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University of Strathclyde Glasgow

Risk Day 2023

Pathways to power system collapse: an updated review of large disturbances & blackout events

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Introduction

Supergen Energy Networks Hub Flex Fund Project: *Credible routes to GB electricity system collapse and the impact of new demand*

- Builds on prior work which developed conceptual model of collapse pathways

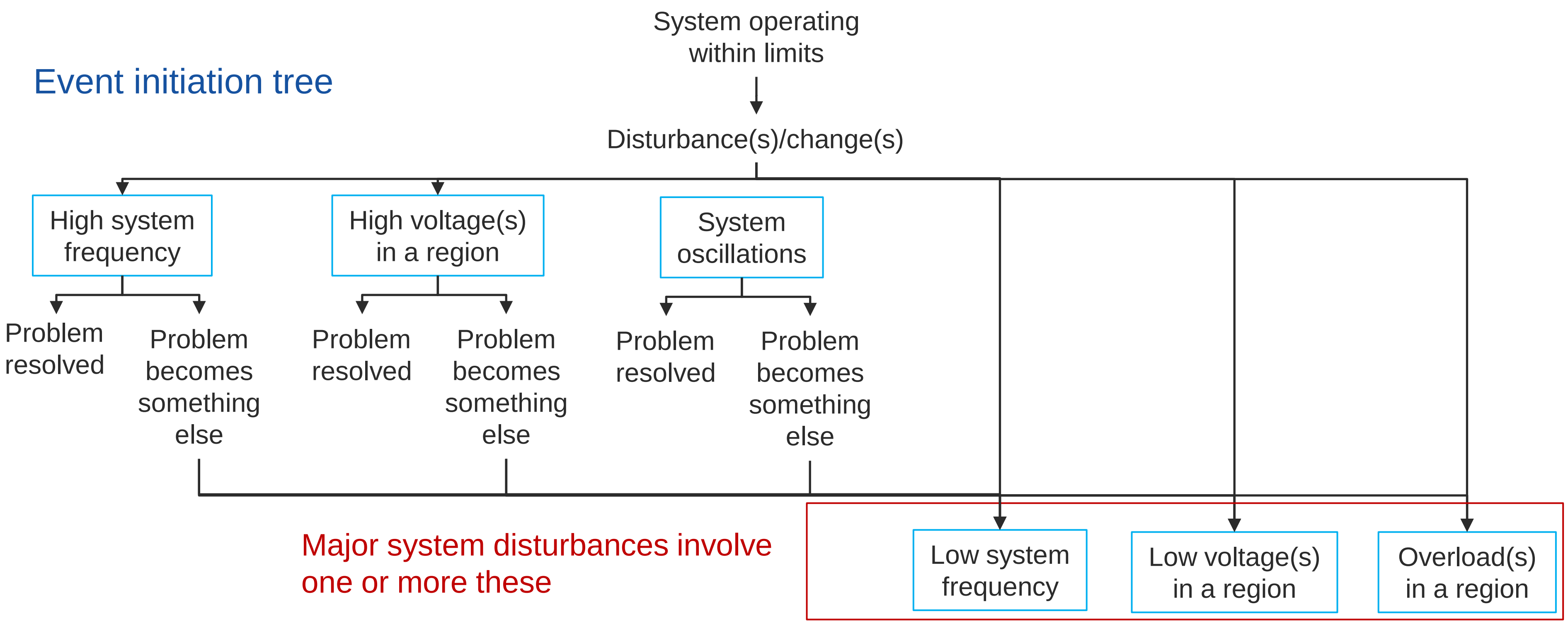
Three main strands to project:

1. Examination of historical events to test model and gain insights
2. Expert Interview/surveys to elicit knowledge on current and future view of potential collapse mechanisms
3. Use outputs to inform modelling of sample collapse scenarios

- Work ongoing - presentation focuses on 1 (and a little bit of 2)

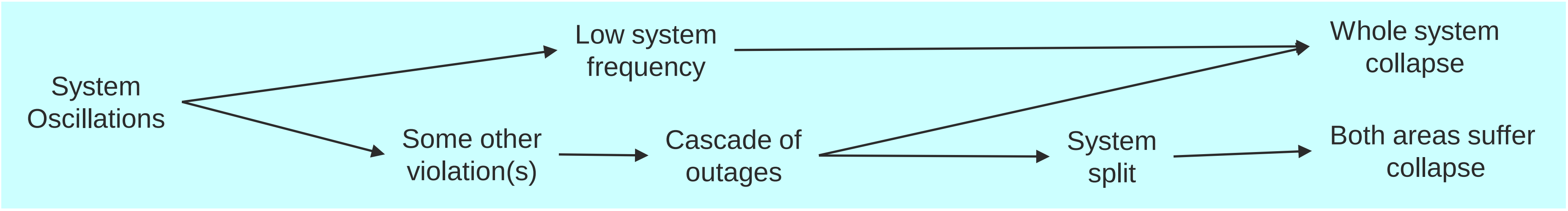
Conceptual model of collapse pathways

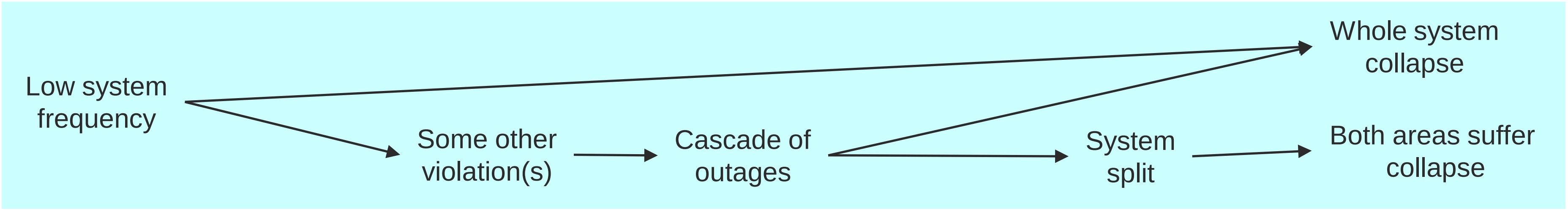
- Conceptual model developed in prior project outlined range of system phenomena that may occur and used event trees to envisage how a power system collapse might manifest:

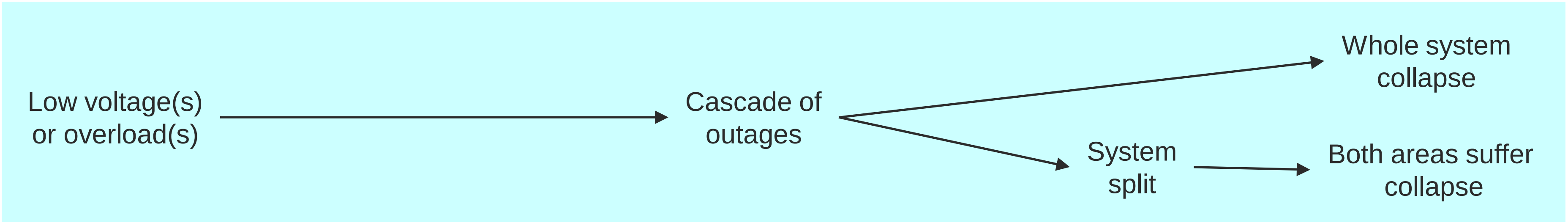


- Aim to enable a range of experts to critically assess (structured expert judgment) probability of events leading to a collapse given knowledge of system design, operation and defence mechanisms

