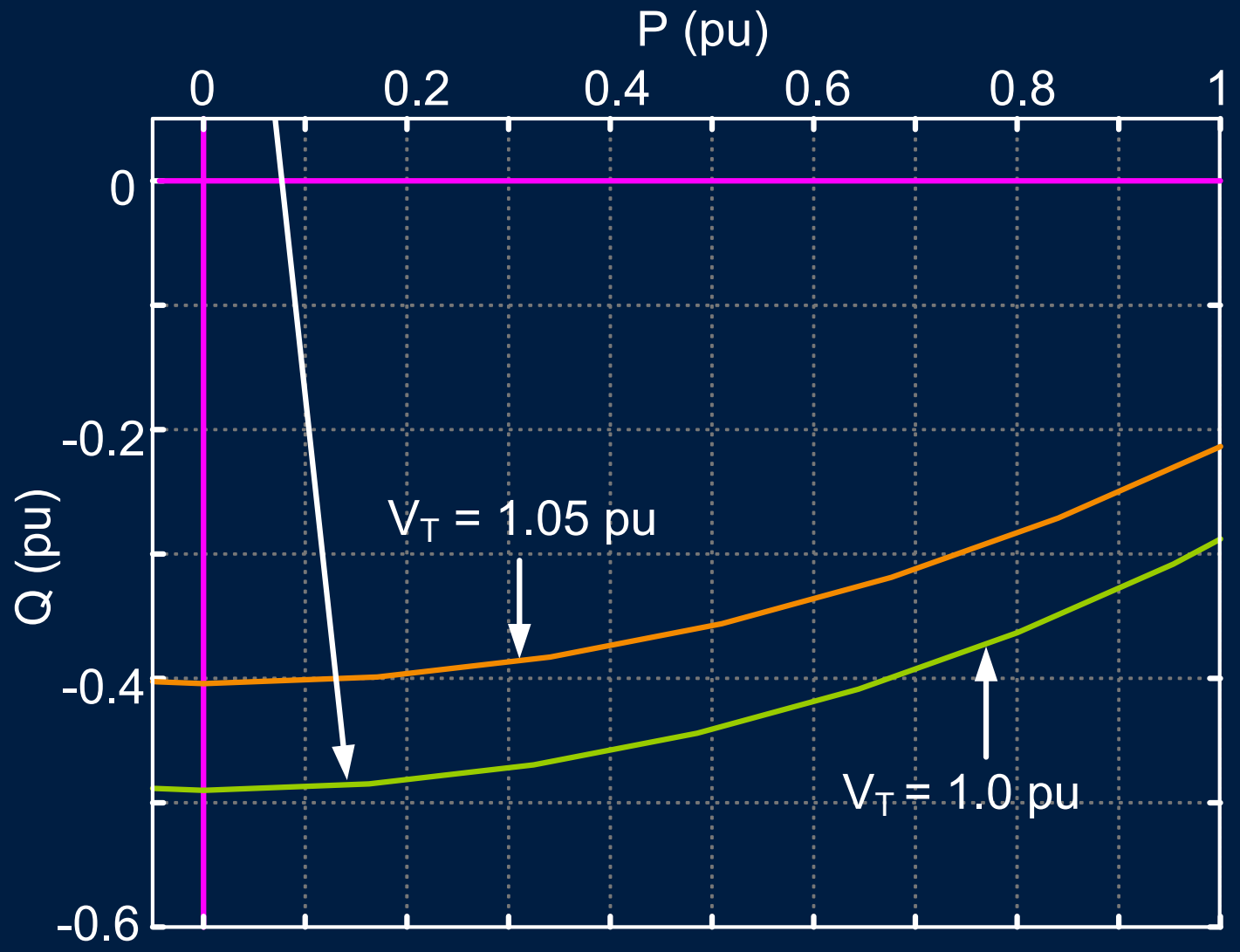
Fringe Flux Increases During LOF Conditions



End-Core Heating Limit Varies With the Terminal Voltage

$$\text{Center}(P,Q) = \left(0, \frac{k_1 \bullet V_T^2}{X_d}\right)$$

$$\text{Radius} = \frac{k_2 \bullet V_T}{X_d}$$

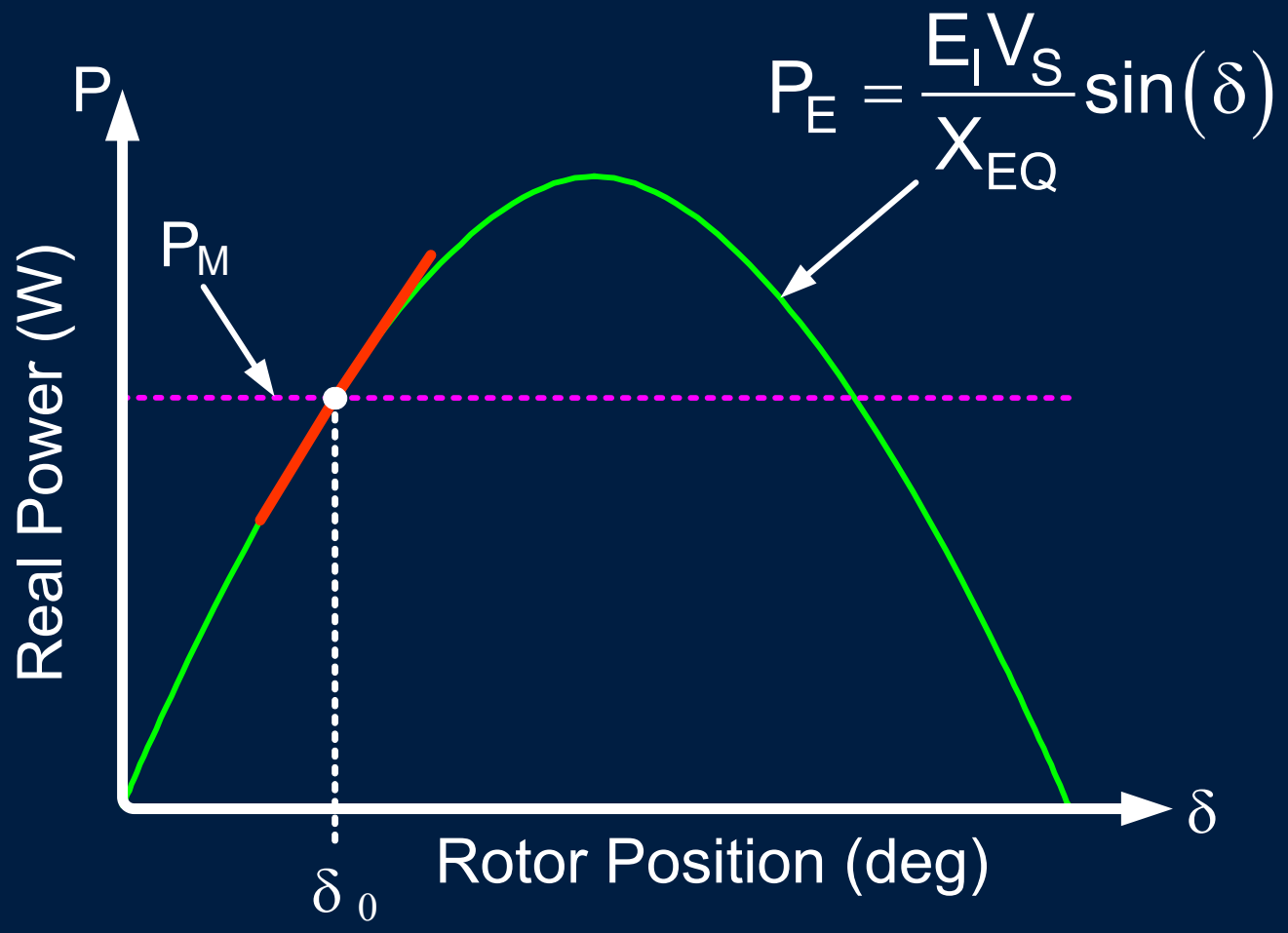


Steady-State Stability Limit (SSSL)

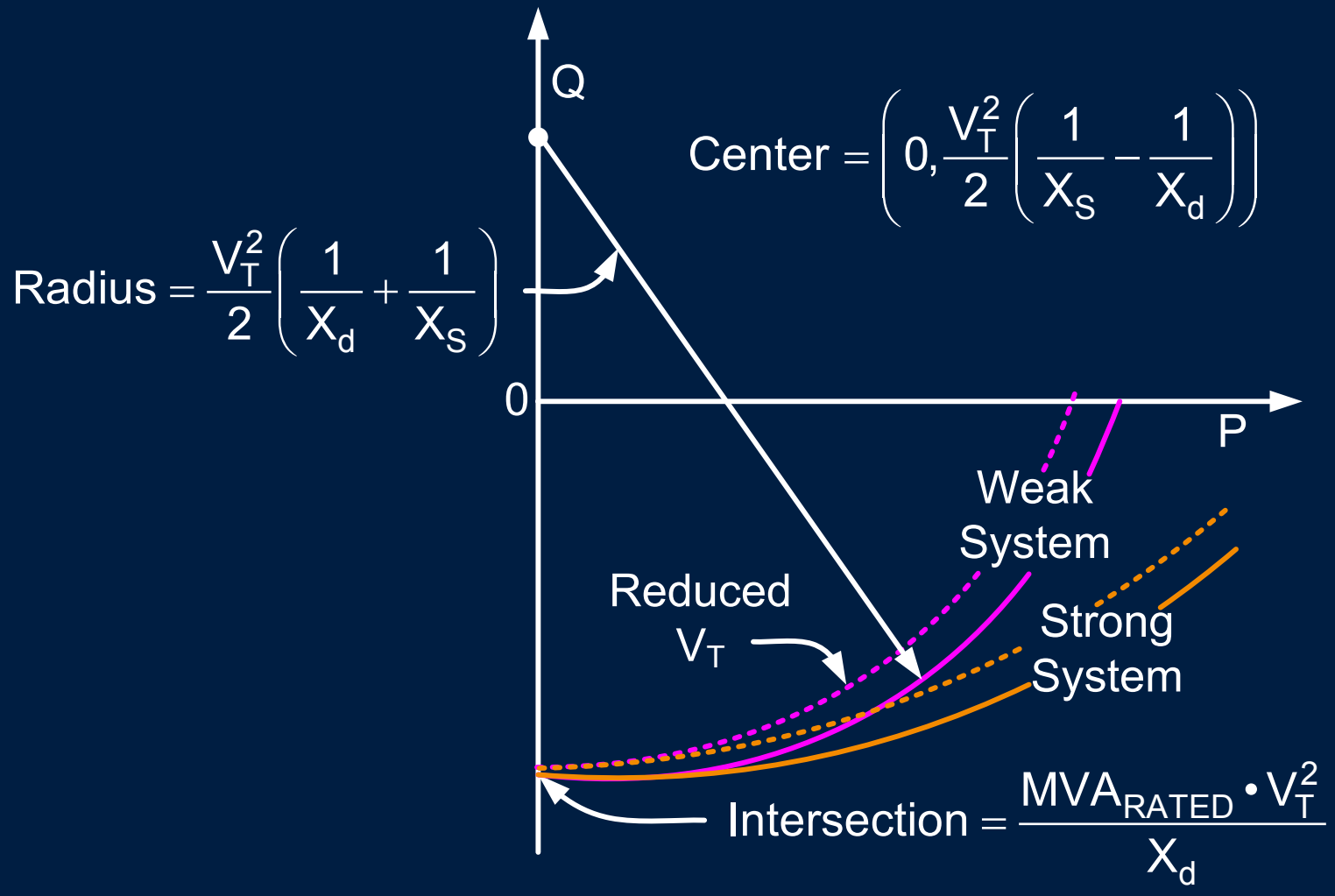
SSSL is

- valid when the automatic voltage regulator (AVR) is in manual mode
- not valid during transients due to changes in X_d

