

## Assessing Small-Signal System Strength Across Modes, Locations and Operating Conditions for Inverter Based Resource Connections

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### Motivation

- Sub-synchronous oscillations (SSO) emerge with increasing IBR penetration
- Need for systematic methods to identify vulnerabilities to SSO during IBR planning
- System strength varies significantly with operating conditions and across modes
- Existing metrics limitations: fundamental-frequency based, lack spatial and modal insights, limited to buses with apparatuses

### Admittance Margin

Admittance Margin (AM) is designed to assess small-signal strength across all transmission level buses, with or without connected devices:

$$AM_{\lambda}^k = \frac{|\sigma|}{\|\Delta Y_{Ak}(\lambda)\|_{\max}} = \frac{|\sigma|}{\|\text{Res}_{\lambda_k}^* Z_{kk}^{\text{sys}}\|}$$

AM quantifies the maximum admittance perturbation before a mode  $\lambda$  goes unstable, defined as the ratio between its real part and the admittance participation factor at that bus.

#### AM characteristics:

- Impedance based metric
- Operating point dependent
- Defined for every bus and oscillatory mode
- Based on whole-system impedance and admittance participation factor concepts
- Computed from white-box models or impedance scans

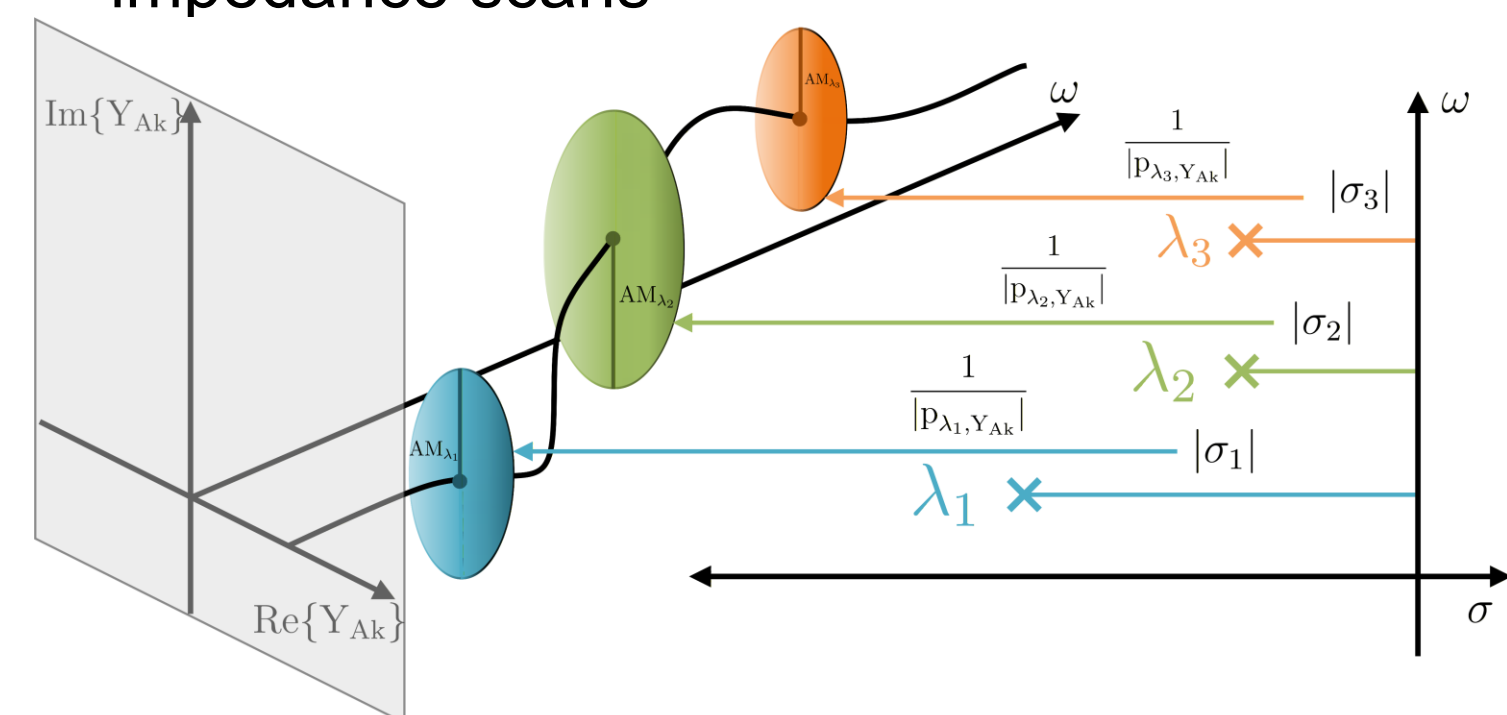


Fig. 1. AM interpretation showing the AMs corresponding to three different poorly damped modes  $\lambda_1$ ,  $\lambda_2$  and  $\lambda_3$  on the complex plane projected on a frequency axis.