Paths to whole system shutdown







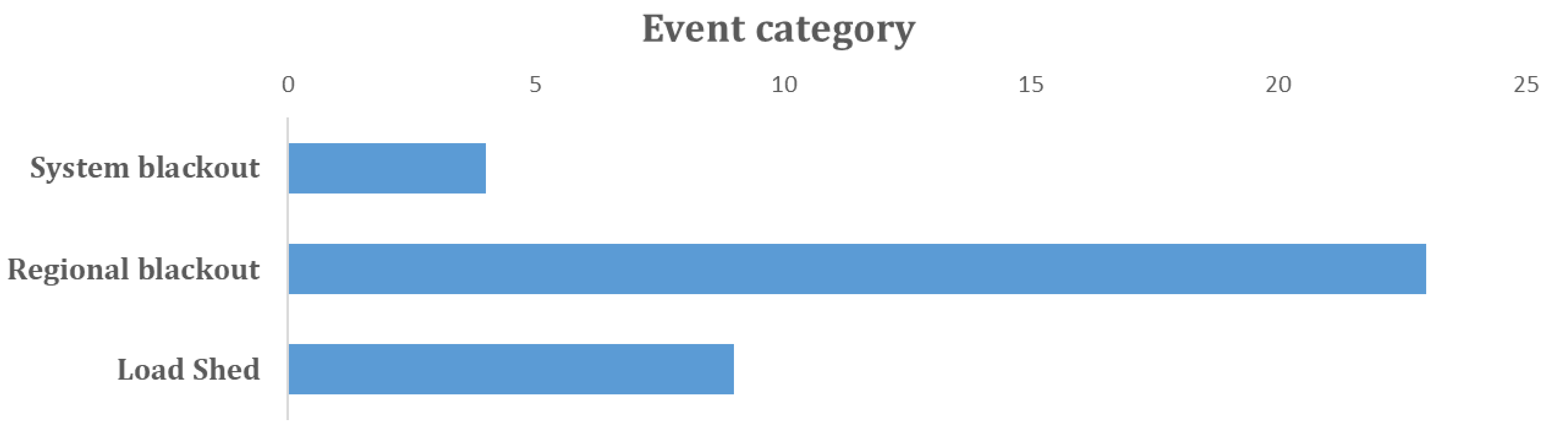
*Note that any adverse impacts of high system frequency or high voltages are assumed subsequently to take the form of low system frequency, low voltages or overloads

This project seeks to use historic events and expert insight to interrogate the validity of the model and gain further understanding of how collapse events may propagate in reality.

Catalogue of major events

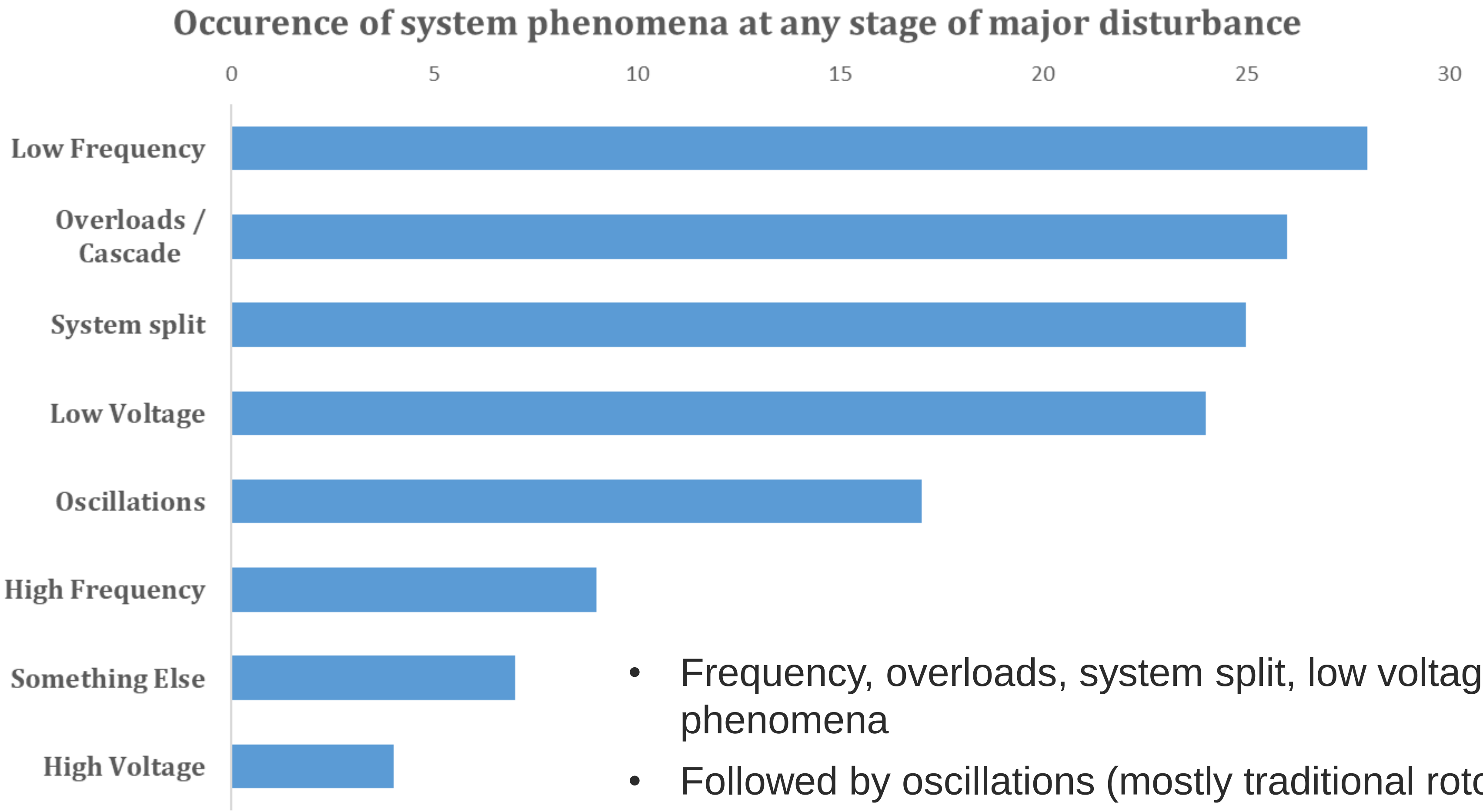
- Aim to develop catalogue of events with a detailed description of event pathway
  - Hundreds of events listed in literature but often these lack detail beyond high level root cause or impact
- Cigré most reliable resource for detailed analysis:
  - TB 433 used as starting point - included detailed summary of a set of major disturbances up to 2008
  - Appended with reference to TB 833, archive of Large Disturbance Workshop presentations and external sources
- Total event archive drawn from Cigré sources reaches ~ 70 large disturbance events
  - Database of ~40 events has been developed where a detailed enough description of the collapse pathway is available
  - Used to interrogate conceptual model and identify trends from historic events

Event analysis - system phenomena



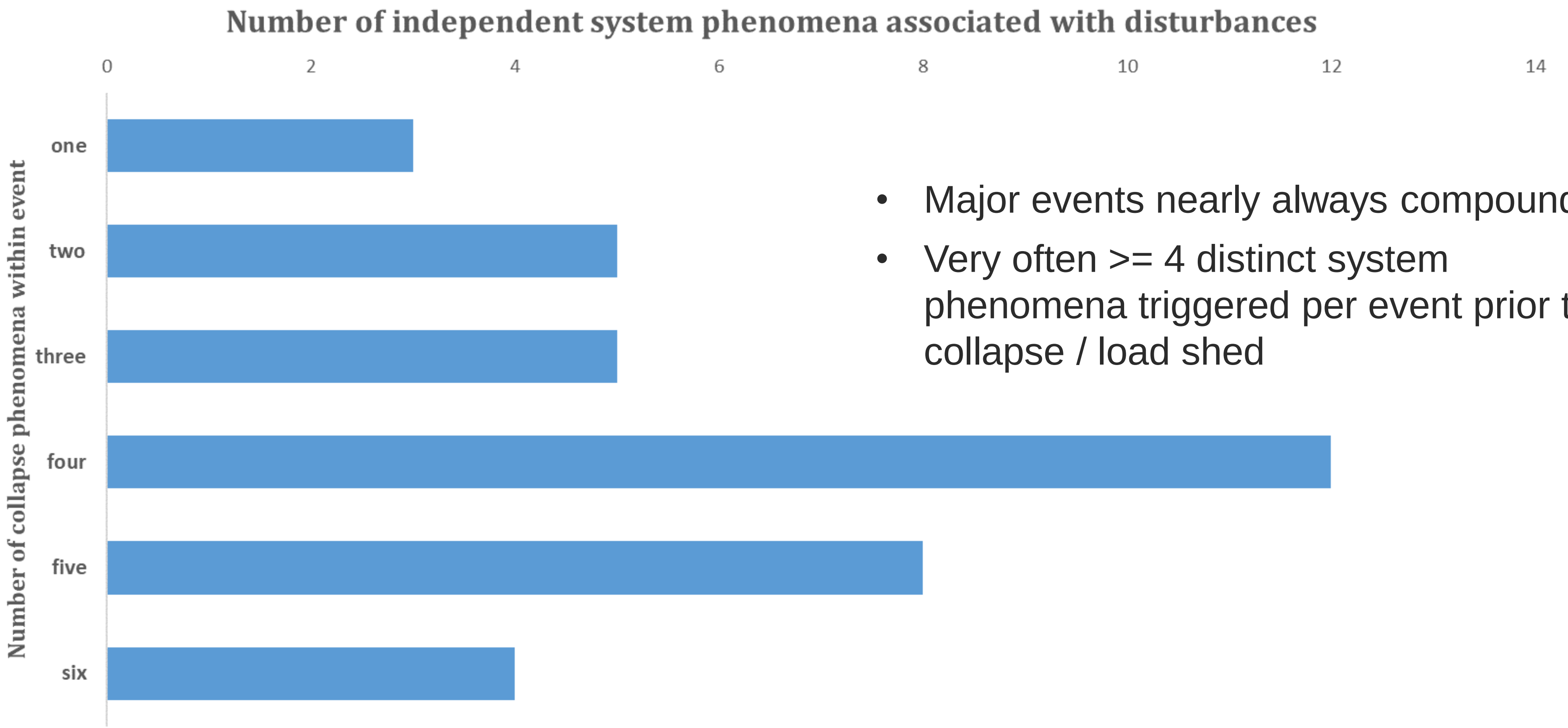
- Relatively few full system blackouts (loss of entire transmission system)
  - Tend to be on smaller island systems or due to very large events
- Majority of events stopped at regional collapse or large scale load shed
  - Scale of these can still be very severe (e.g. whole countries within large interconnected systems) to the extent that the distinction is often functionally meaningless from PoV of consumer…
  - Load shed in most instances due to under-frequency load shedding or system operator action
- Further category of near misses not included in this analysis