Loss of SSSL rarely occurs with modern AVRs

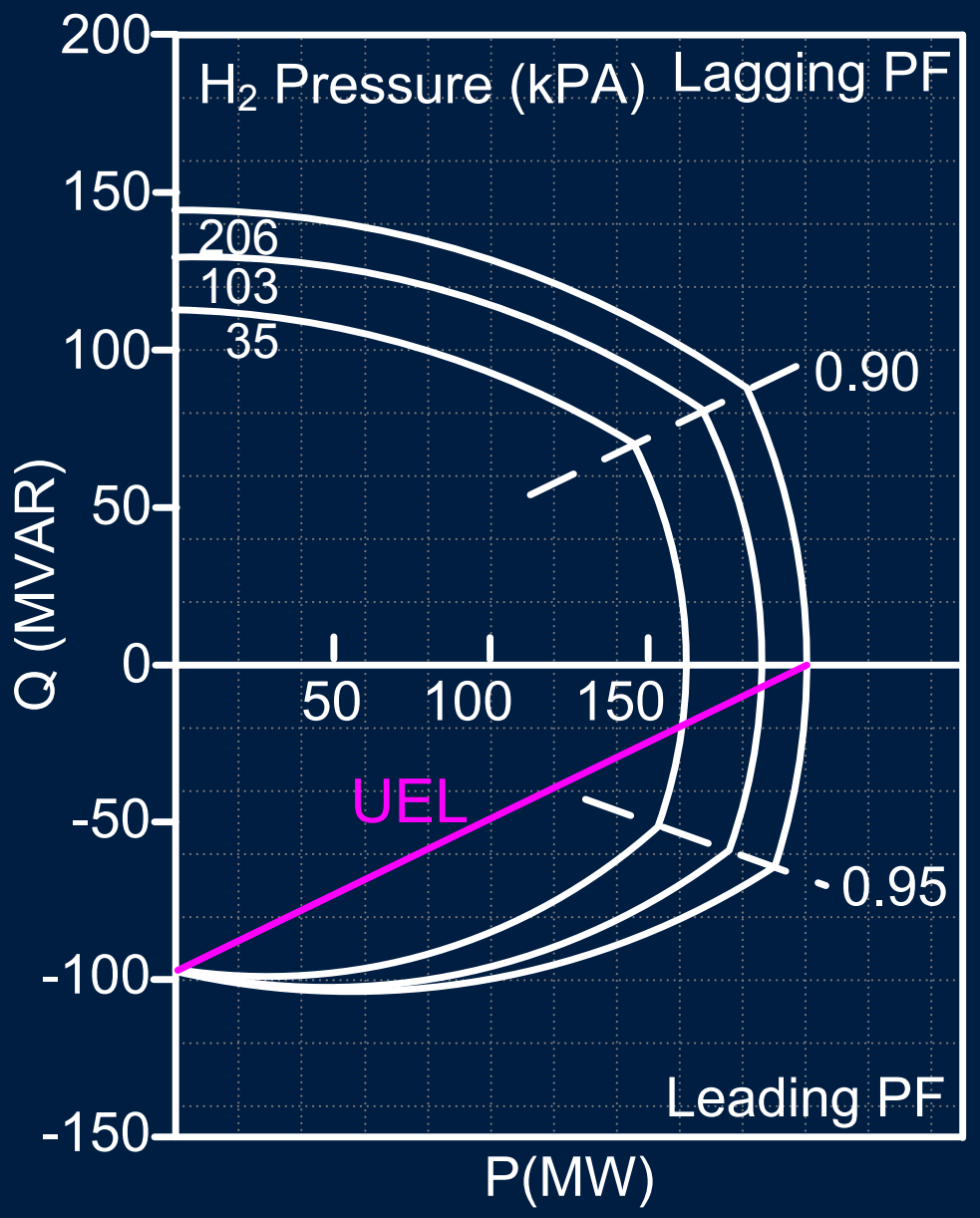


SSSL Varies With Terminal Voltage and System Impedance

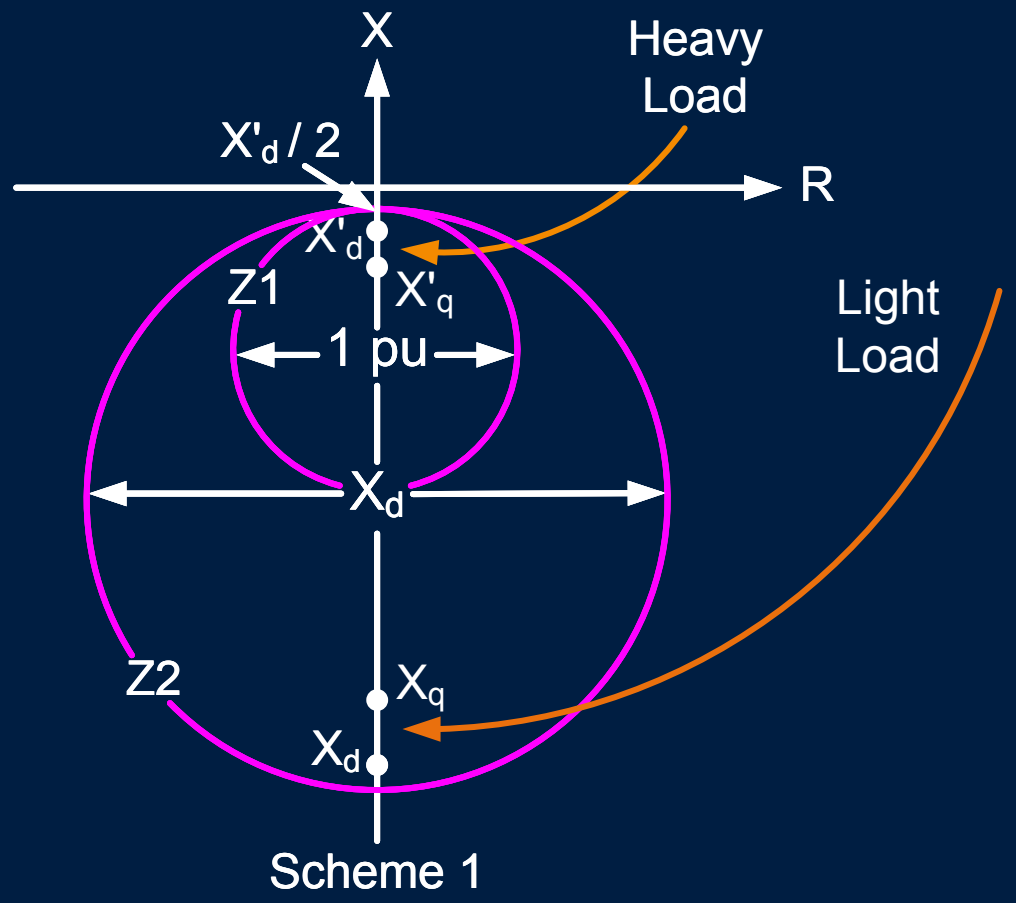


Underexcitation Limiter

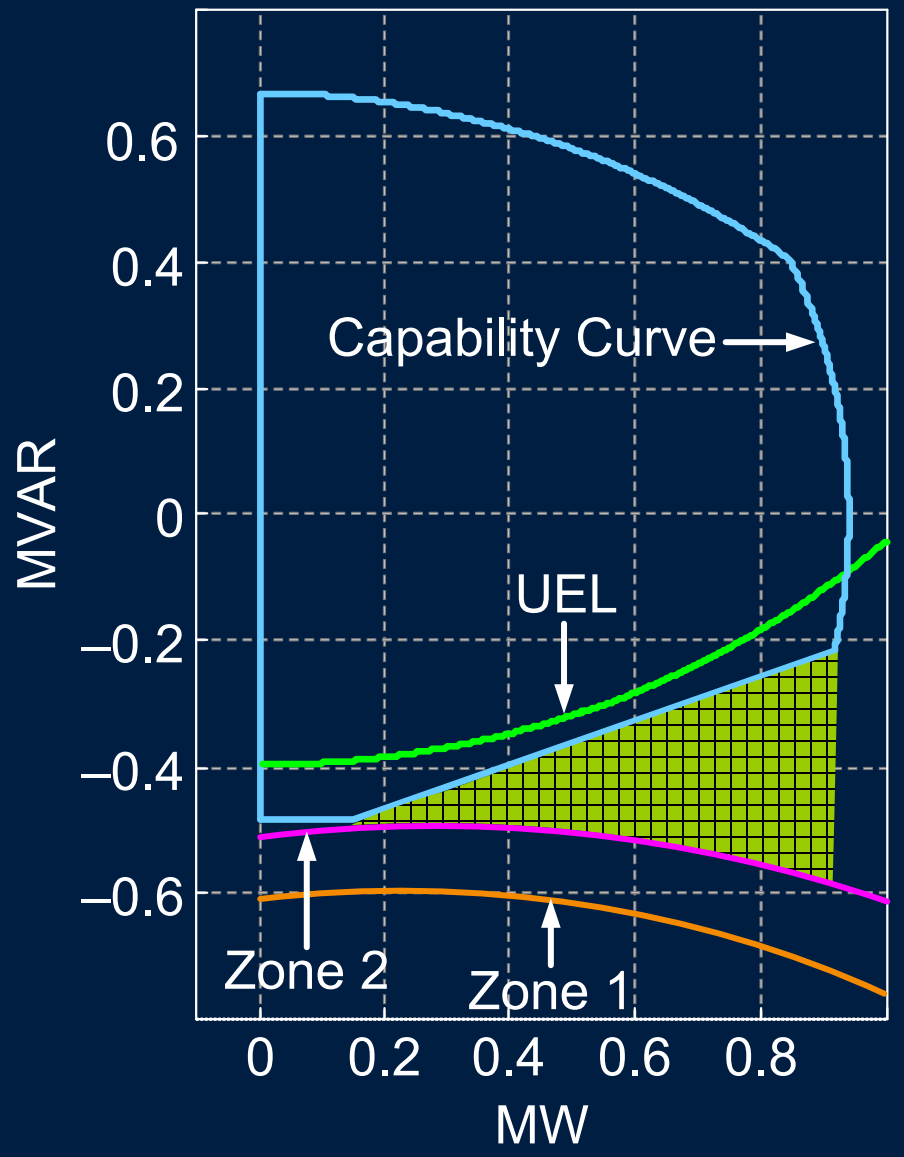
- The UEL acts to increase the V_T setpoint to prevent generator underexcitation
- The UEL should coordinate with SSSL and end-core heating
- The UEL can change based on
  - V_T^K, where K = 0, 1, or 2
  - Coolant pressure/temperature



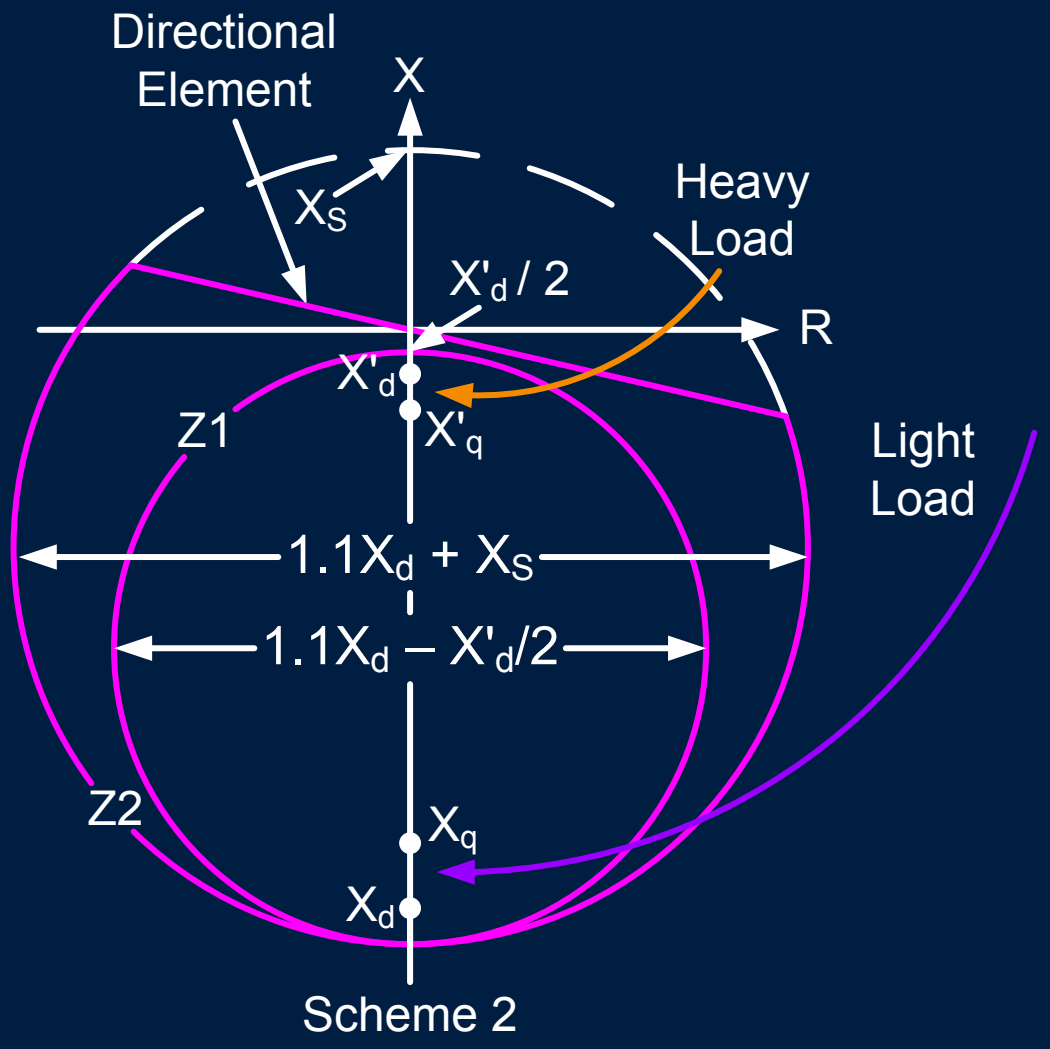
LOF Element – Impedance Plane



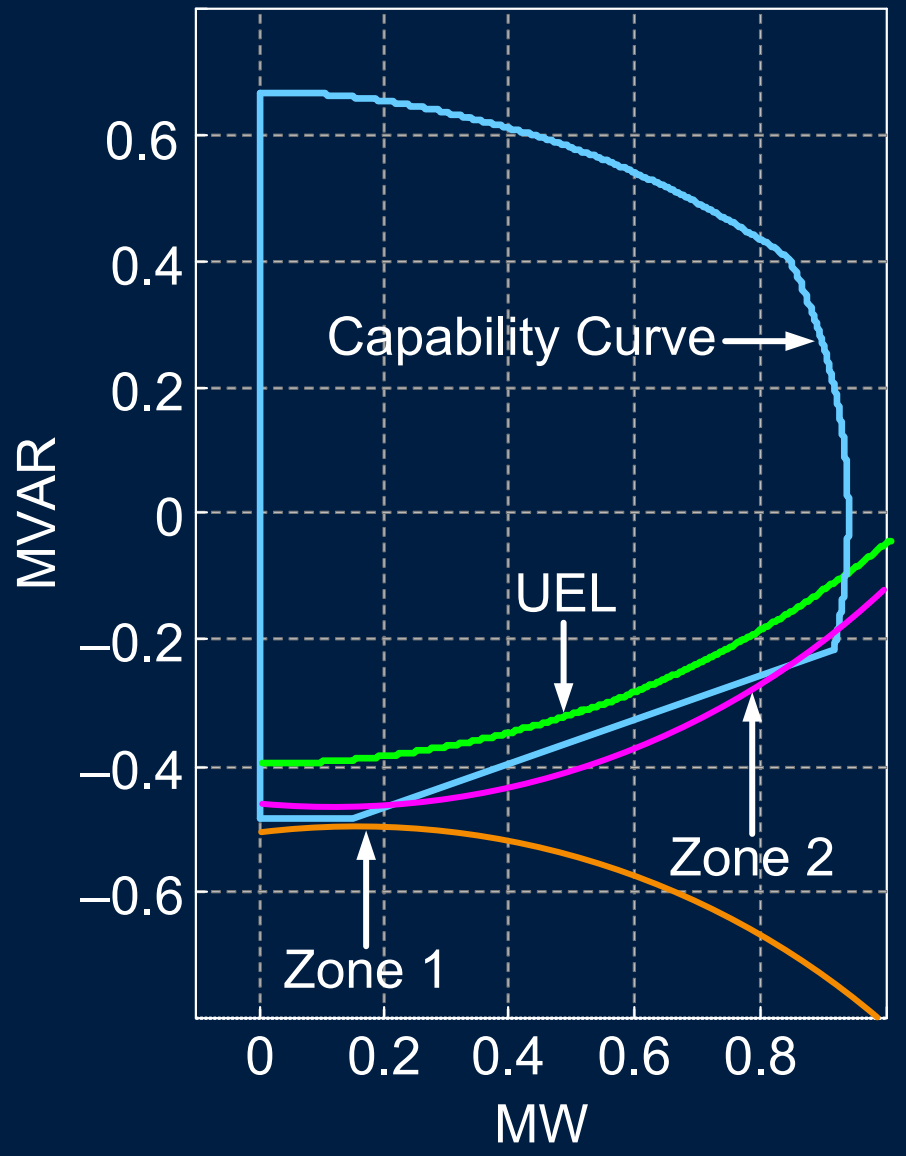
LOF Protection – Impedance Scheme 1



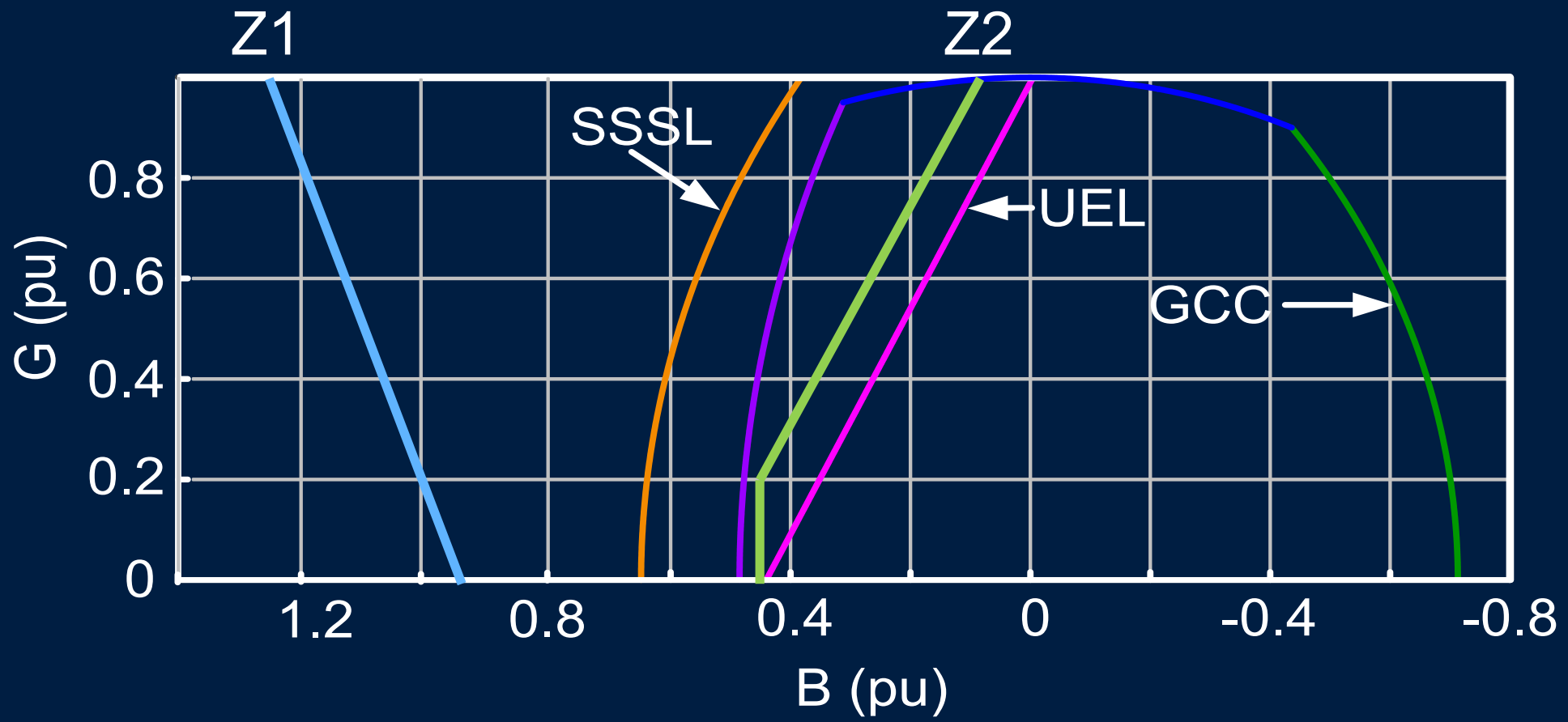
LOF Element – Impedance Plane



LOF Protection – Impedance Scheme 2



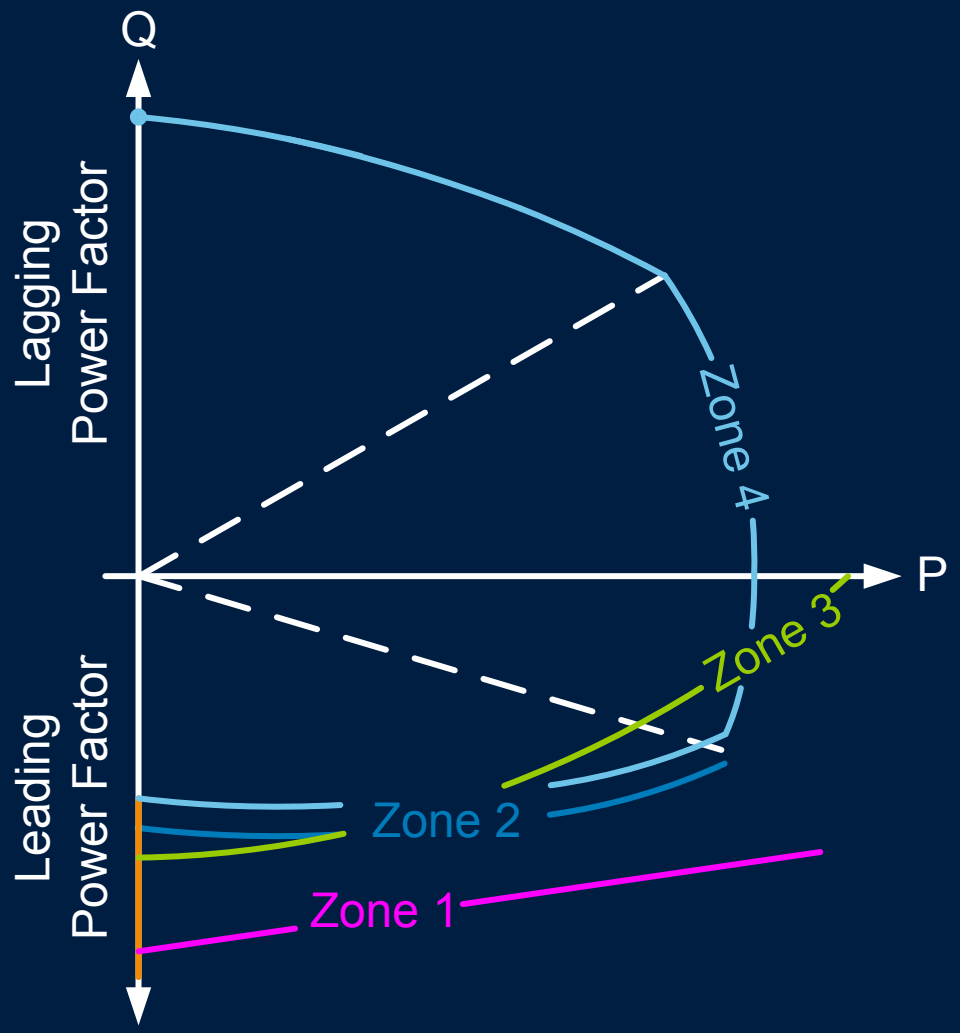
LOF Protection in the Admittance Plane



- The admittance plane preserves the shape of GCC
- GCC varies with voltage
- SSSL is fixed