### Case Study

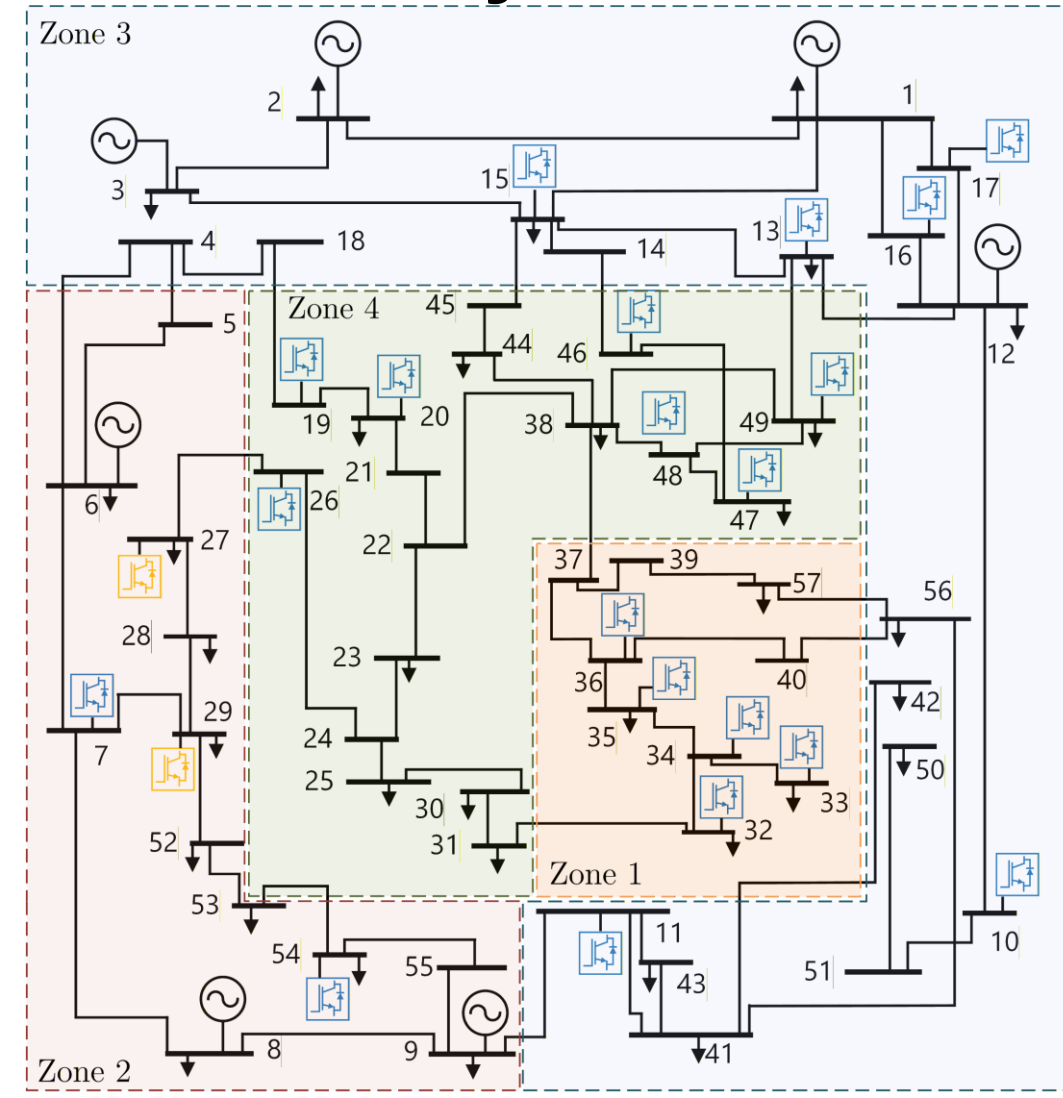


Fig. 2. Modified IEEE 57-Bus system with 22 added IBRs, including variations of both GFL and GFM inverters. System separated into four zones using K-means clustering.