Event analysis - system phenomena



- Frequency, overloads, system split, low voltage most common phenomena
- Followed by oscillations (mostly traditional rotor angle stability issues)
- High frequency and high voltage issues less common
- ‘Something Else’ dominated by human interventions in error

Event analysis – system phenomena

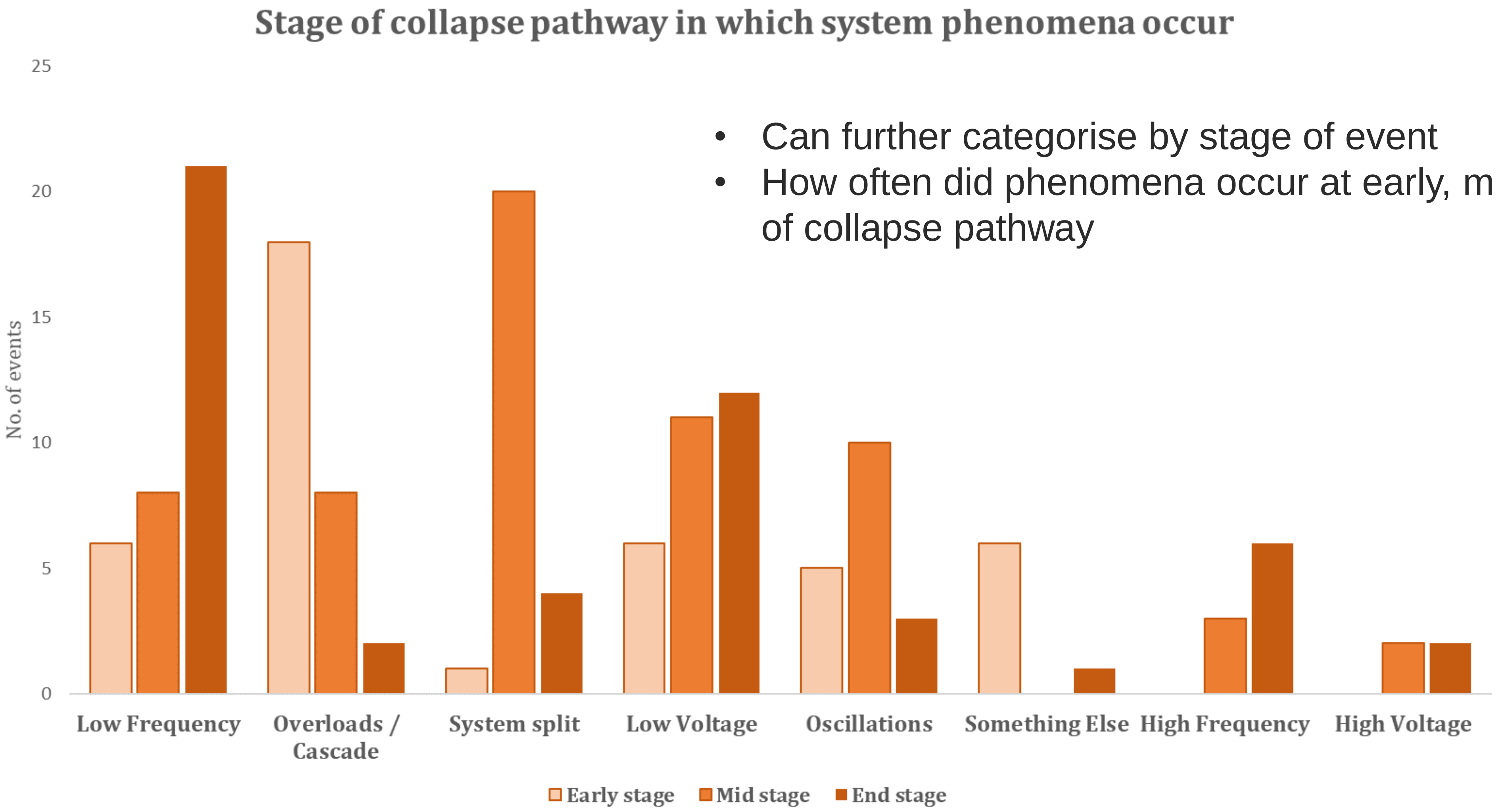


- Major events nearly always compound
- Very often >= 4 distinct system phenomena triggered per event prior to collapse / load shed

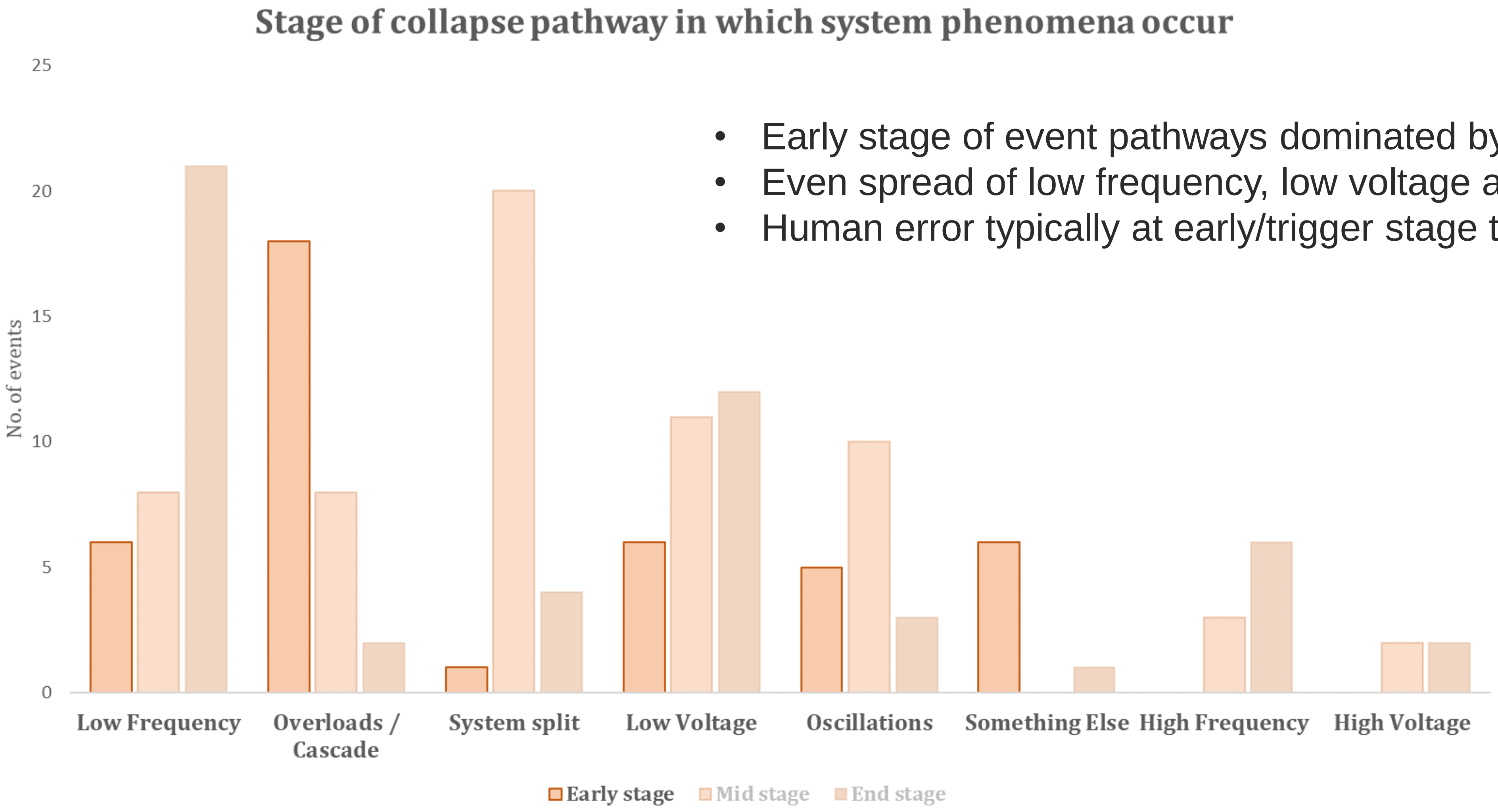
* From 8 categories - 6 identified system phenomena + system splits + ‘something else’