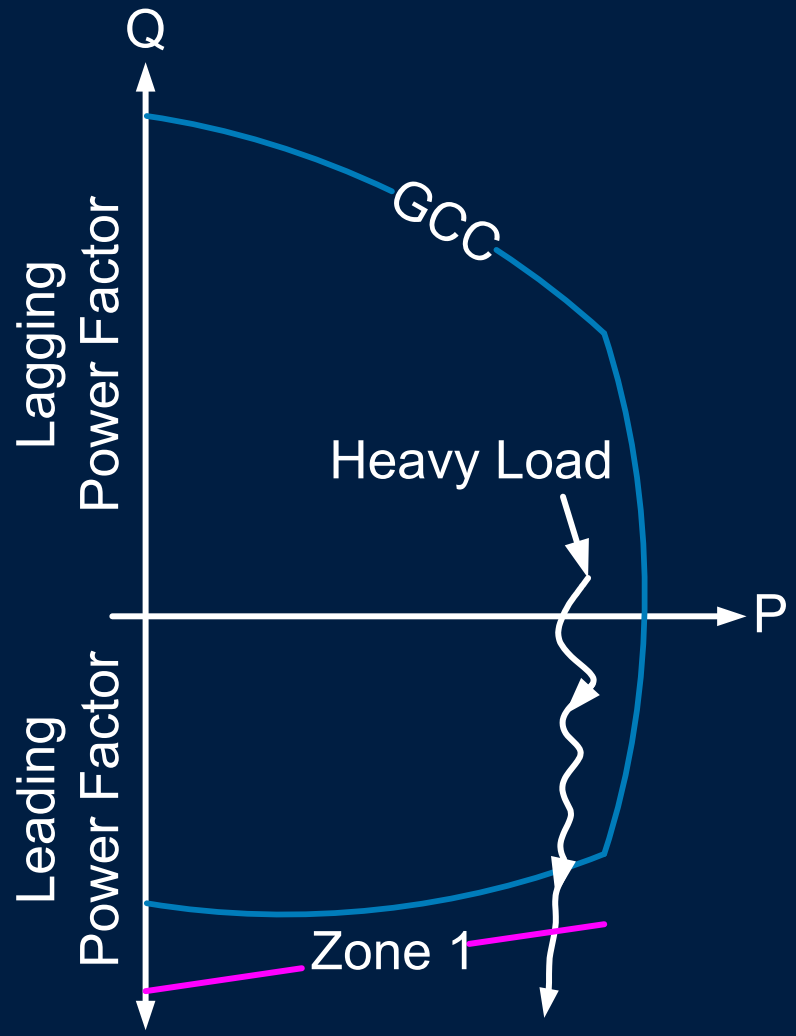
GCC-Based LOF Protection and Monitoring

- Zone 1 operates quickly for severe events
- Zone 2 coordinates with the UEL
- Zone 3 provides an alarm for operating point encroachment on SSSL
- Zone 4 provides an alarm for generator operation near GCC limits



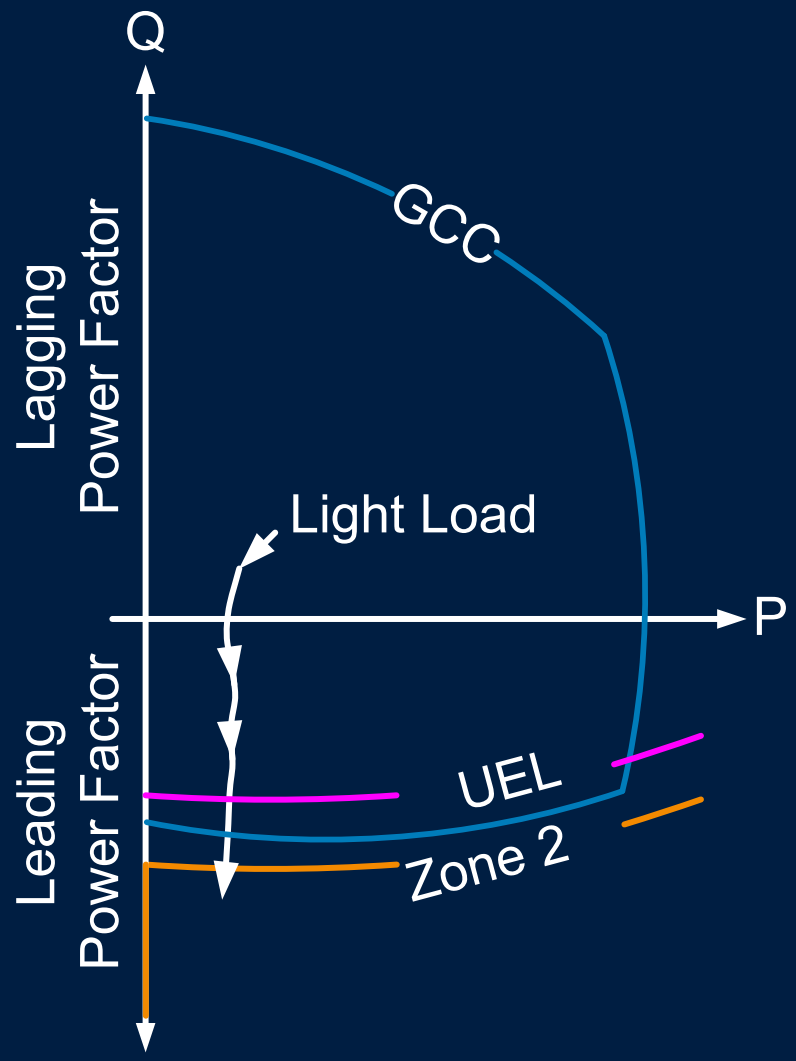
Zone 1 Operates for Severe LOF Conditions

- Operates for LOF at heavy loading conditions
- Is set in the power plane but operates in the admittance plane
- Can be set similarly to traditional approaches



Zone 2 Coordinates With UEL

- UEL can have a curved or multi-segmented characteristic
- Zone 2 element matches the shape of the UEL and varies with V_T^K , where K = 0, 1, or 2
- Zone 2 element includes an accelerated path for undervoltage conditions



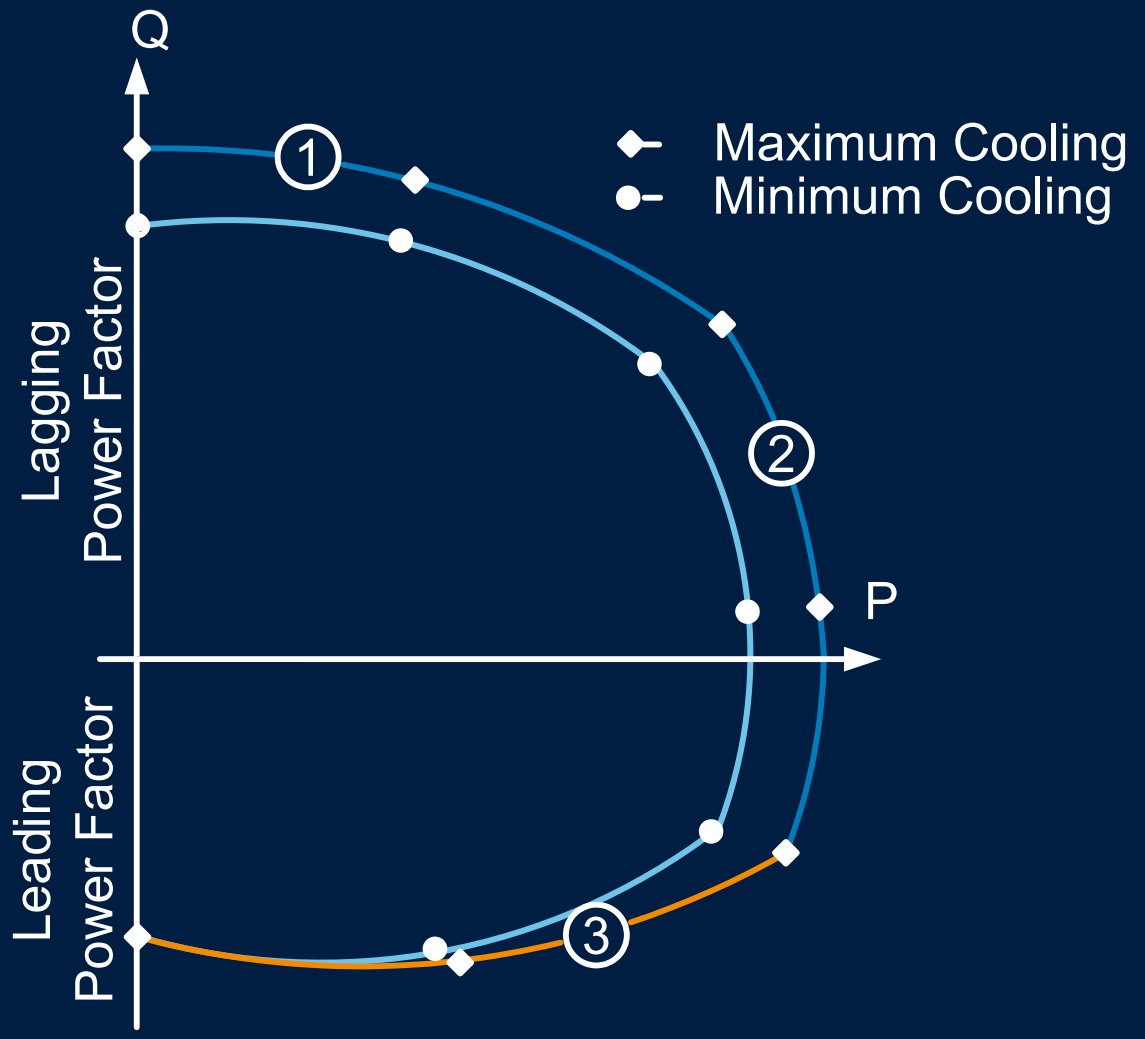
Zone 3 Is Dedicated to Coordinate With SSSL

- Implements the SSSL equation by using only X_d and X_S
- Varies with V_T^2
- Alarms when the PQ locus crosses the SSSL
- Trips when the PQ locus crosses the SSSL AND the AVR is in manual mode OR V_T collapses

$$Z3_{pu} = \mathrm{Re}\left(\left(S - \frac{j3 \bullet V_T^2}{X_S}\right) \bullet \left(\frac{-j3 \bullet V_T^2}{X_d} - S\right)^*\right)$$

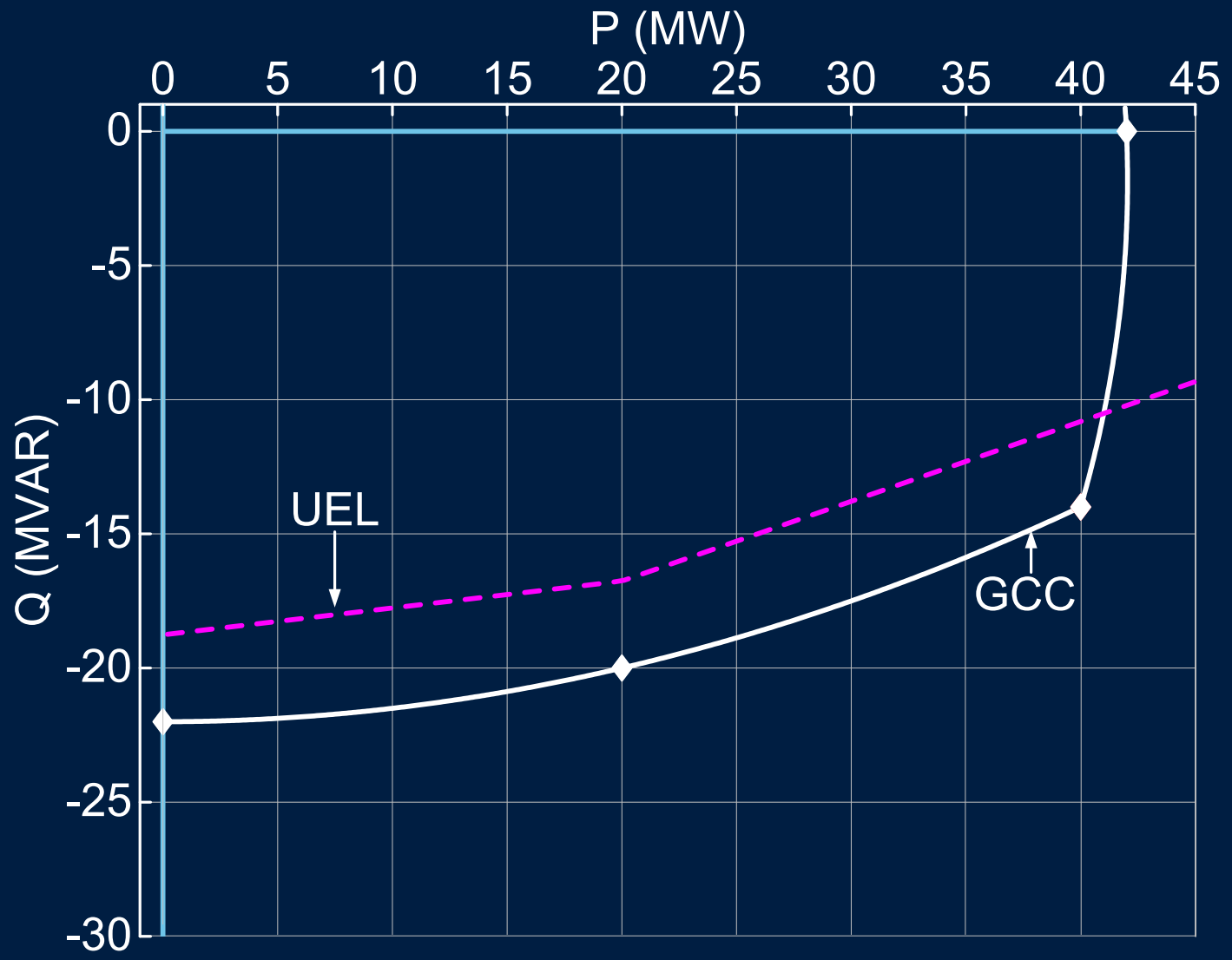
Zone 4 Monitors GCC Limits

- Is set based on GCC
- Adapts to changes in cooling capabilities
- Alarms for any segment violation