Index	Mode (Hz)	$\zeta$ (%)	Largest Participants
$\lambda_1$	$-2.33 + 41.41j$	5.6	GFL 19 & 20
$\lambda_2$	$-2.41 + 28.11j$	8.6	GFL 32 & 33
$\lambda_3$	$-2.00 + 17.71j$	11.1	GFM 27 & 29

Table 1. Selected system oscillatory modes of interest ( $\zeta < 15\%$ )

#### AM ranges

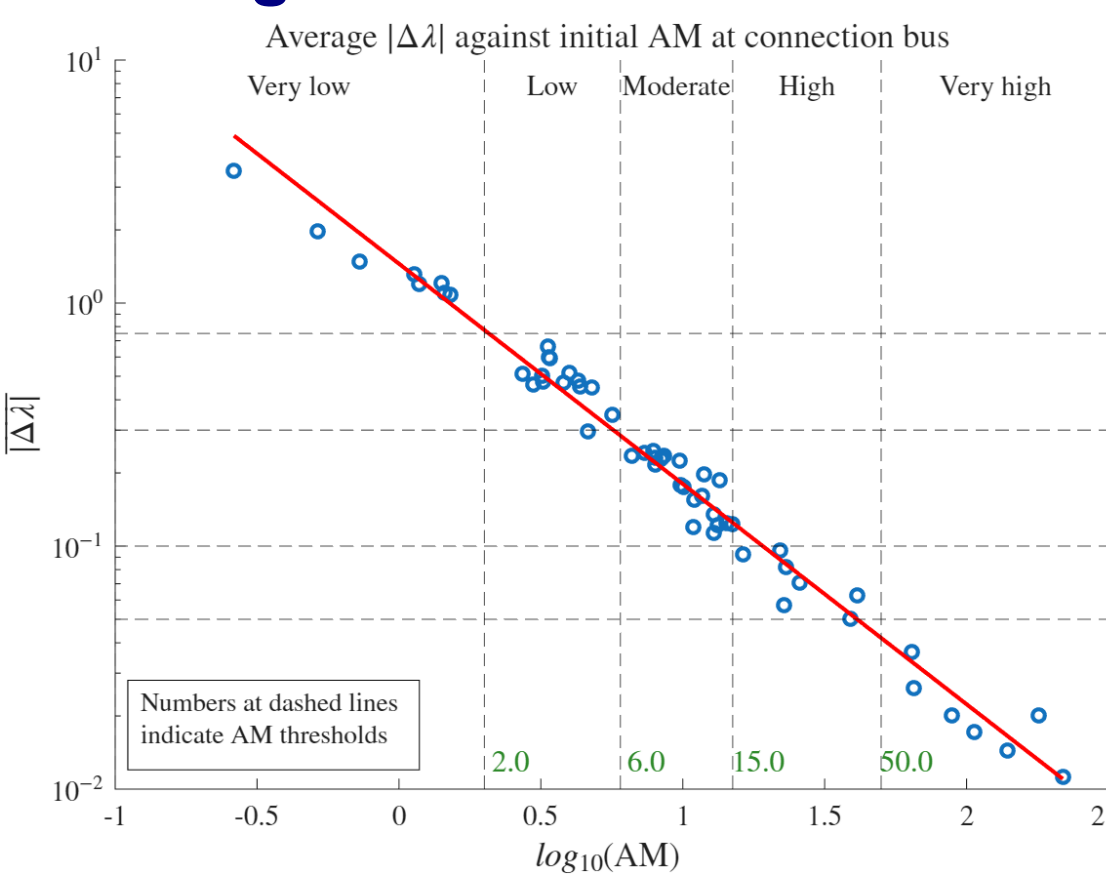


Fig. 3. Average mode shift  $|\Delta\lambda|$  after IBR connection against AM at connection bus. Correlation between  $|\Delta\lambda|$  and AM is illustrated enabling the empirical definition of AM ranges.