Event analysis – system phenomena

- Can further categorise by stage of event
- How often did phenomena occur at early, mid or end stage of collapse pathway

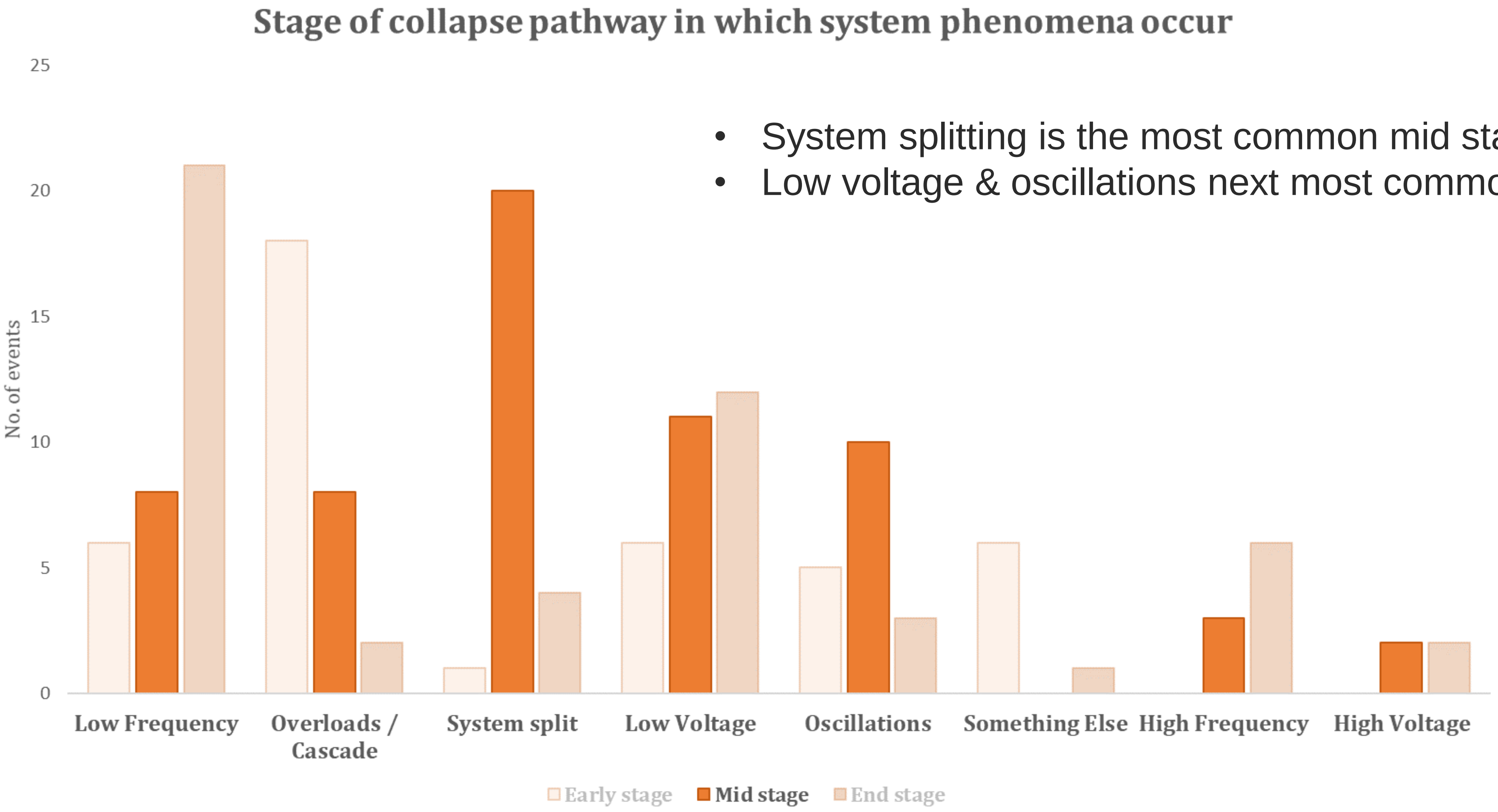


Event analysis – system phenomena



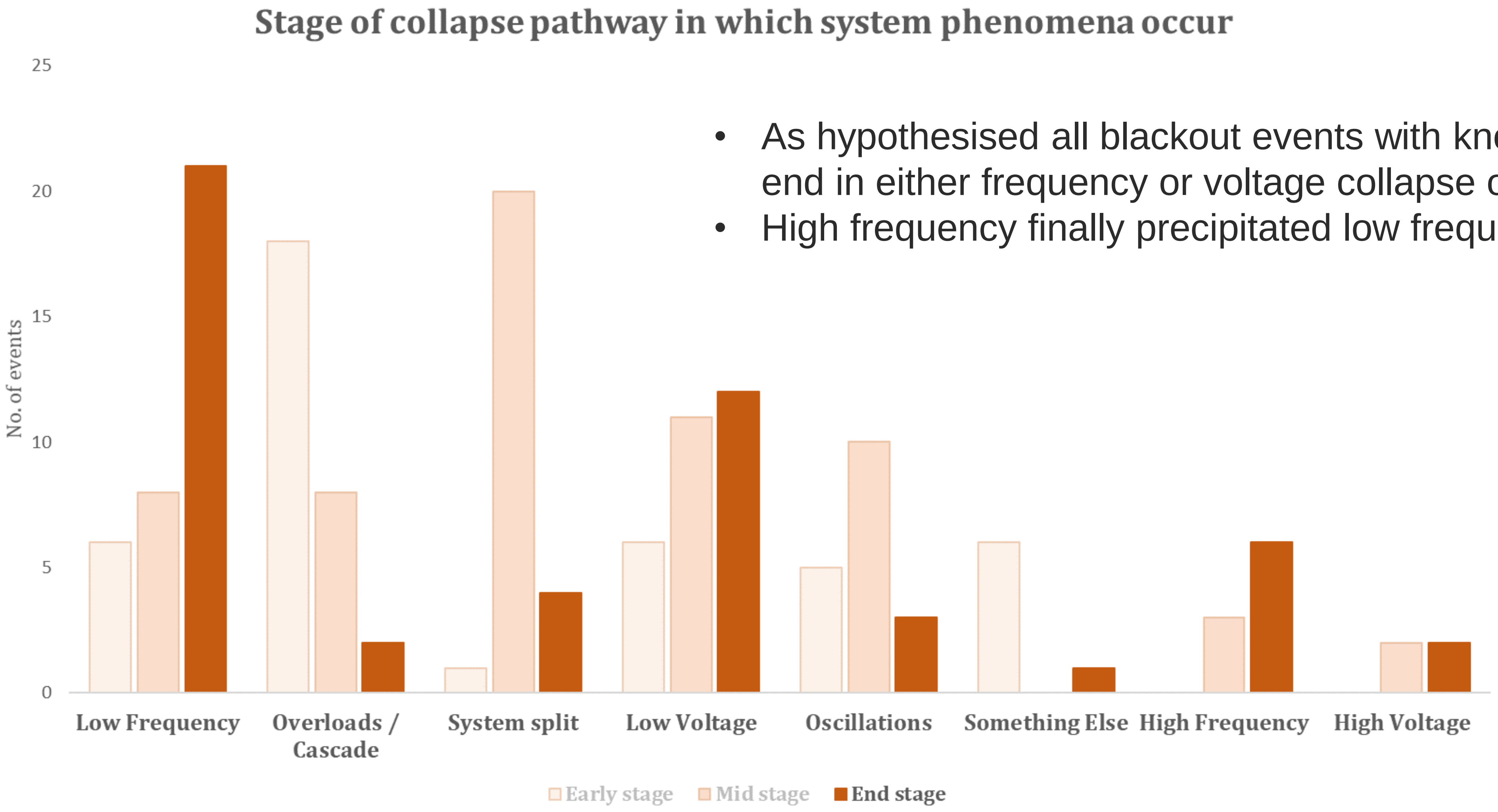
- Early stage of event pathways dominated by overloads
- Even spread of low frequency, low voltage and oscillations
- Human error typically at early/trigger stage too