UEL With Static Characteristic in the Power Plane

K = 0 at V_T = 1.00 pu



UEL With Static Characteristic in the Power Plane

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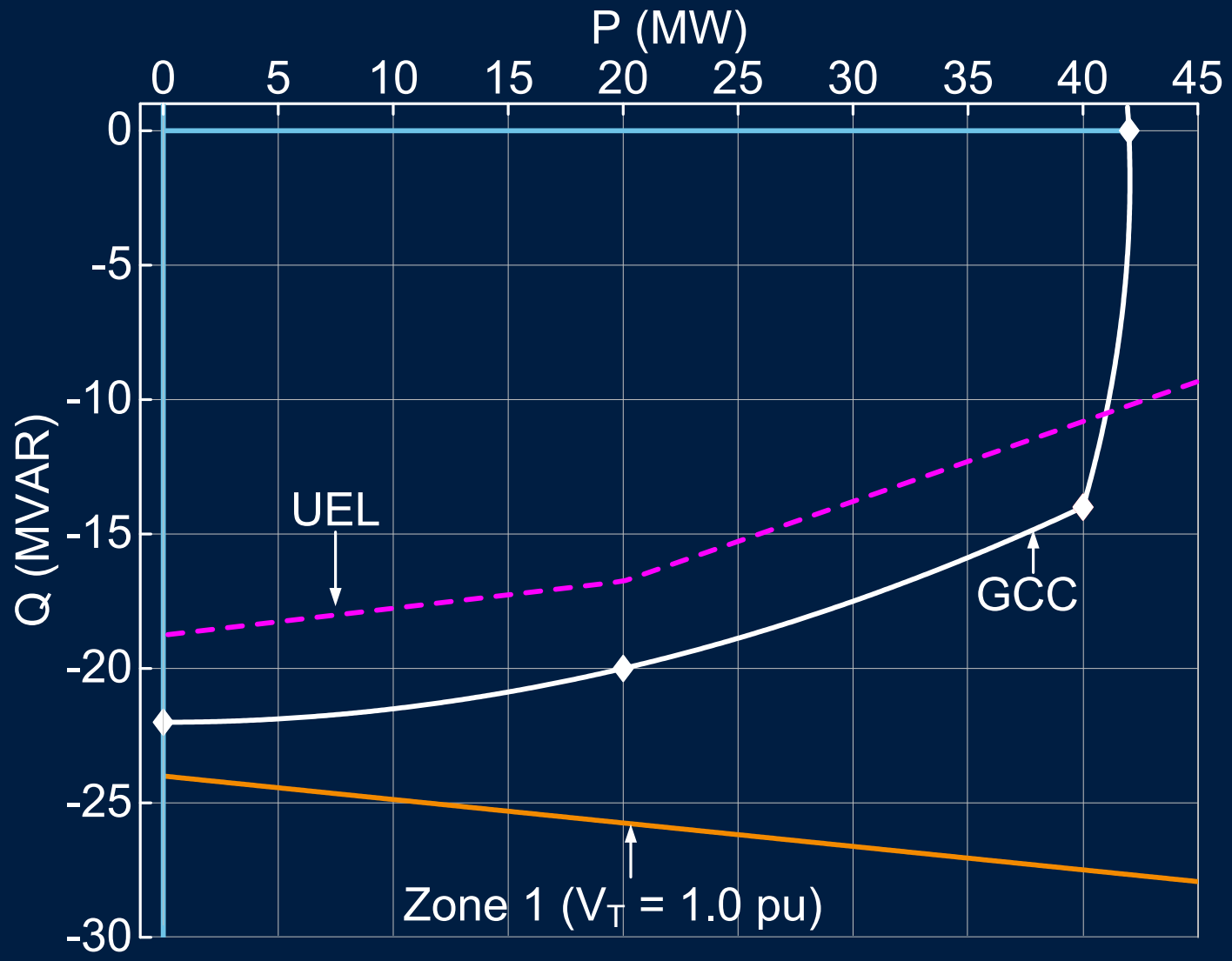
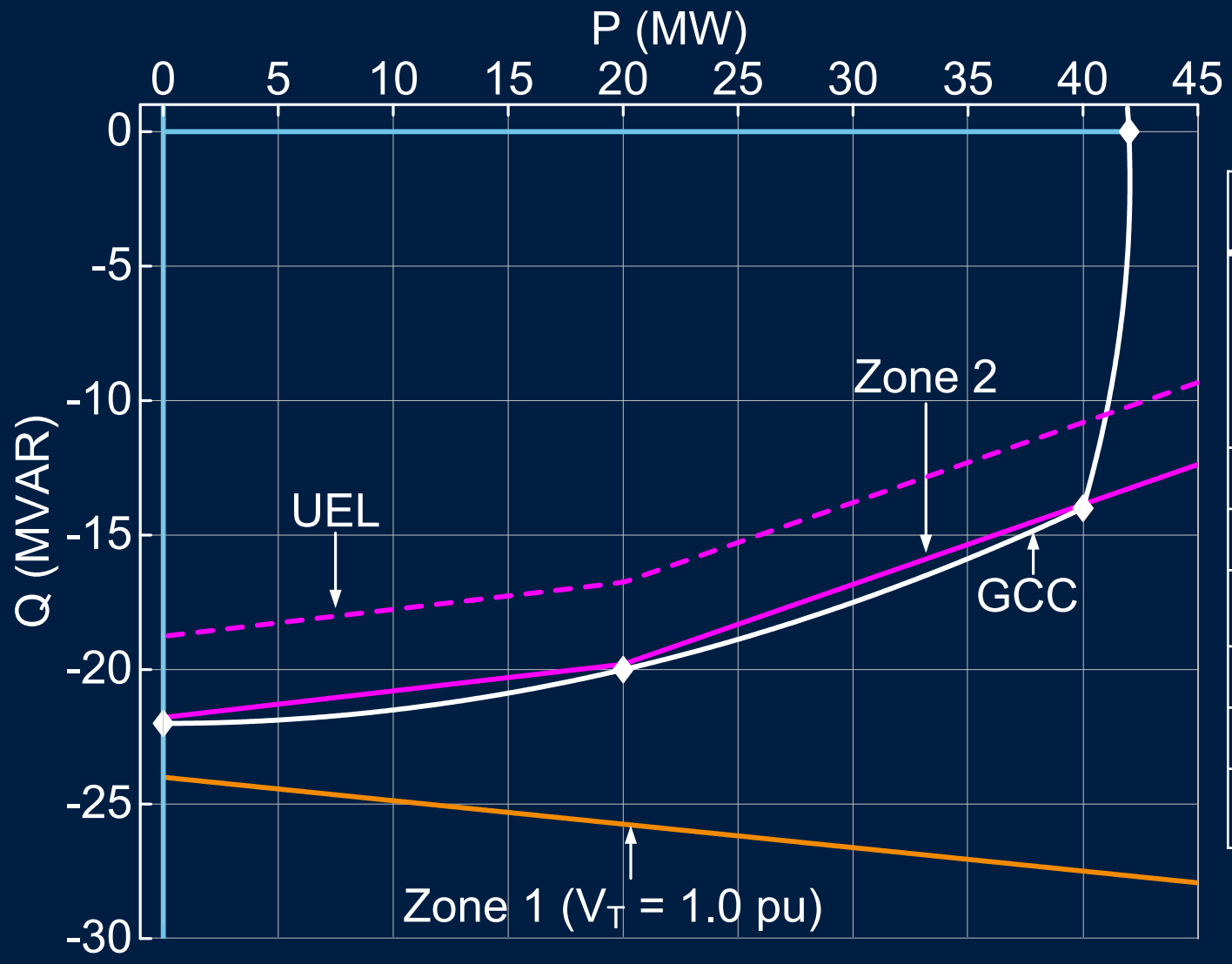


Zone 1 Per Impedance Scheme 2	
Zone 1 Settings	**Value (pu)**
40P1P	0.6 pu
Tilt	–5 deg

UEL With Static Characteristic in the Power Plane

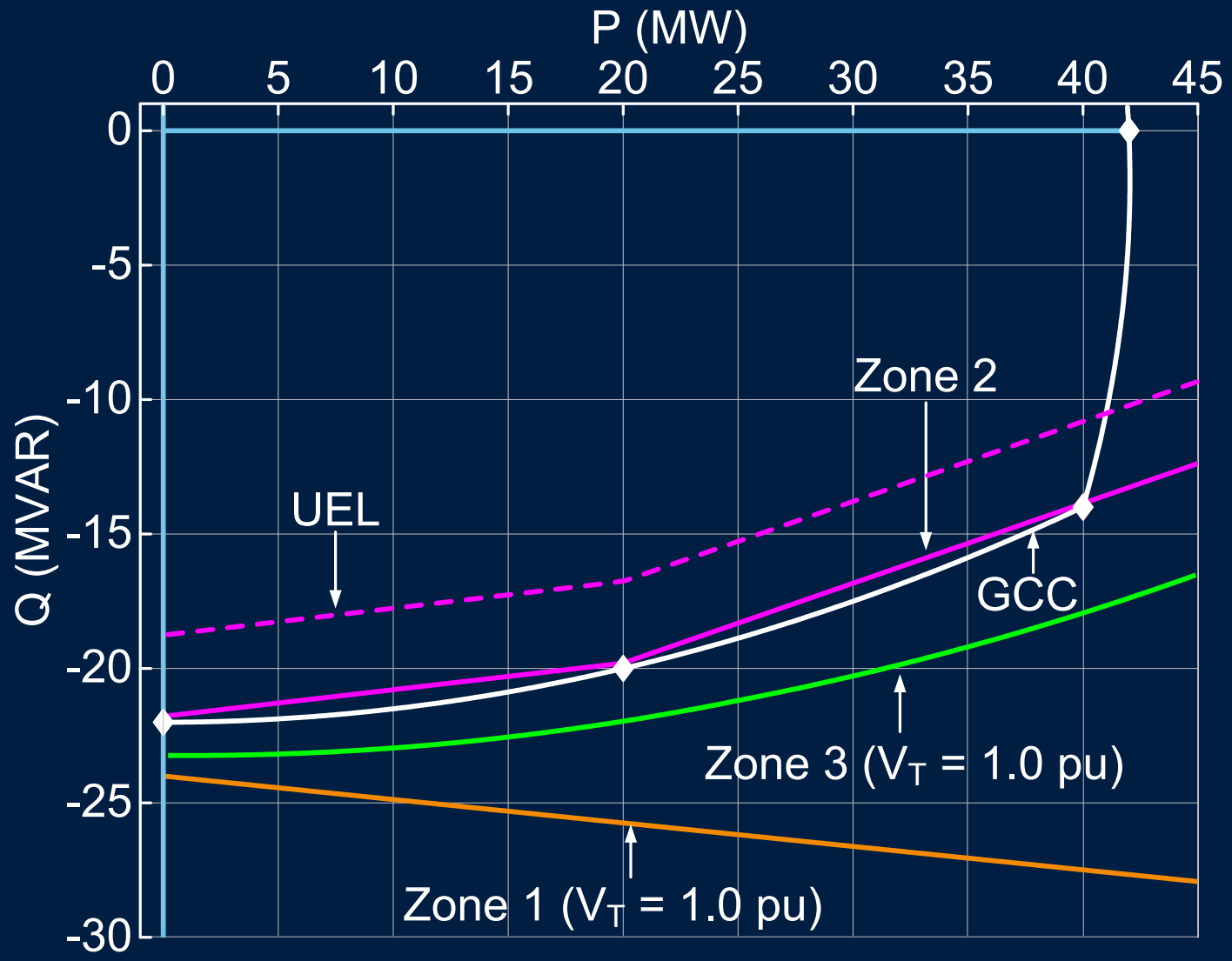
K = 0 at V_T = 1.00 pu



Coordination of UEL and Zone 2 Characteristics		
UEL Settings in AVR [P, Q] (Primary)	**Zone 2 Settings**	**Value (Primary)**
[40, –12.6]	[UELP1, UELQ1]	[40, –12.6]
[20, –18]	[UELP2, UELQ2]	[20, –18]
[0, –19.8]	[UELP3, UELQ3]	[0, –19.8]
	Margin	10%
	Characteristic	Linear
	Voltage Dependency (k)	0

UEL With Static Characteristic in the Power Plane

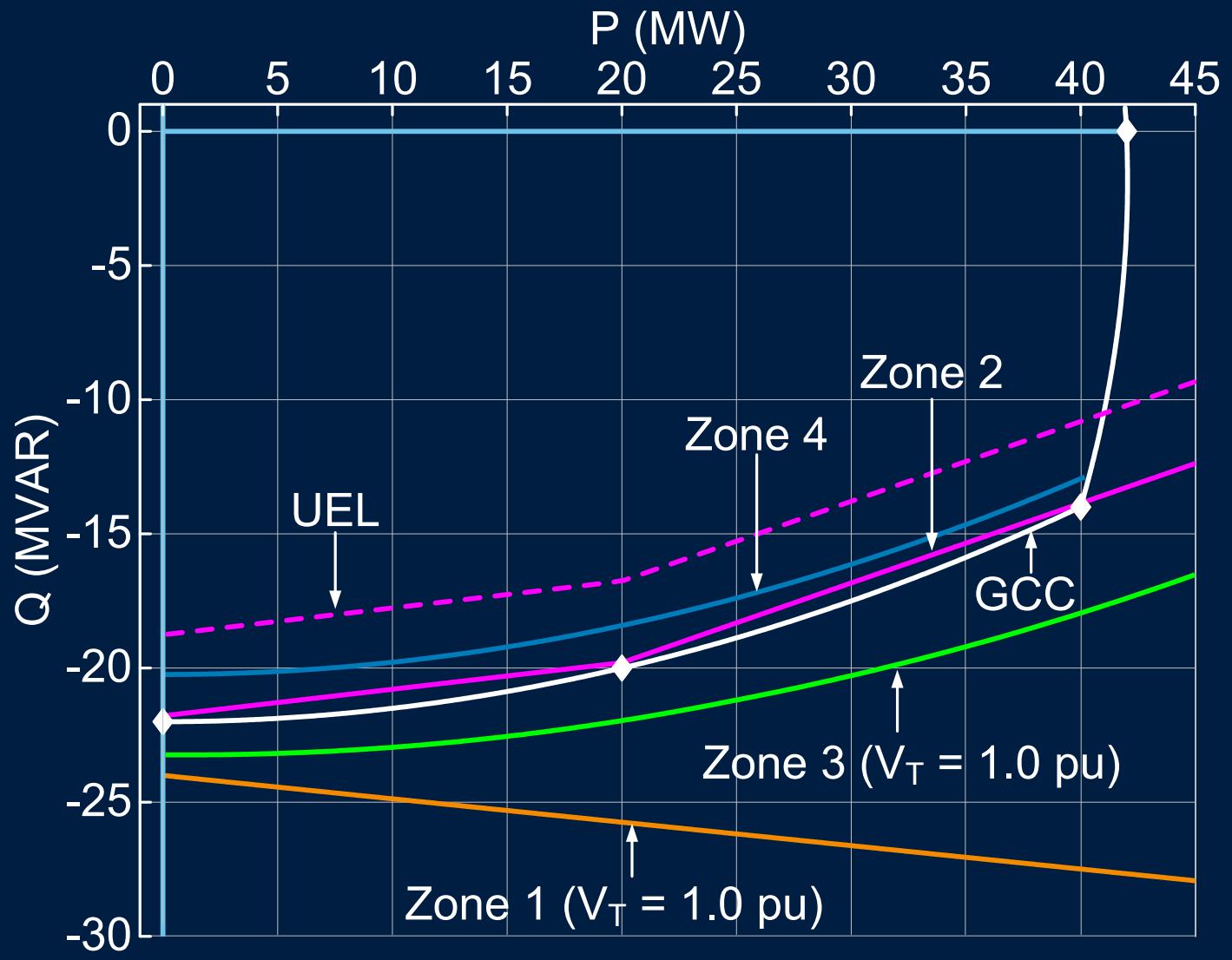
K = 0 at V_T = 1.00 pu



SSSL Characteristic	
Zone 3 Settings	**Value (pu)**
X_d	1.8
X_S	0.2
Voltage Acceleration	0.8

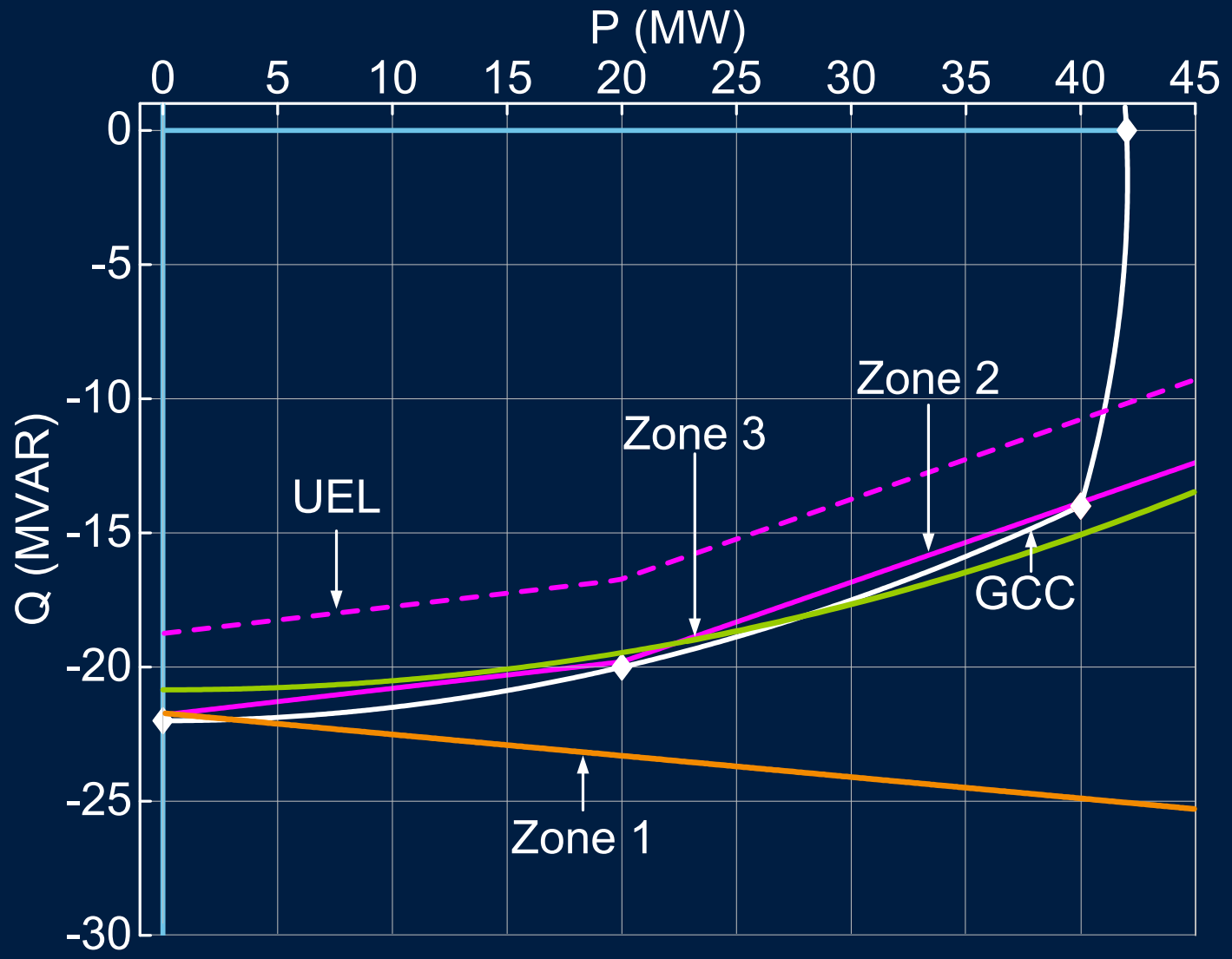
UEL With Static Characteristic in the Power Plane