Bus	$AM_{\lambda_1}$	$AM_{\lambda_2}$	$AM_{\lambda_3}$
18	1.16	18.64	71.32
25	22.03	0.75	86.97
52	95.29	173.69	5.63

Table 2. AM at selected empty buses. Bus 25 is "strong" with respect to  $\lambda_1$  but "weak" with respect to  $\lambda_2$ . Highlights the importance of assessing small-signal system strength with respect to multiple poorly damped modes, not just the most critical.

### Locational and Modal System Strength Variability

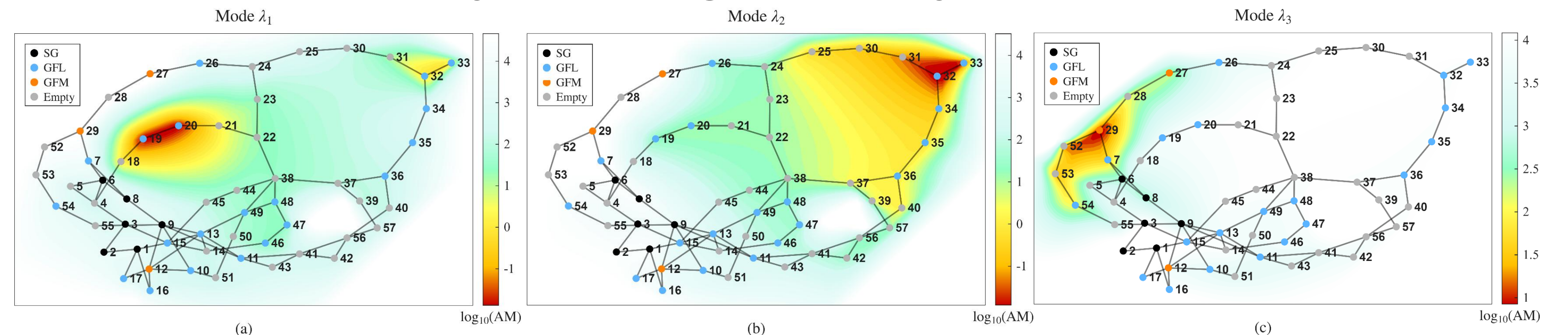


Fig. 4. System-wide AM variation heat-maps for modes (a)  $\lambda_1$ , (b)  $\lambda_2$  and (c)  $\lambda_3$  enabling quick identification of weak locations. The most critical mode varies across locations in the system.

### System Strength Operating Point Dependence

AM is operating point dependent, therefore should be reevaluated when the system operating point changes

#### Operating Scenarios Development

Four-level structure of varying system conditions to construct set of realistic operating scenarios for system strength analysis:

- **Level 1 (L1):** Variation of total system demand
- **Level 2 (L2):** Variation in IBR share of total system generation
- **Level 3 (L3):** Distribution of IBR generation between zones
- **Level 4 (L4):** Distribution of IBR generation within zones

Probabilities of L1-L2 scenarios obtained using GB network data.