Event analysis – system phenomena



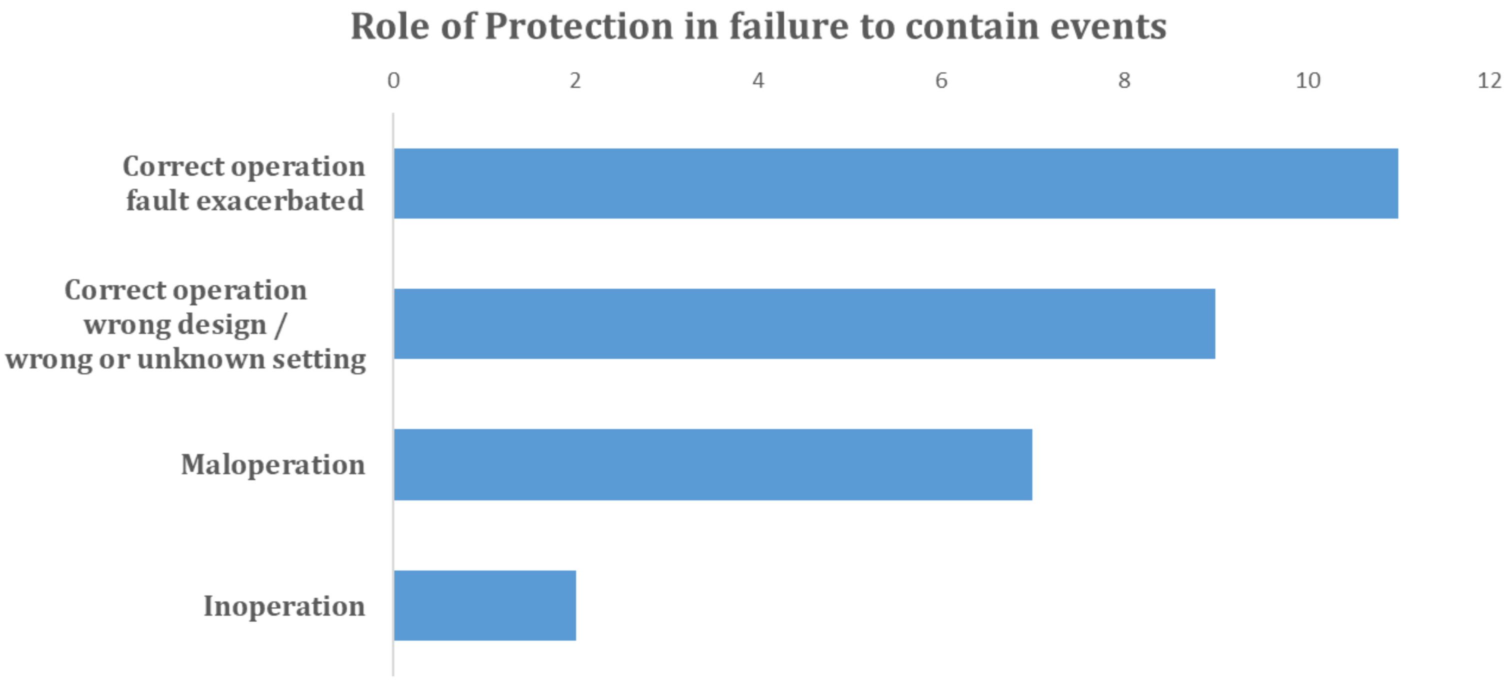
- System splitting is the most common mid stage phenomena
- Low voltage & oscillations next most common

Event analysis – system phenomena



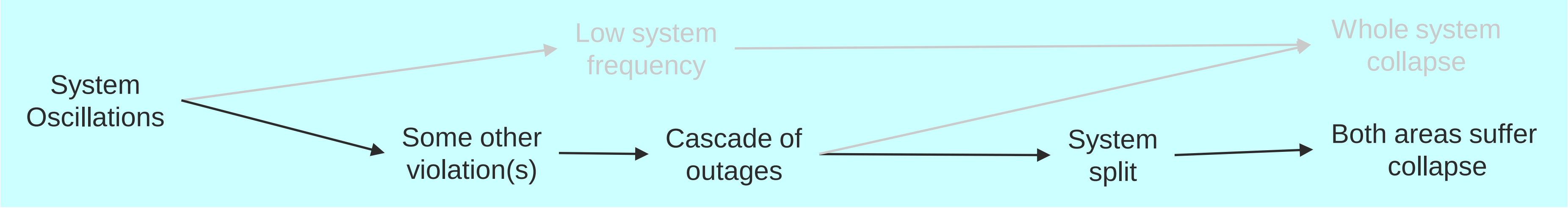
- As hypothesised all blackout events with known pathway end in either frequency or voltage collapse or both
- High frequency finally precipitated low frequency collapse

Event analysis – protection systems



- Failure of protection systems had a prominent role in most major disturbances
- Most common occurrence was for correct operation of protection to exacerbate event pathways
- Correct operation with wrong design or wrong or unknown settings next most common issue