K = 0 at V_T = 1.00 pu



UEL With Static Characteristic in the Power Plane

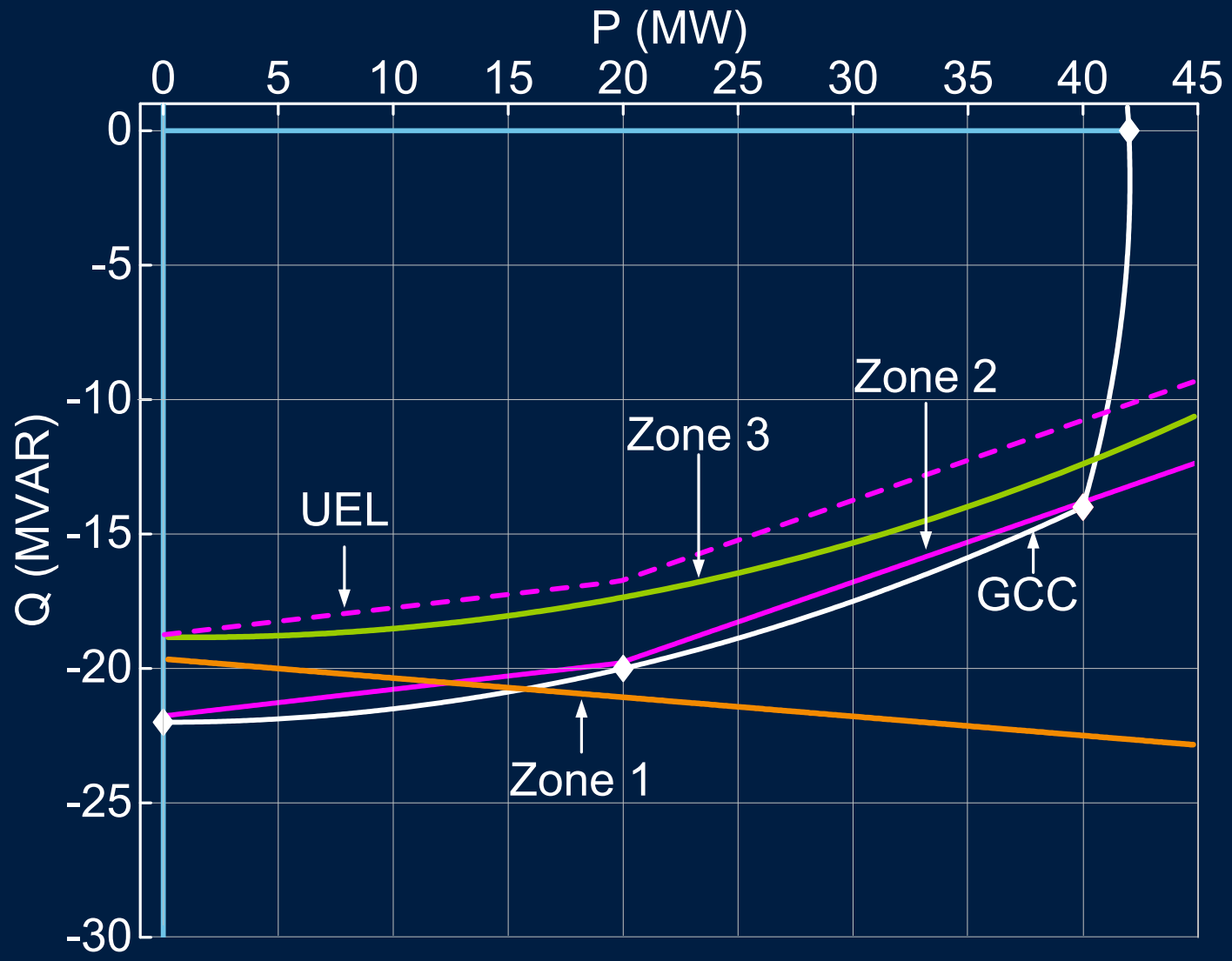
K = 0 at V_T = 0.95 pu



- UEL, Zone 2, and Zone 4 are static
- Zone 1 and Zone 3 change in direct proportion to V_T^2

UEL With Static Characteristic in the Power Plane

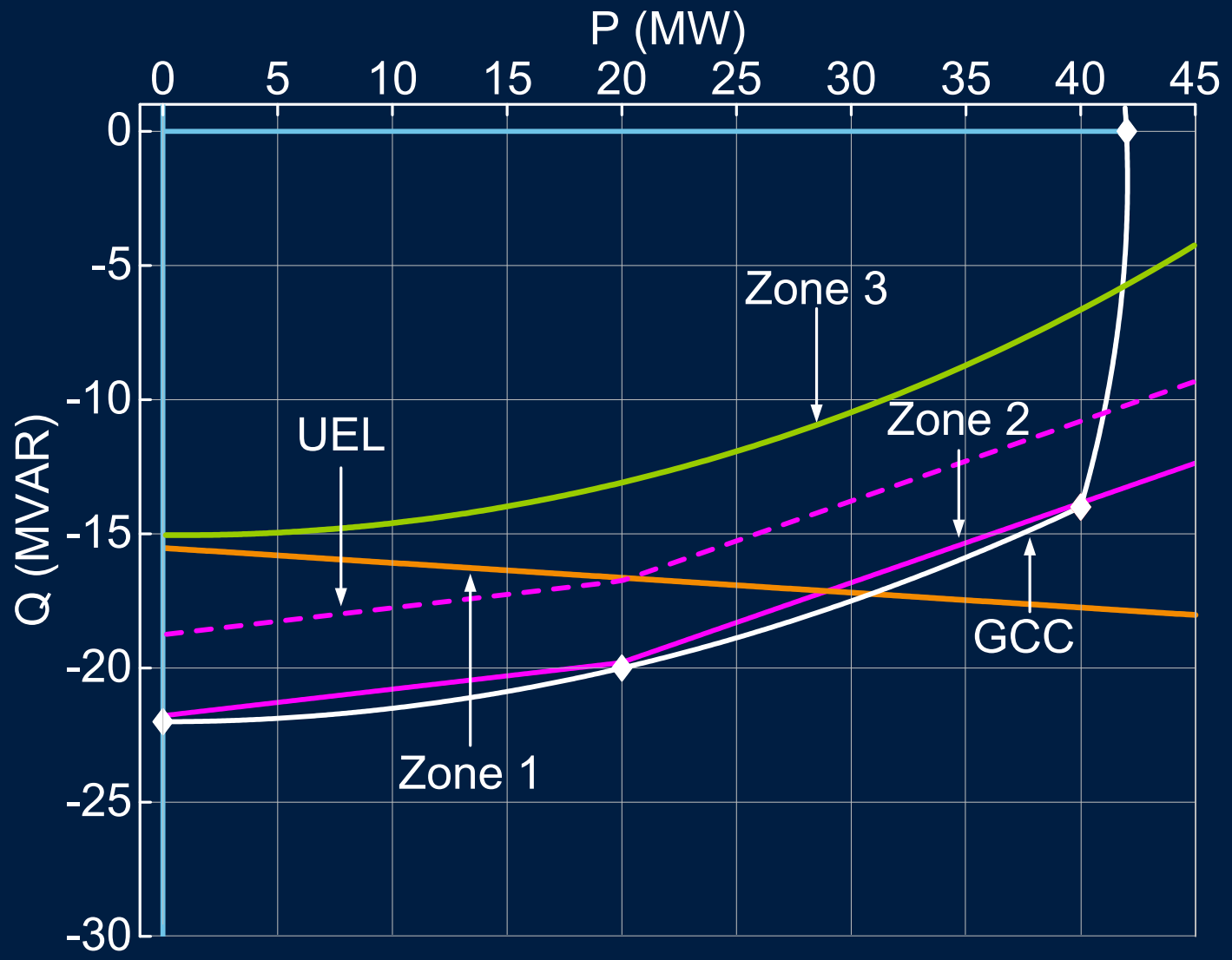
K = 0 at V_T = 0.90 pu



Zone 3 moves closer to UEL

UEL With Static Characteristic in the Power Plane

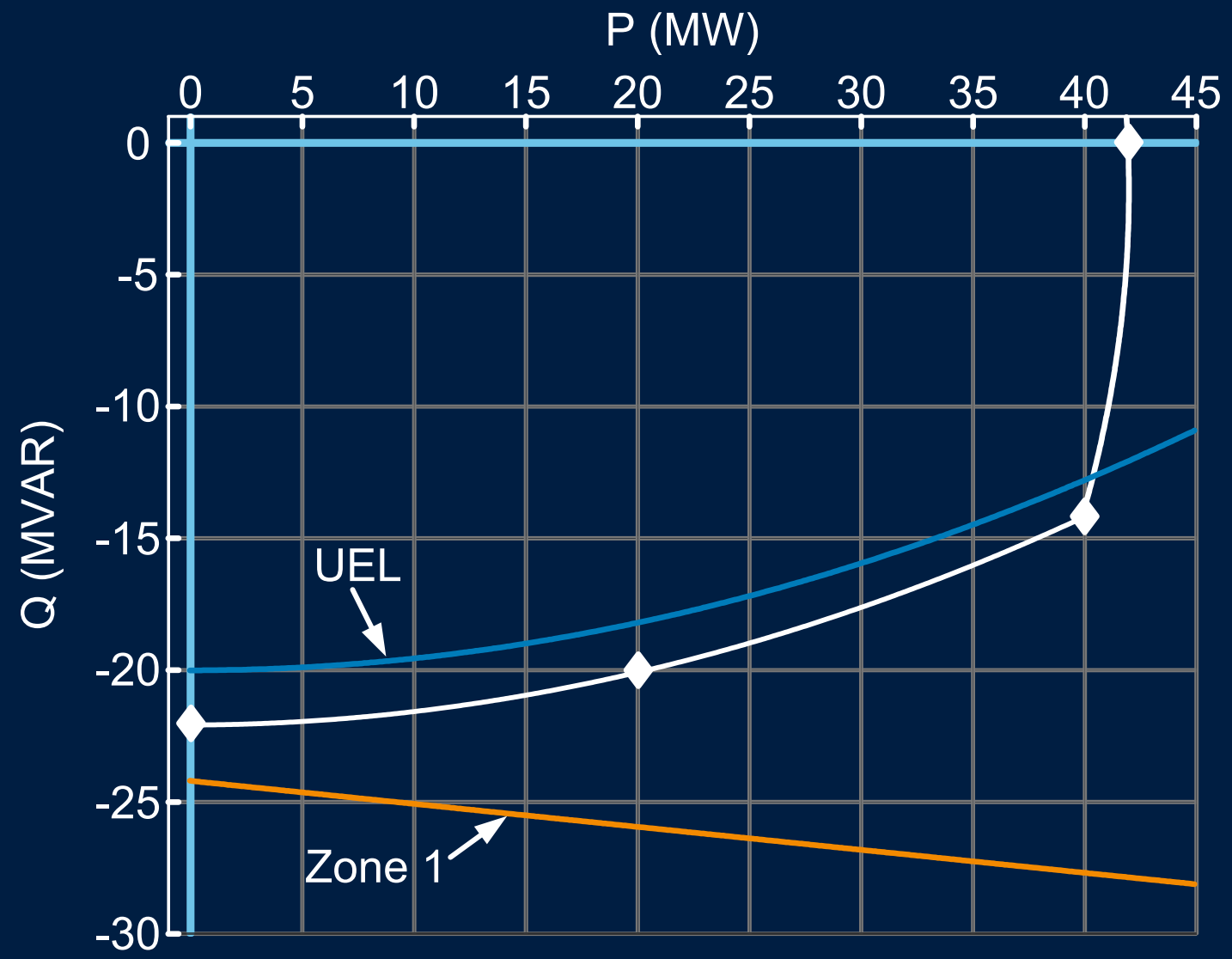
K = 0 at V_T = 0.80 pu



- LOF conditions for weak systems can lead to pole slipping
- Stable power swings can enter Zone 3 and Zone 1