#### AM variation with operating point

Modes have varying sensitivity to operating conditions

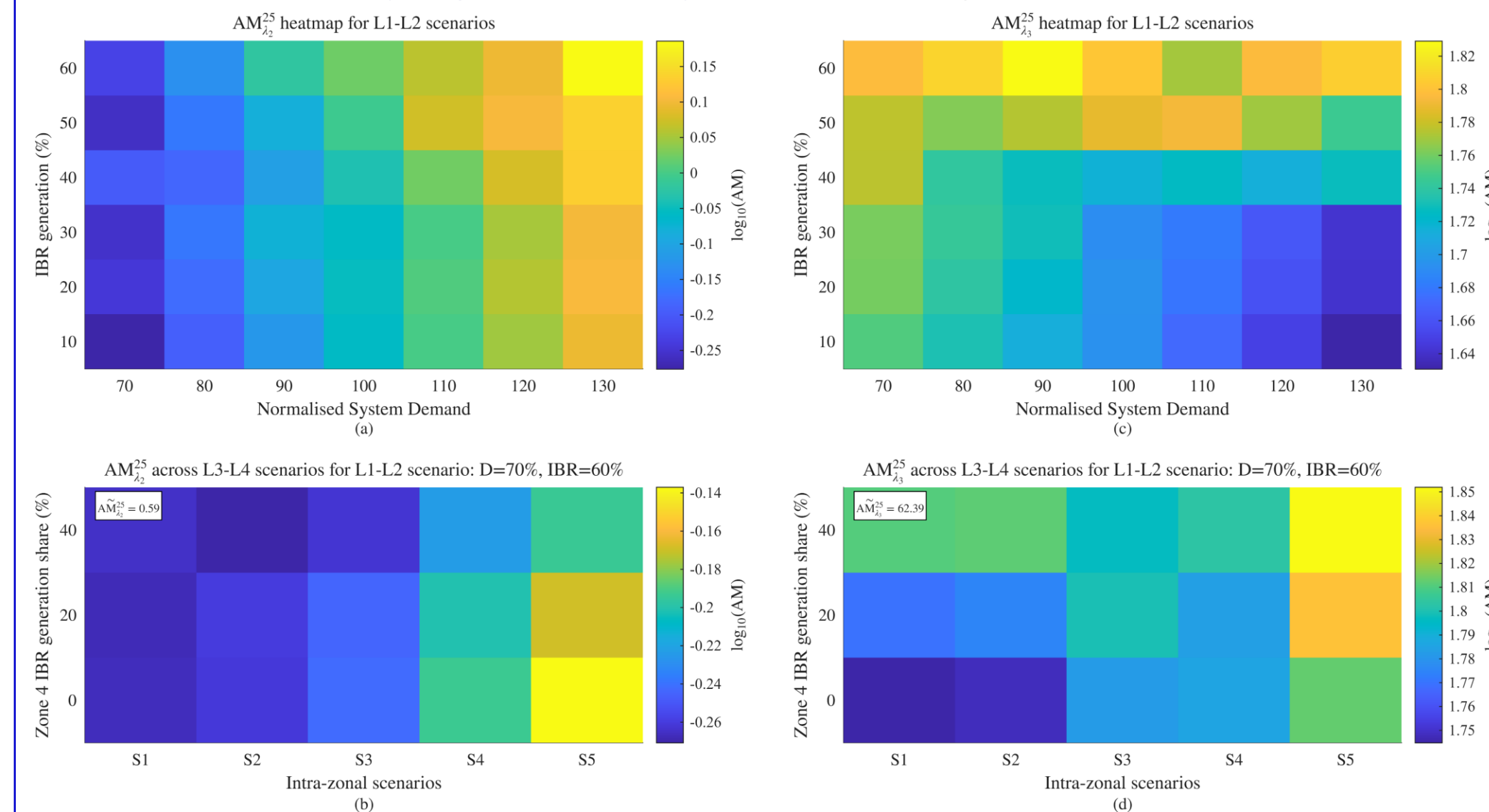


Fig. 5. AM operating point variation heat-maps at bus-25: (a) L1-L2 scenarios for  $\lambda_2$  (b) L3-L4 scenarios for L1-L2 scenario D = 70% & IBR = 60% for  $\lambda_2$  (c) L1-L2 scenarios for  $\lambda_3$  (d) L3-L4 scenarios for L1-L2 scenario D = 70% & IBR = 60% for  $\lambda_3$ .

#### Critical Operating Points (COPs)

Large operating scenario space makes exhaustive system strength studies impractical, motivating the selection of representative scenarios.

#### Selection Criteria:

- 1) Most frequent operating scenarios
- 2) Operating scenarios with lowest AM at the connection bus
- 3) Operating scenarios with lowest average AM across all system buses

Criterion 1: Most Frequent Scenarios			Criterion 2: Lowest AM at bus 25			Criterion 3: Lowest system average AM					
D	IBR	Frequency	D	IBR	min $AM_{25}^{\lambda_1}$	D	IBR	AM			
1	90%	60%	0.074	1	70%	10%	0.529	1	70%	40%	28.86
2	80%	50%	0.051	2	70%	50%	0.552	2	80%	40%	30.48
3	100%	60%	0.048	3	70%	30%	0.557	3	80%	50%	30.65
4	100%	40%	0.047	4	70%	20%	0.568	4	80%	30%	31.16

D: Normalised System Demand, IBR: IBR Generation Share

Fig. 6. Example L1-L2 COPs selection for bus 25

COPs identification enables faster yet thorough planning and connection system strength studies for new IBRs.

#### Full Paper:

Andreas Hadjileonidas, Yue Zhu, Debargha Brahma, Timothy C. Green, "Assessing Small-Signal System Strength Across Modes, Locations and Operating Conditions for Inverter Based Resource Connections". TechRxiv. March 2026.