Example: Argentina 2019 blackout pathway

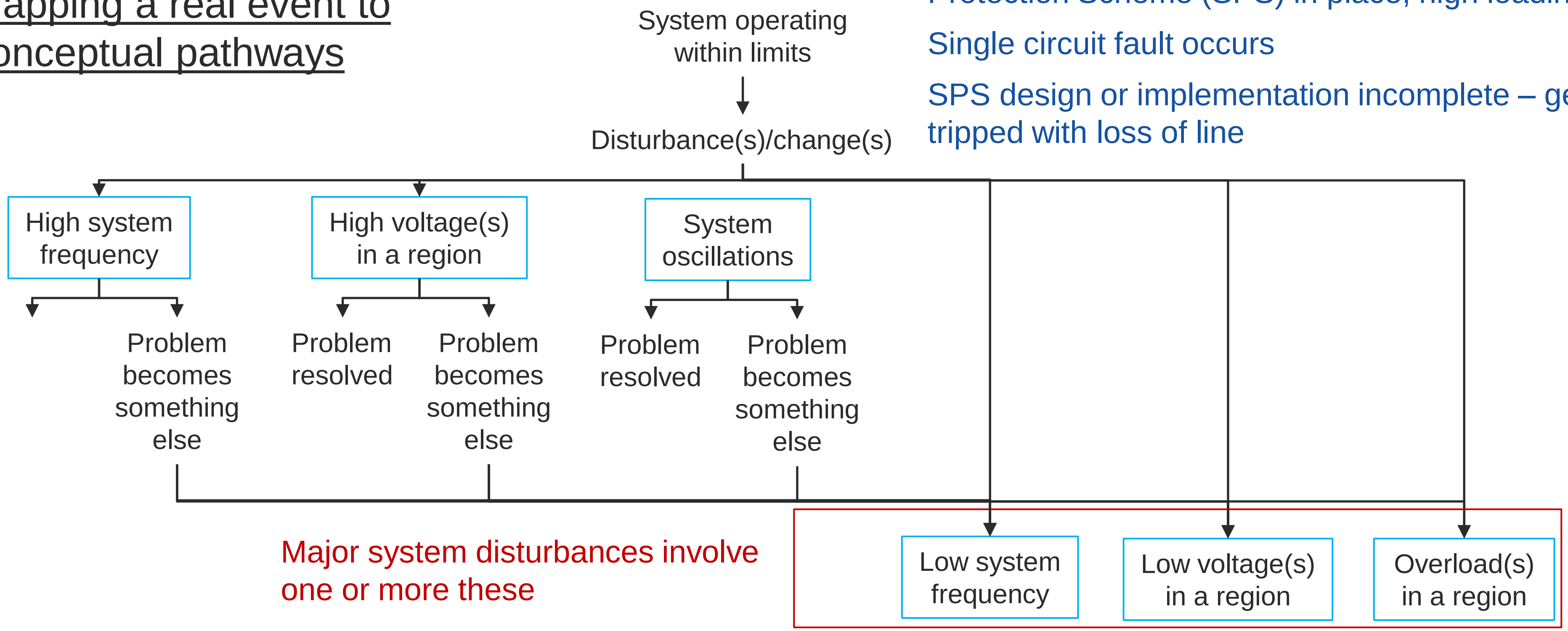


Mapping a real event to conceptual pathways

Pre-fault: 500kV line out of service and temporary Special Protection Scheme (SPS) in place, high loading on N-1 corridor

Single circuit fault occurs

SPS design or implementation incomplete – generation not tripped with loss of line



Major system disturbances involve one or more these

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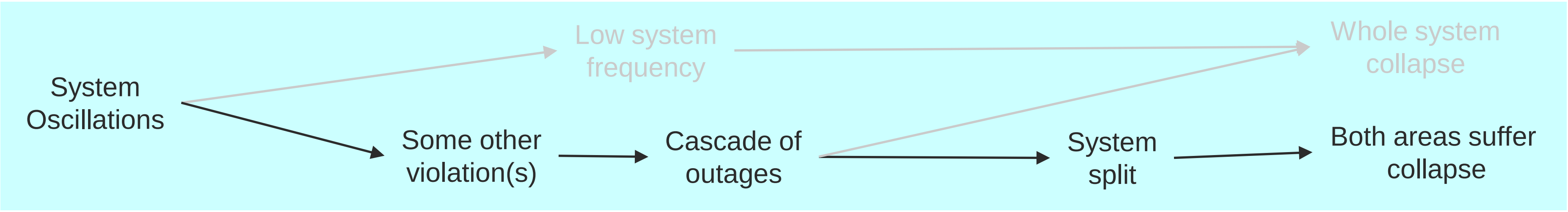
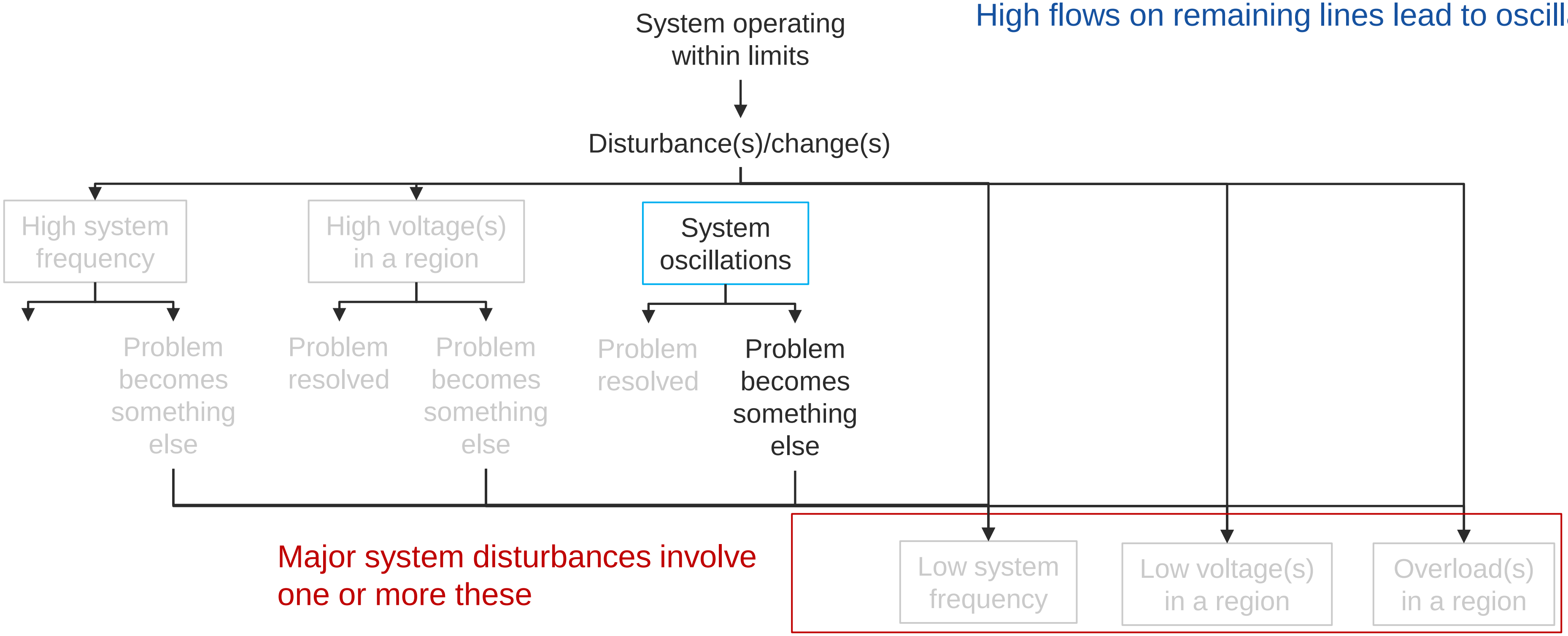
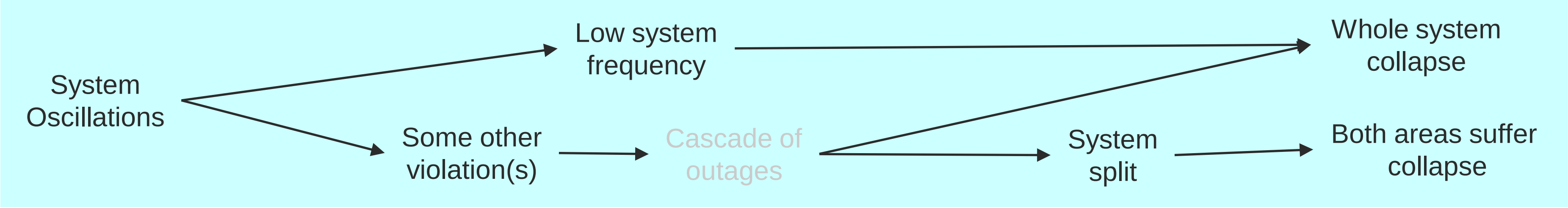
Example: Argentina 2019 blackout pathway