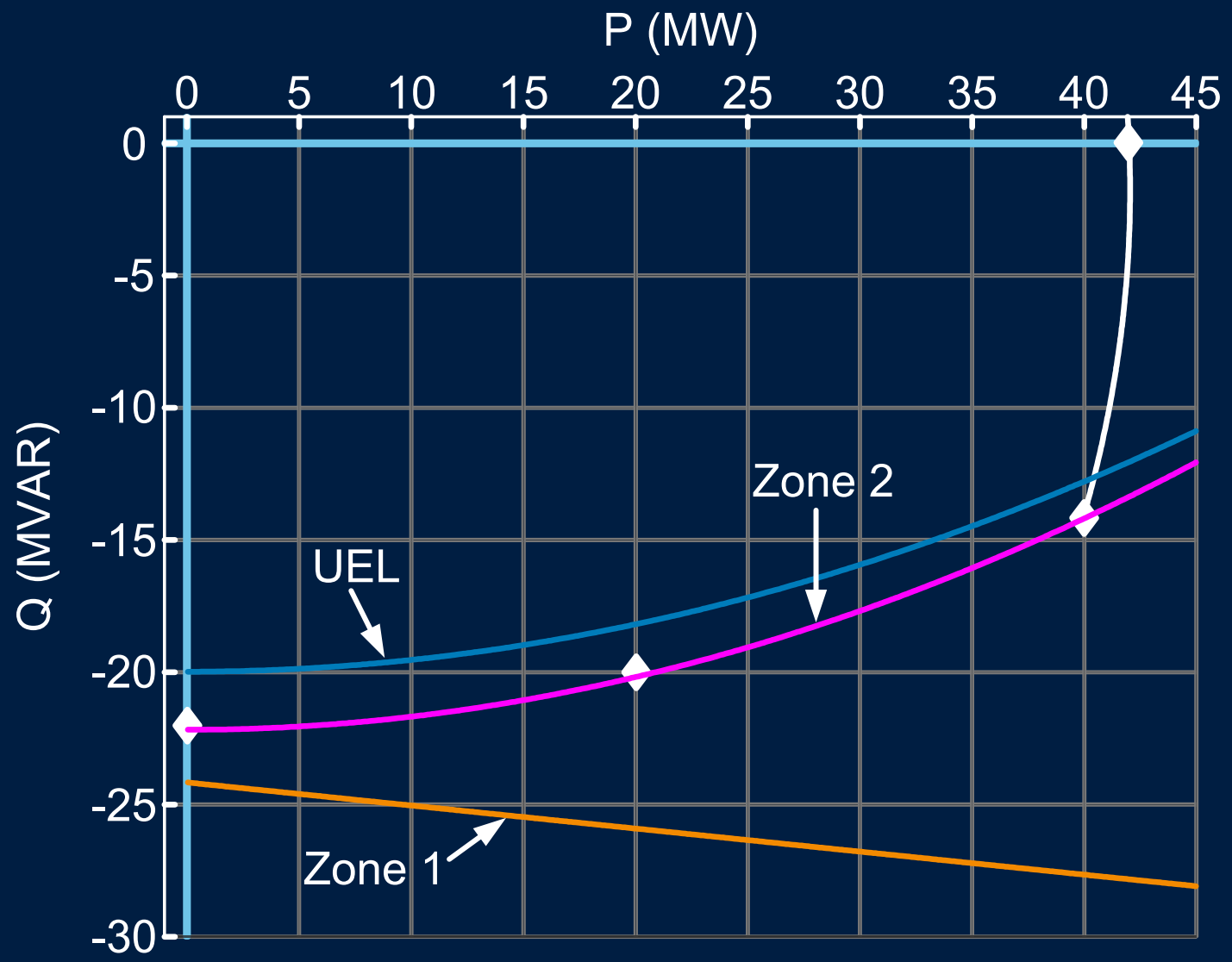
UEL With Dynamic Characteristic

K = 1 at V_T = 1.00 pu



UEL With Dynamic Characteristic

K = 1 at V_T = 1.00 pu



Coordination of UEL and Zone 2 Characteristics		
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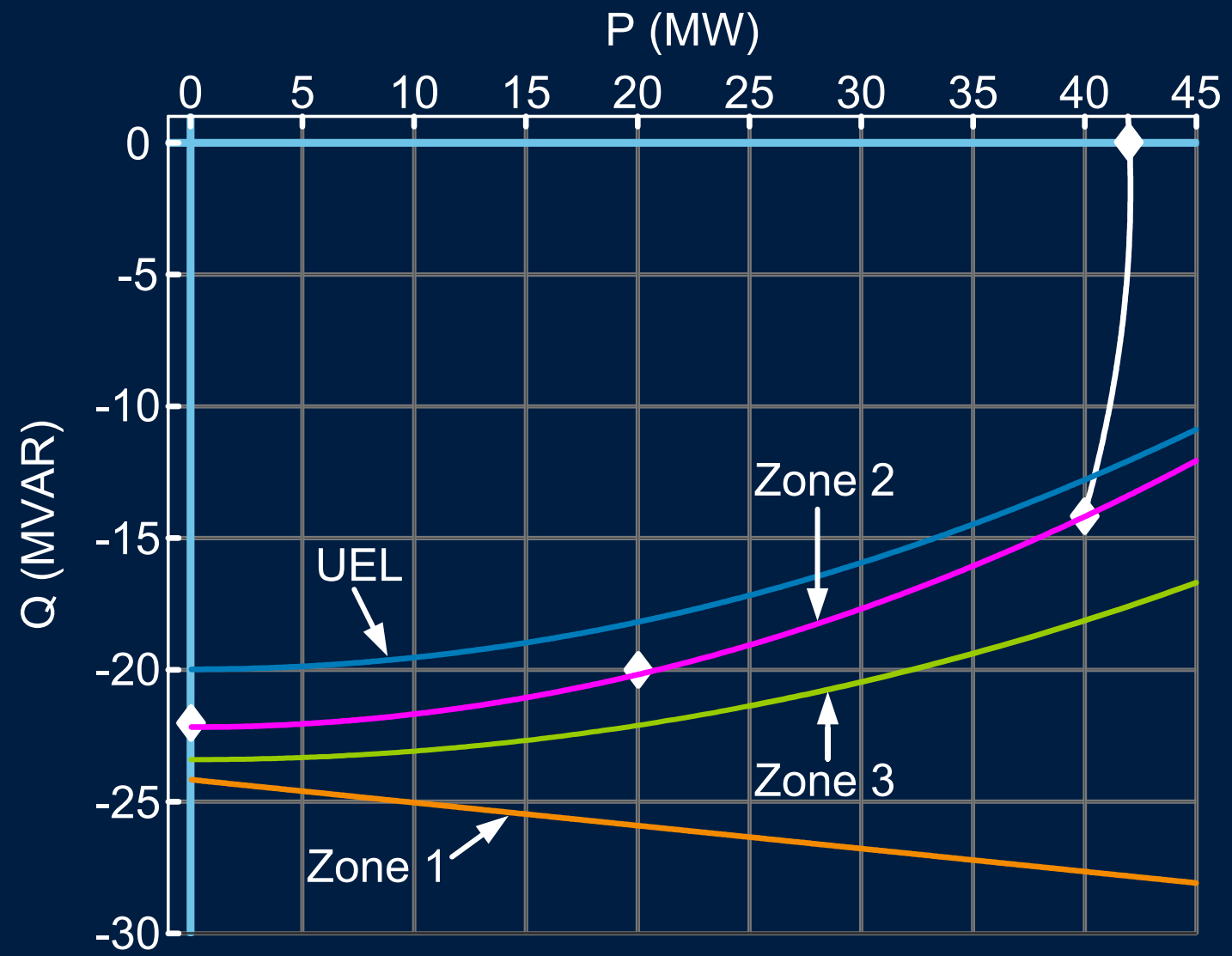
[20, –18]	[UELP2, UELQ2]	[20, –18]
[0, –19.8]	[UELP3, UELQ3]	[0, –19.8]
	Margin	10%
	Characteristic	Quadratic
	Voltage Dependency (k)	1

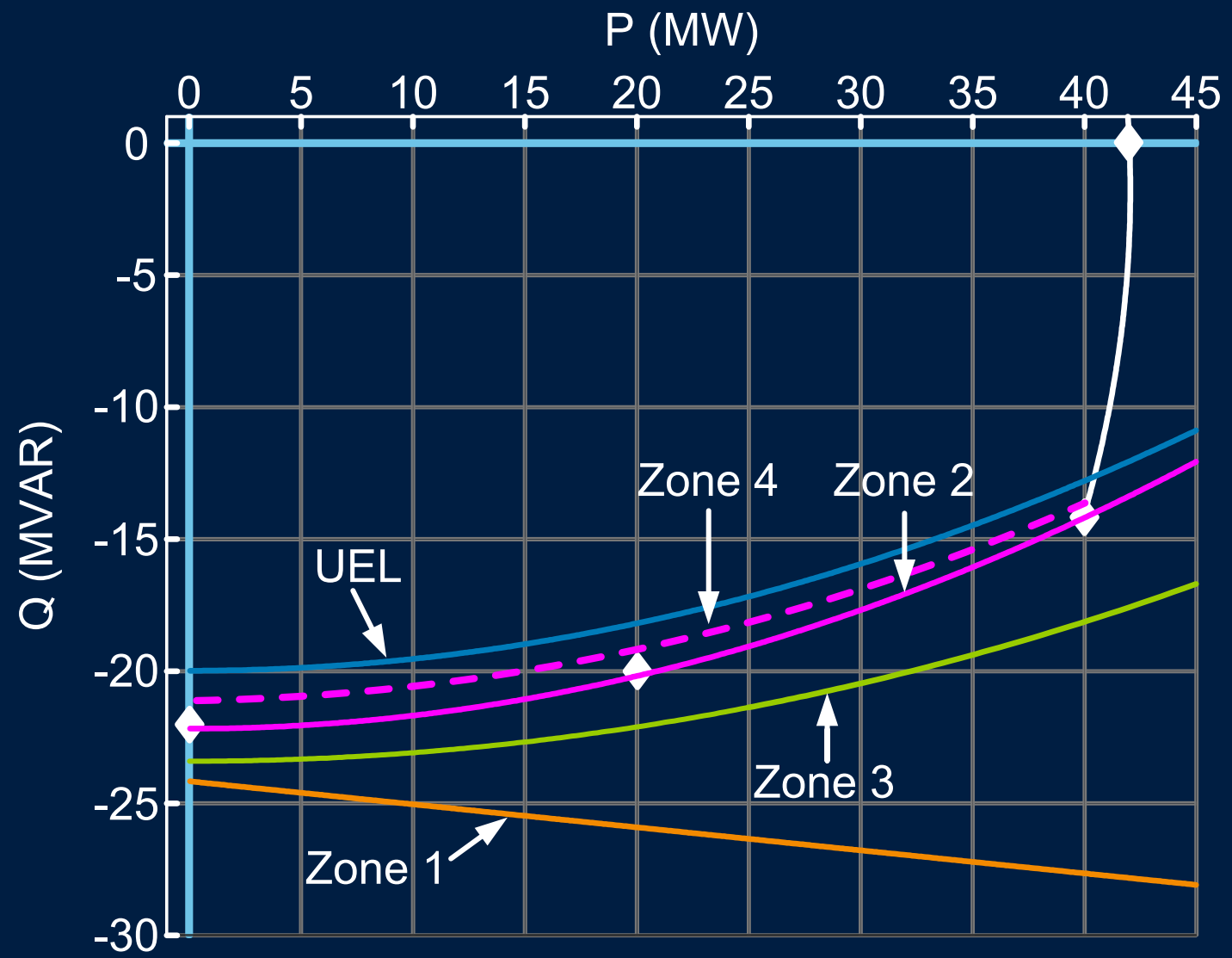
UEL With Dynamic Characteristic

K = 1 at V_T = 1.00 pu



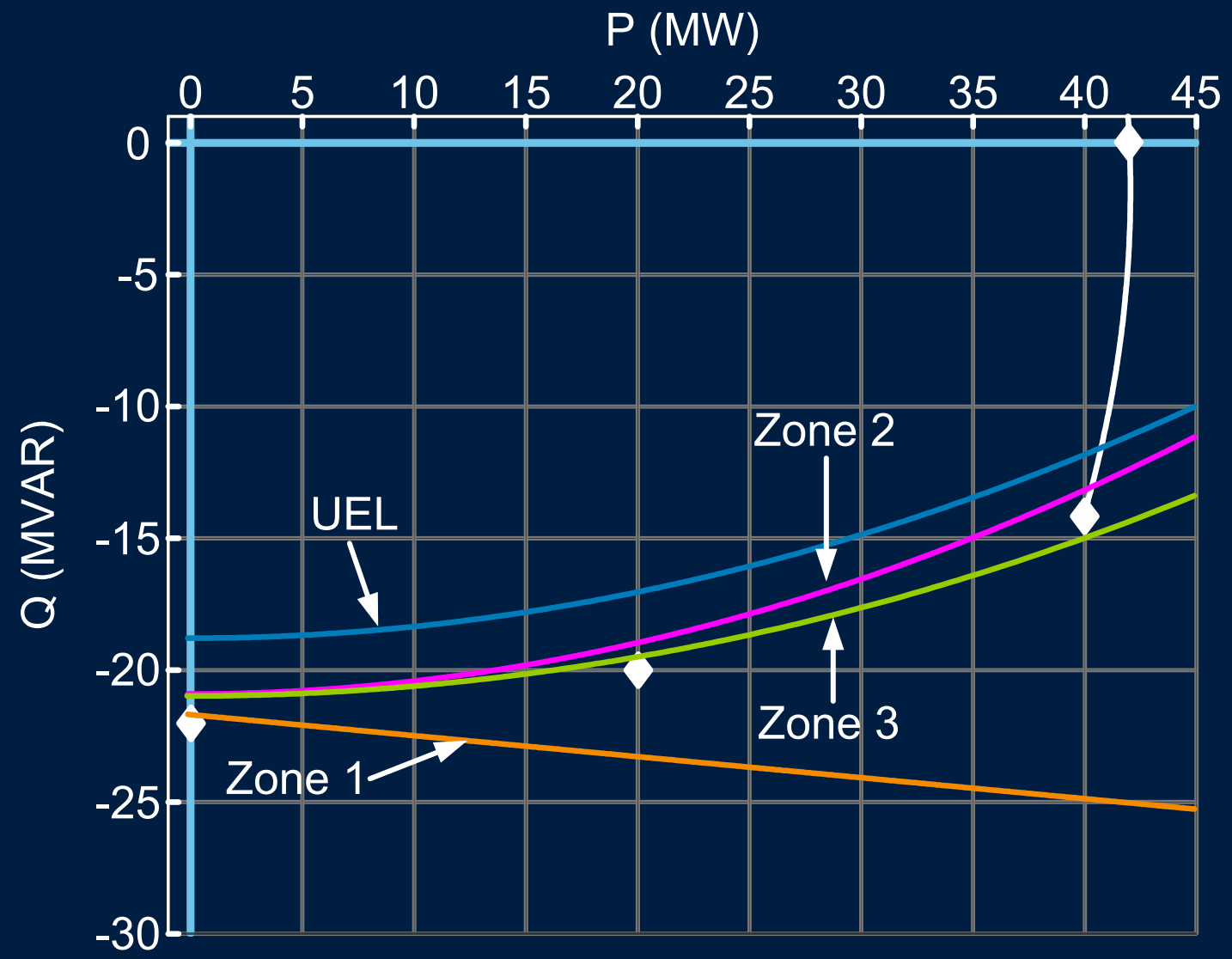
UEL With Dynamic Characteristic

K = 1 at V_T = 1.00 pu



UEL With Dynamic Characteristic

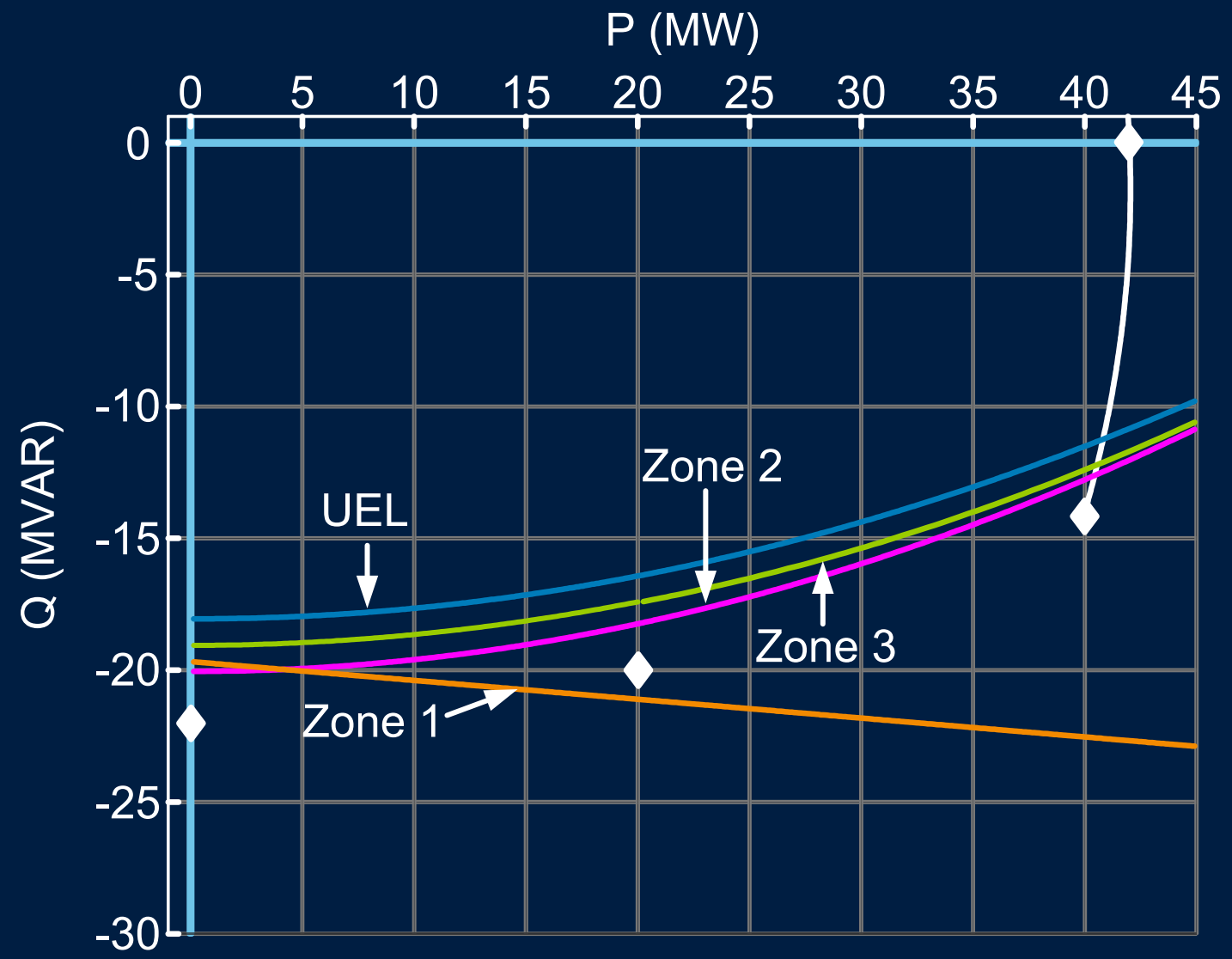
K = 1 at V_T = 0.95 pu



- UEL, Zone 2, and Zone 4 vary in direct proportion to V_T
- Zone 1 and Zone 3 vary in direct proportion to V_T^2