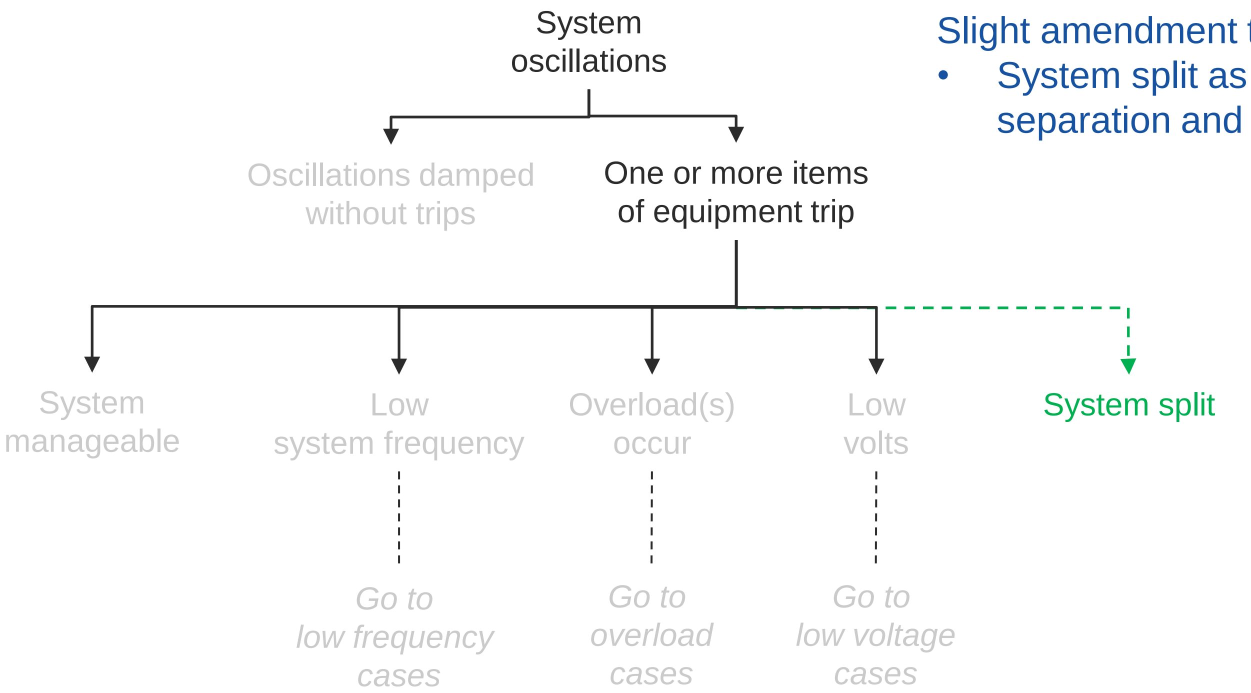
High flows on remaining lines lead to oscillation



Example: Argentina blackout pathway



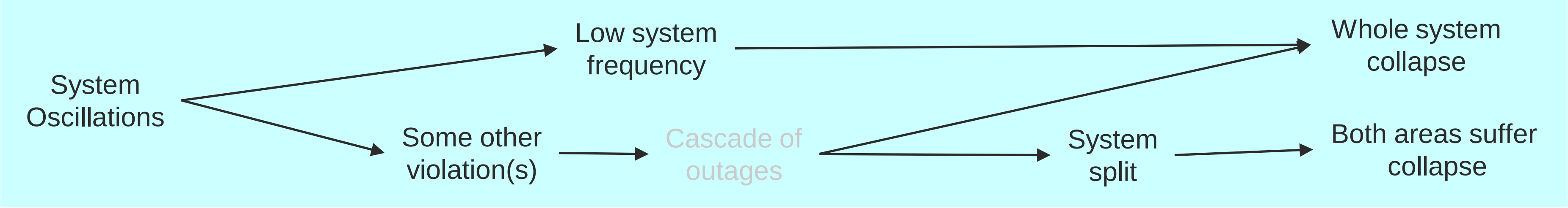
High flows on remaining lines lead to oscillation and angle separation between regions and trip of remaining two lines on corridor



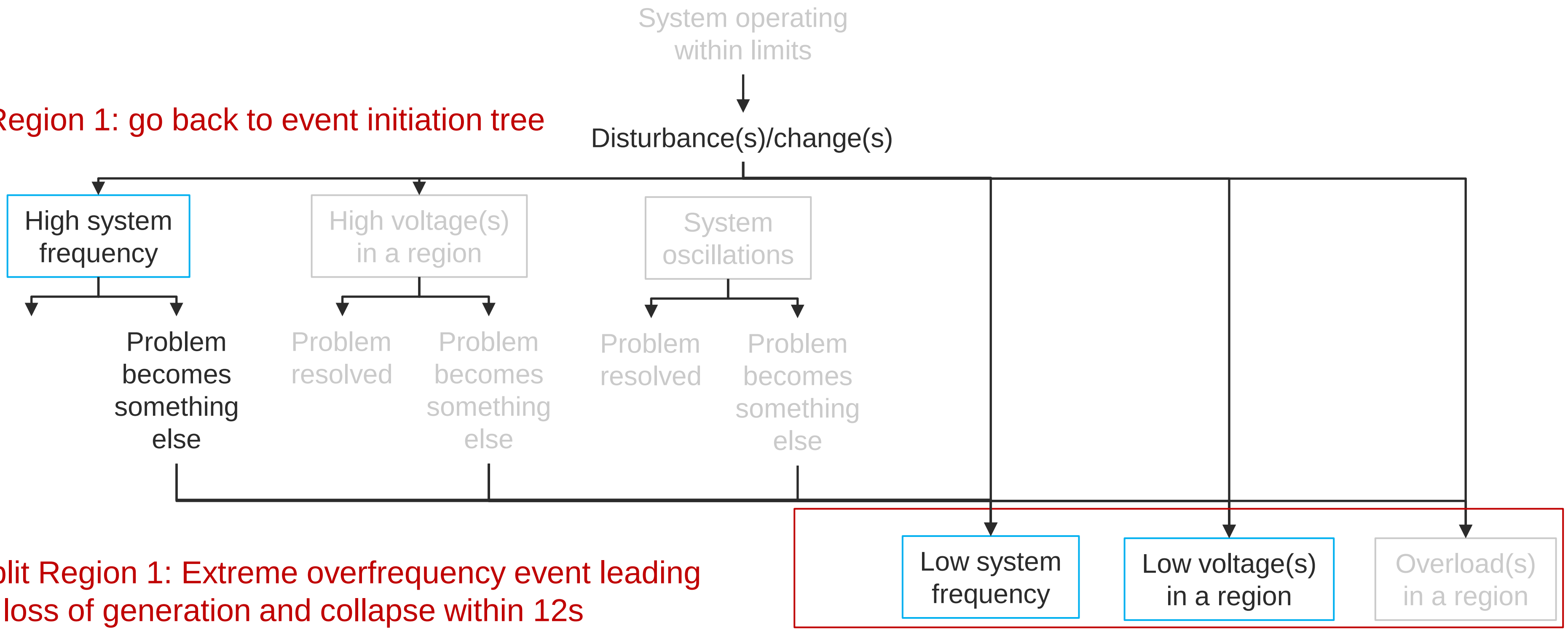
Slight amendment to conceptual model identified:

- System split as a direct consequence of angle separation and action of network protection

Example: Argentina 2019 blackout pathway



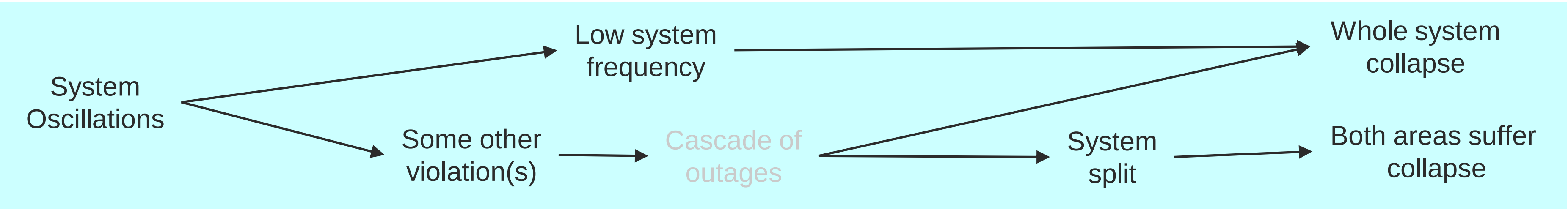
Split Region 1: go back to event initiation tree