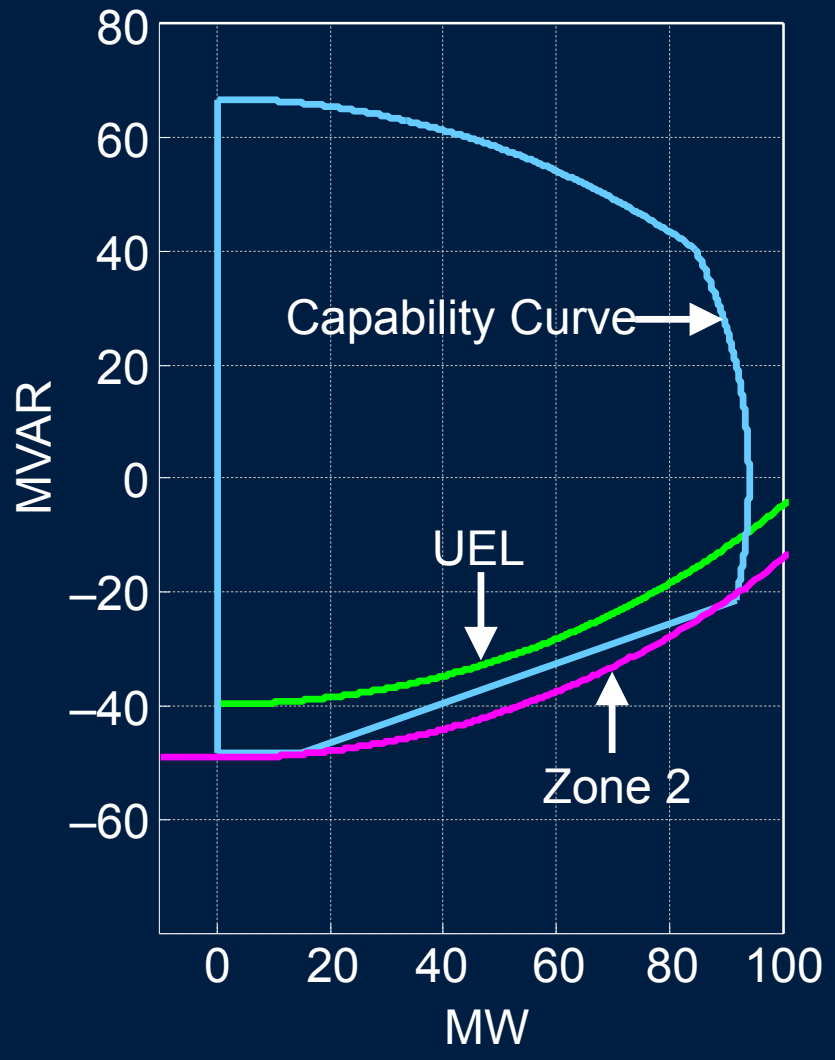
UEL With Dynamic Characteristic

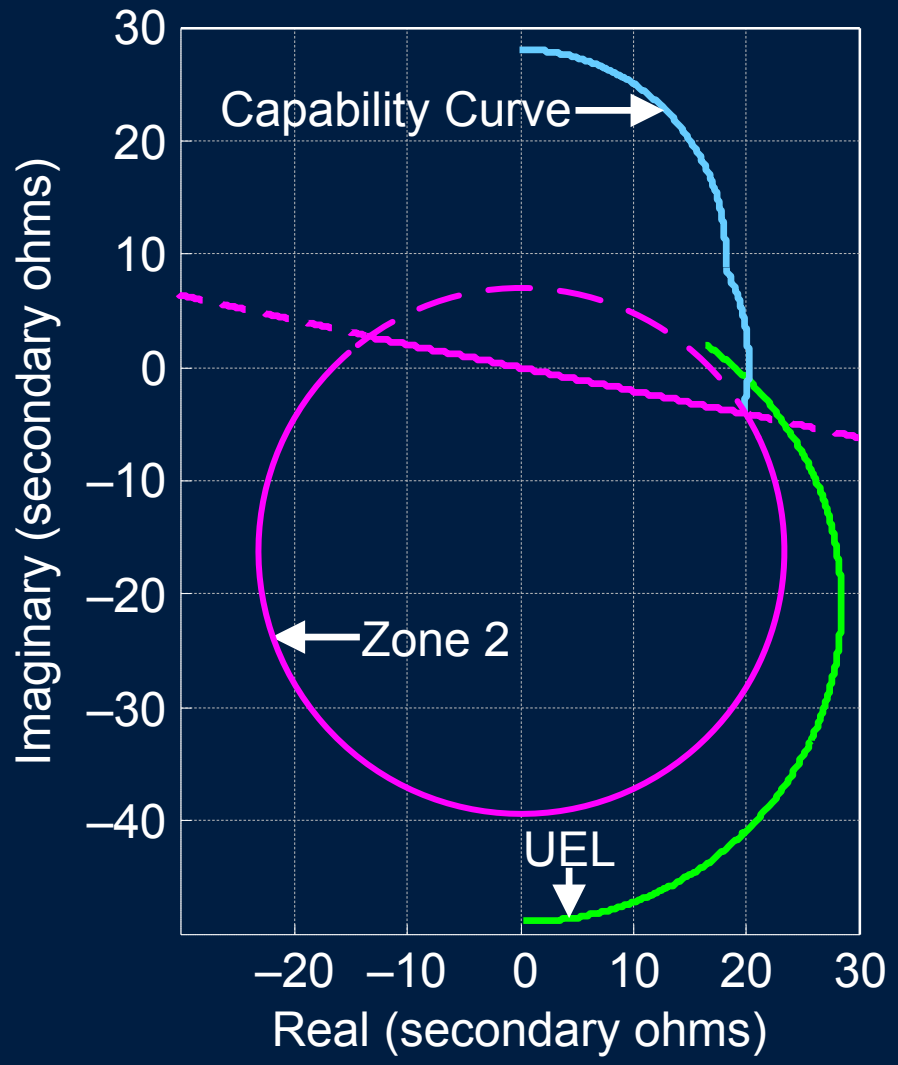
K = 1 at V_T = 0.90 pu



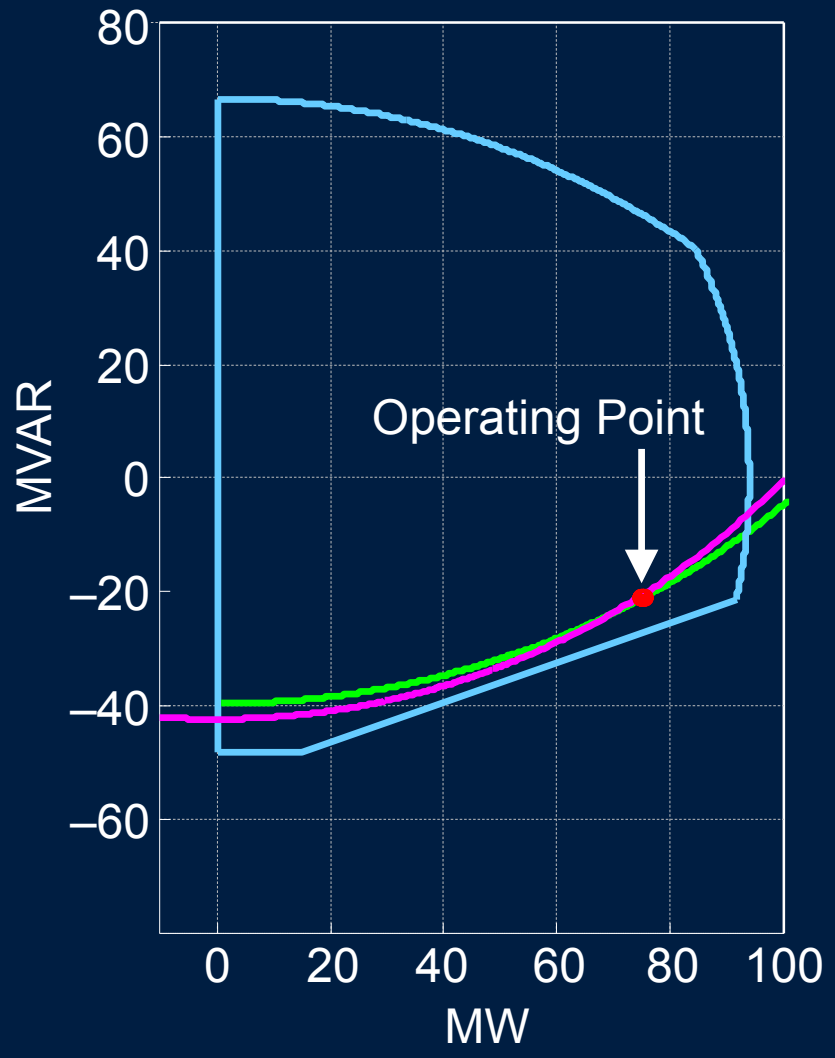
- Zone 3 encroaches into GCC
- UEL can protect generator operation from reaching SSSL

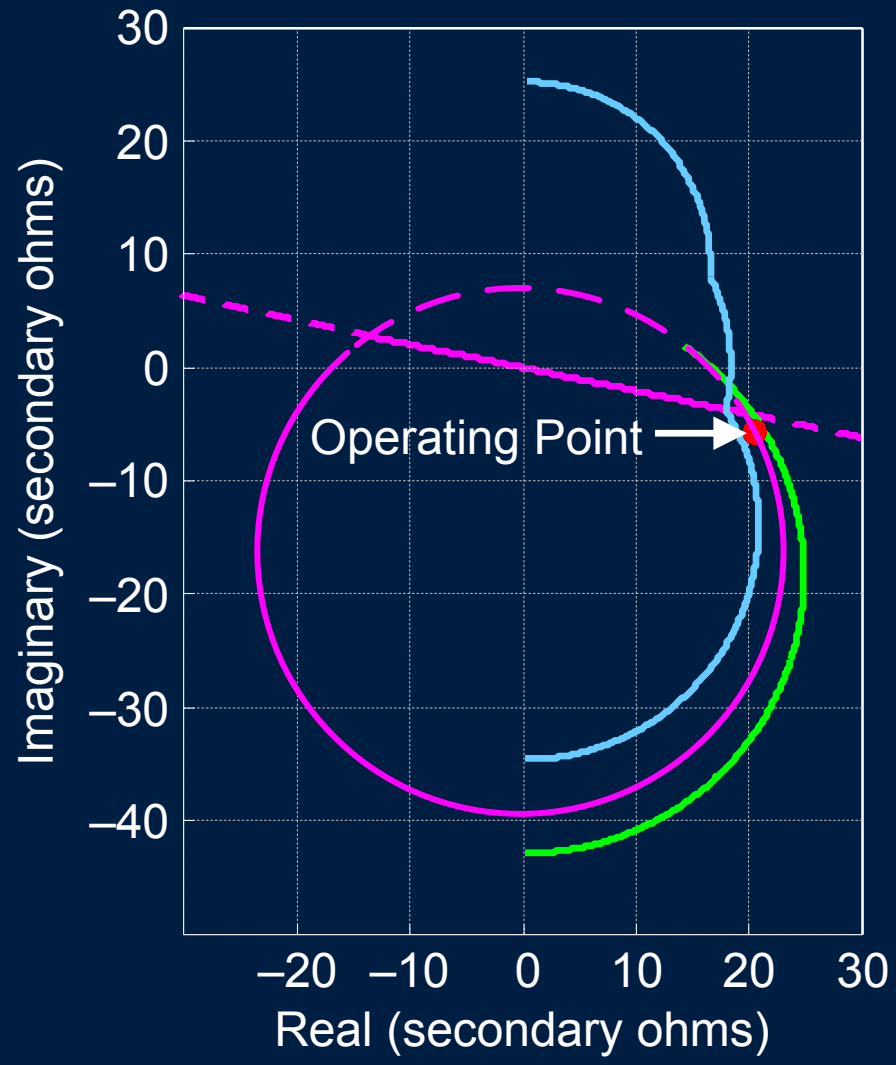
Case 1: Lack of Coordination Between Zone 2 and UEL



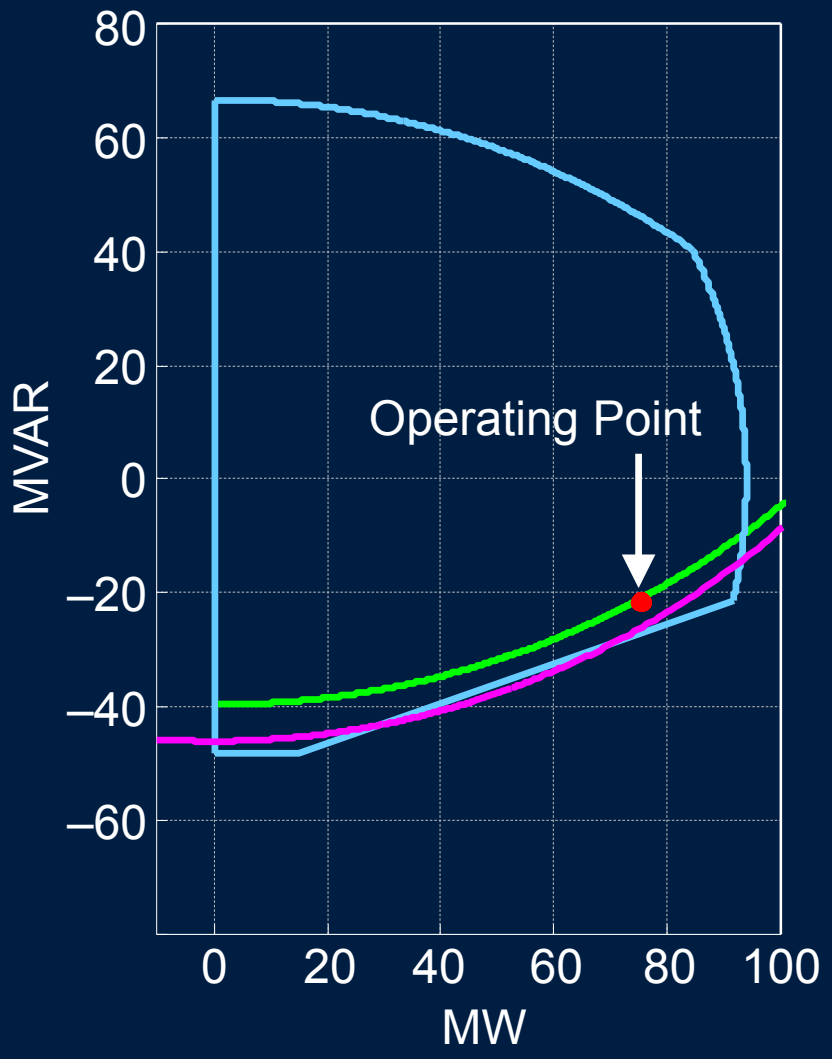


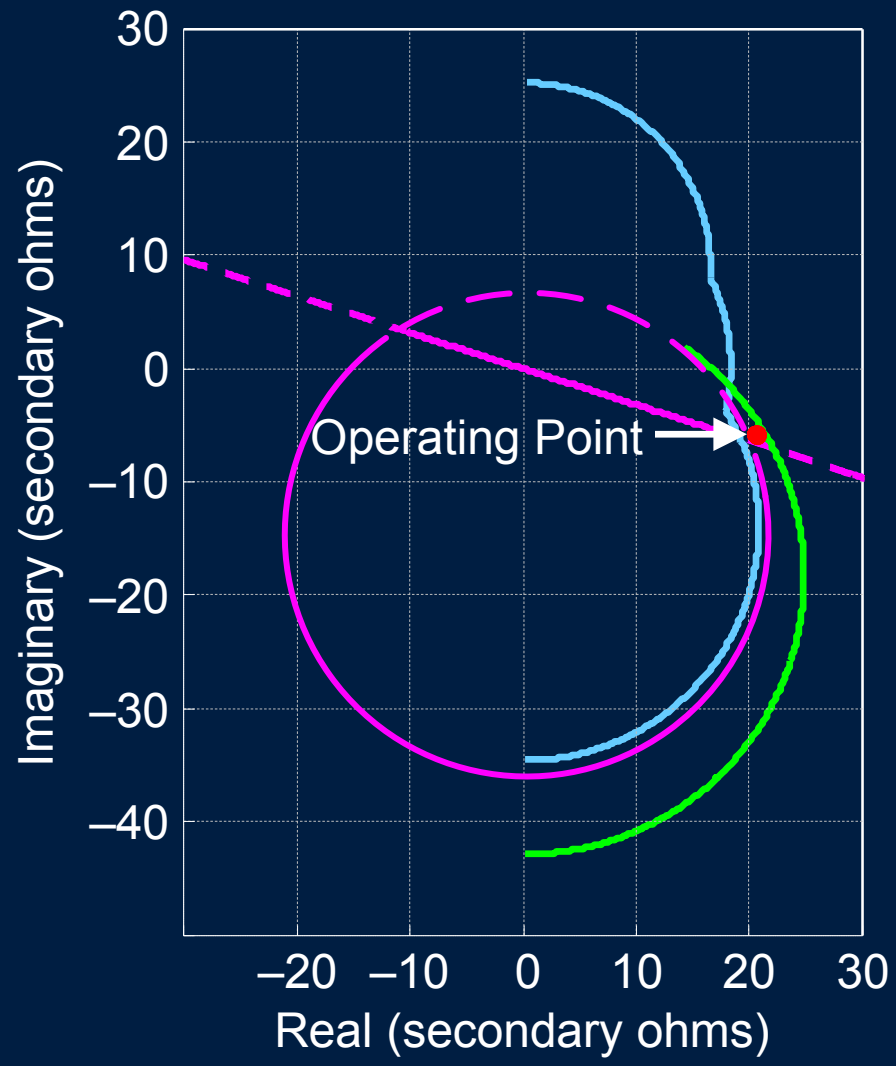
Apparent Impedance Entered Zone 2, Causing Undesired Operation



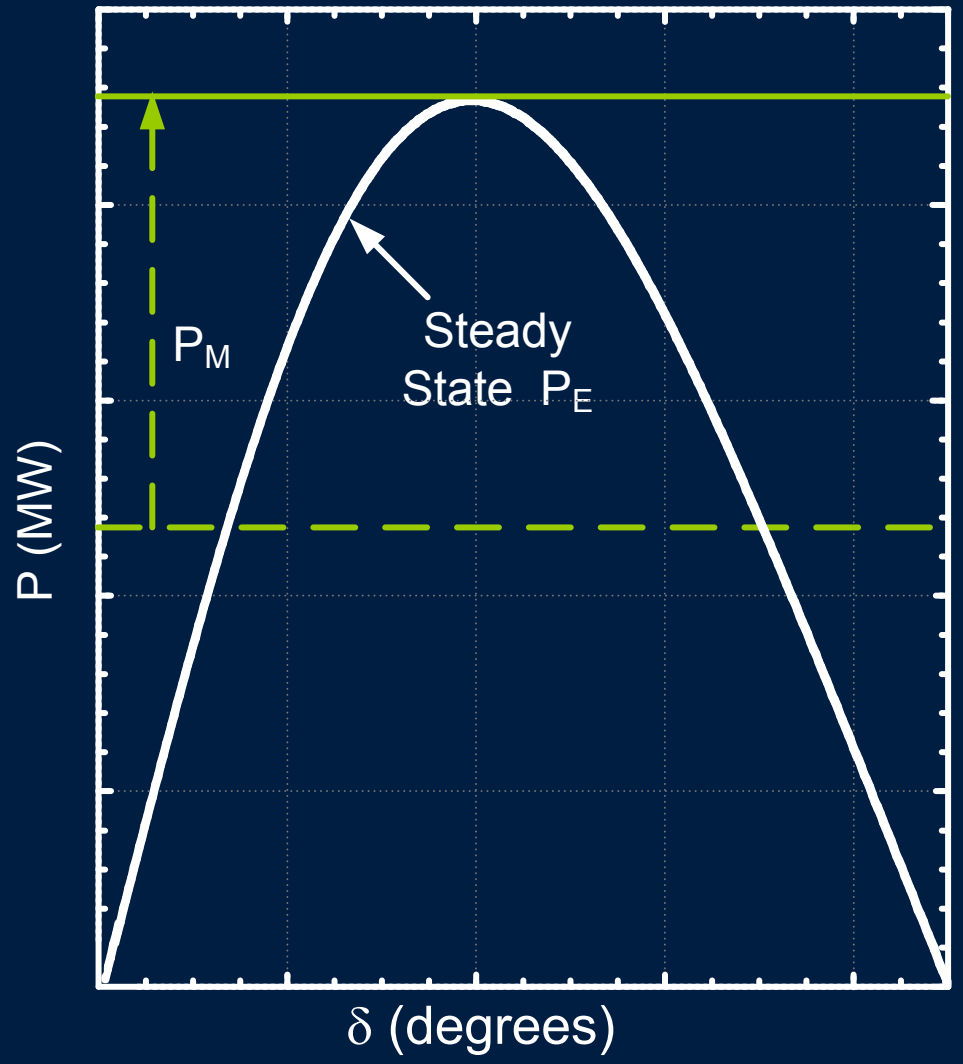


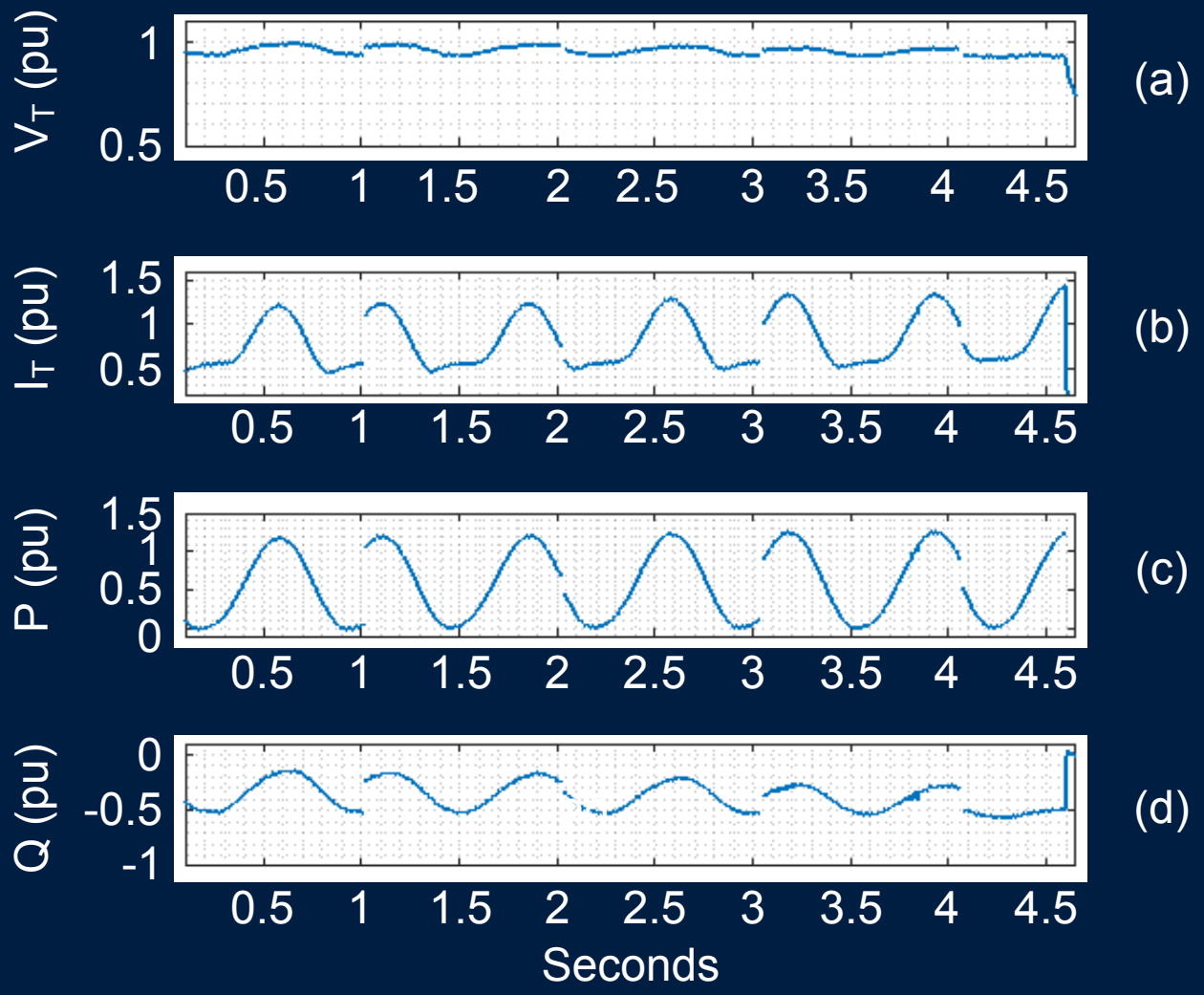
After Improving Coordination, Apparent Impedance Is Outside Zone 2



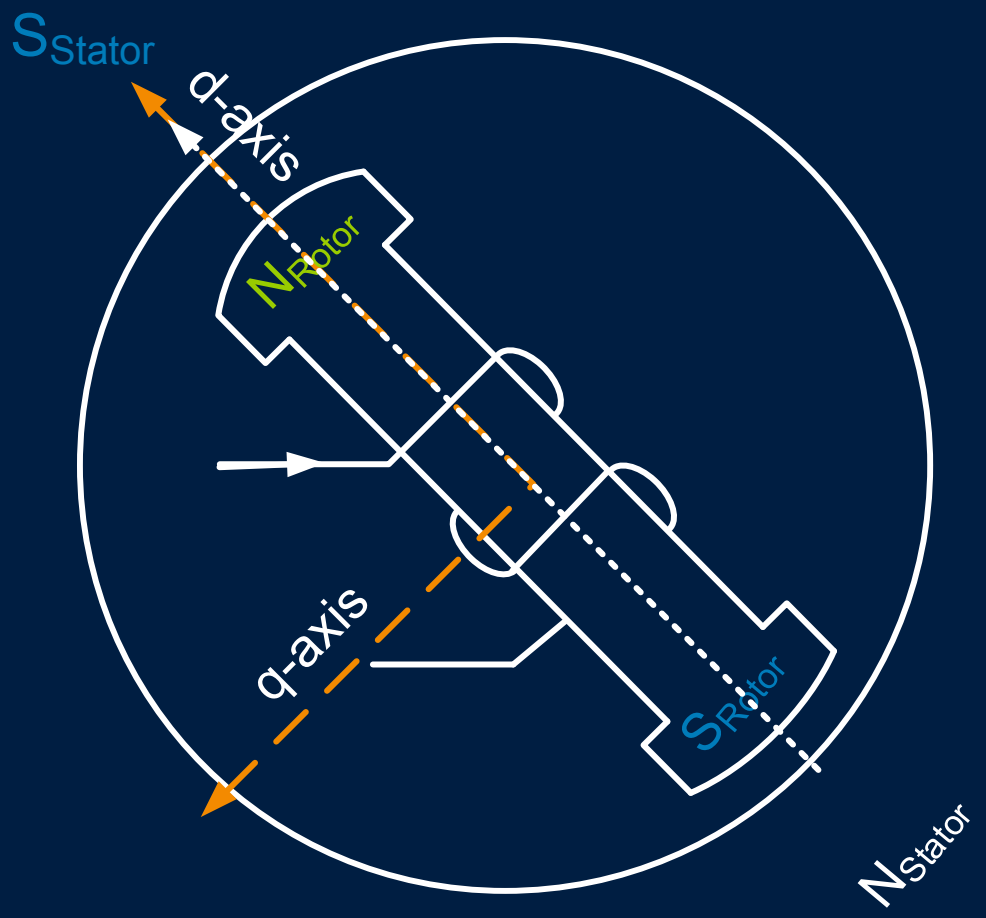


Case 2: Loss of Stability When AVR Was in Manual Mode During Black Start

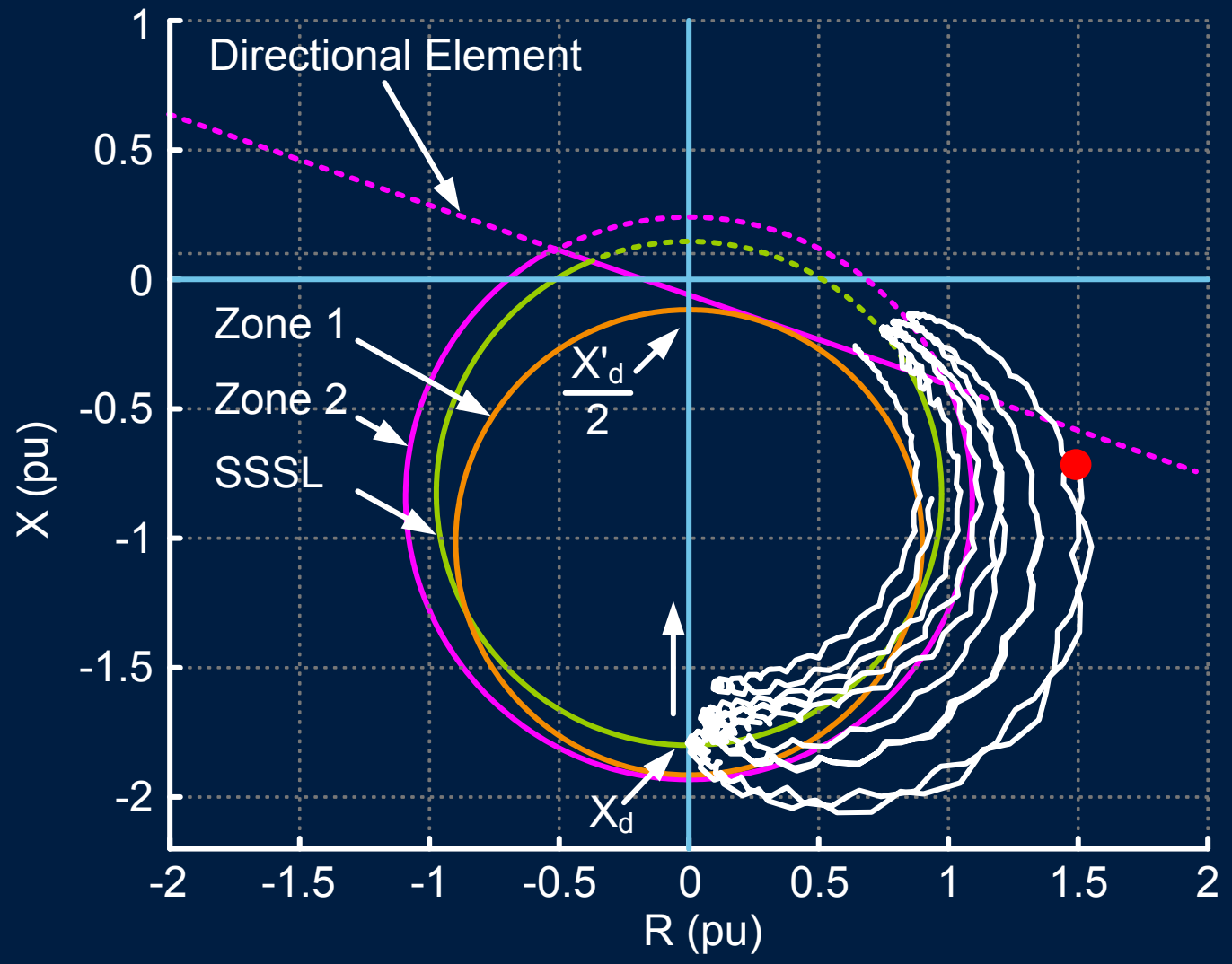




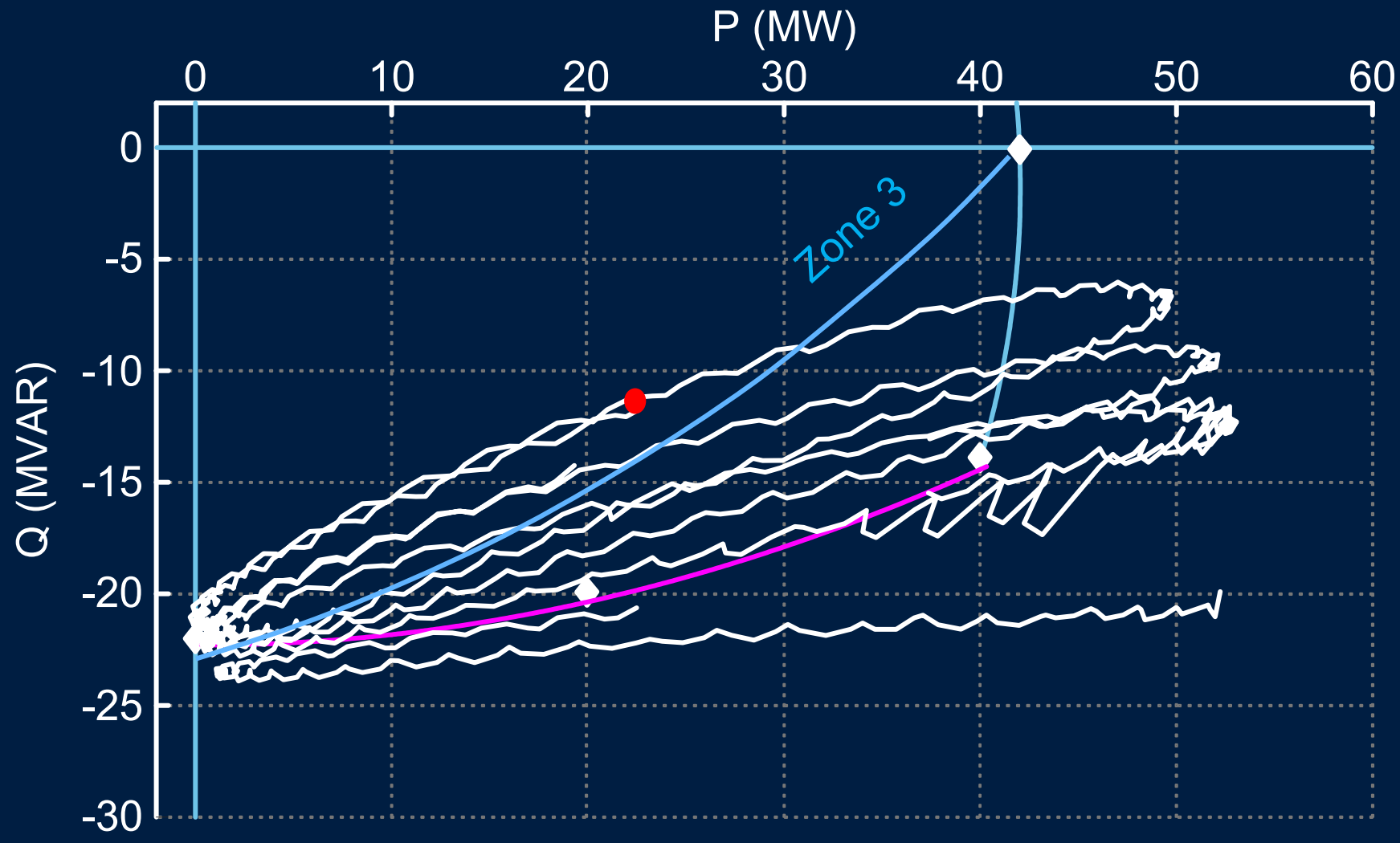
Generator Lost Stability When Mechanical Power Was Increased Beyond SSSL



The Relay Operated When the Apparent Impedance Entered Zone 2



Zone 3 Would Have Operated Faster Than Traditional Protection



Conclusions

- LOF scheme is tailored to GCC and improves generator protection and monitoring
- LOF scheme includes four zones, each with a specific purpose
- Scheme is easy to set
  - Enter UEL and GCC characteristics directly to configure the scheme
  - Enter X_S and X_d to replicate SSSL

Conclusions

- A graphical view of the elements in the PQ and impedance planes minimizes setting errors
- Achieve improved coordination with UEL
  - The K setting allows the relay to exactly match the dynamics of the UEL
  - The characteristic can expand and contract according to a measurement of cooling capability
  - Improved coordination can maximize utilization of the generator

Questions?