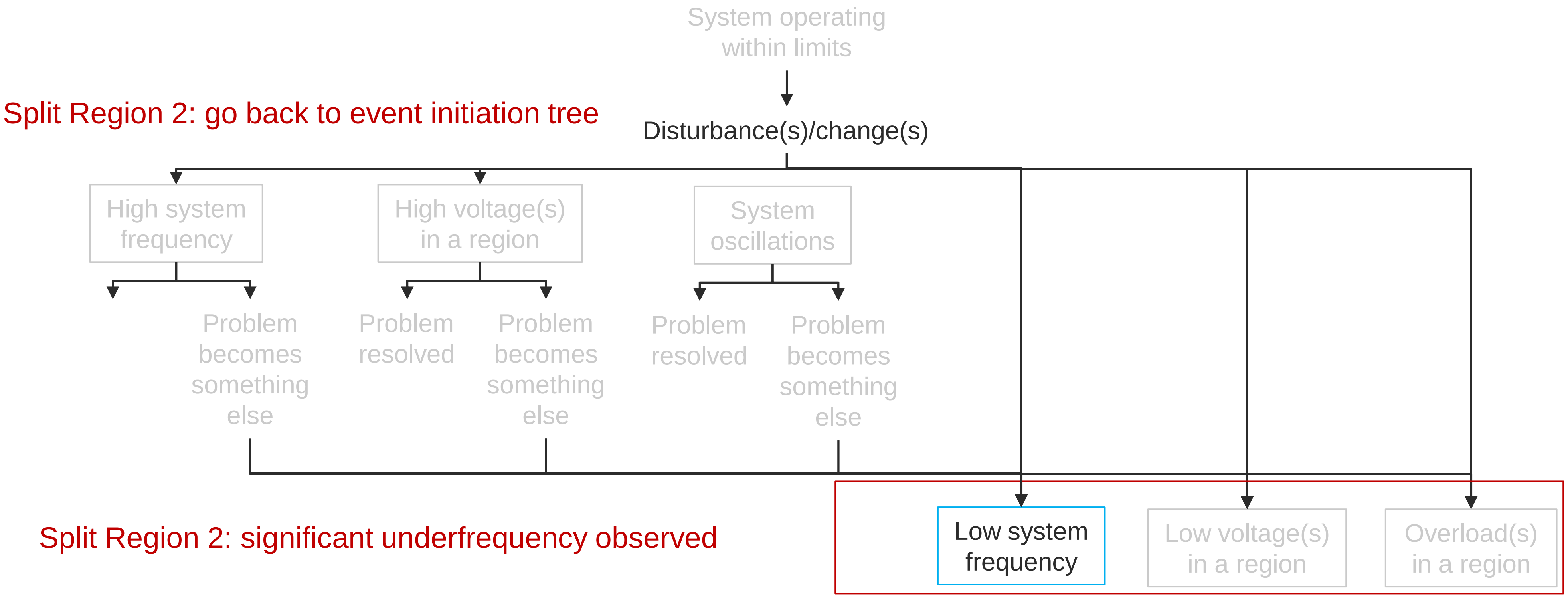


Split Region 1: Extreme overfrequency event leading to loss of generation and collapse within 12s

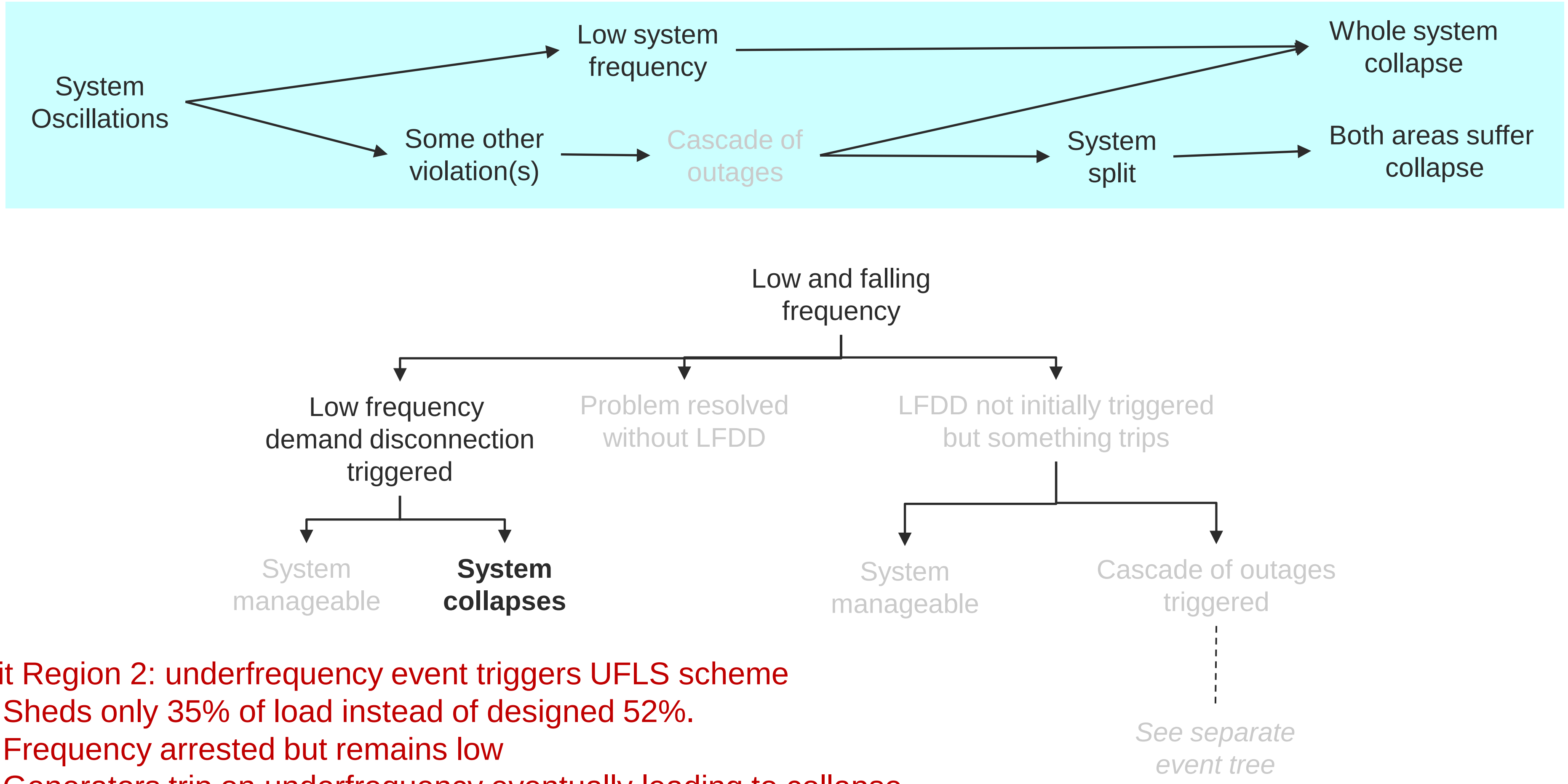
- can assume frequency and/or voltage

Example: Argentina 2019 blackout pathway





Example: Argentina 2019 blackout pathway



Split Region 2: underfrequency event triggers UFLS scheme

- Sheds only 35% of load instead of designed 52%.
- Frequency arrested but remains low
- Generators trip on underfrequency eventually leading to collapse

In total the event involves oscillations, a system split, high and low frequency conditions, failure of special protection system and underperformance of load shedding scheme.

Conclusion: Conceptual model holds with some minor tweaks. No major gaps evident in results to date

Emerging Trends: Interviews & initial insights

- 14 expert survey + interviews also conducted to illicit views of possible collapse pathways and trends to be most concerned about
- Early insight – experts rank oscillations 2nd most likely phenomena to be main cause of collapse
  - Driven by traditional angular stability
  - Also emerging challenges with HVDC and inverter based resources.
    - How controllers interact with each other and with existing systems.
    - Complex and numerous control modes – non-linearities, hard to model comprehensively.
    - A worry that recent near miss higher frequency oscillation events remain unexplained

Q. Which of the following do you expect to be the main cause of a system-wide or regional collapse? Please rank in order of likelihood

Rank	Low Frequency	Oscillations	Low Voltage	High Voltage	Overloads	High Frequency	Something Else
1	10	5	2	0	1	1	1
2	3	2	4	1	0	1	0
3	1	2	1	3	2	0	0
4	0	2	4	5	3	2	0
5	0	1	2	2	1	4	1
6	0	0	0	2	6	4	0
7	0	0	0	0	0	1	1
no rank							
Avg Rank	**1.4**	**2.3**	**3.0**	**4.1**	**4.6**	**4.8**	**4.3**

Emerging Trends: Interviews & initial insights

- Increased reliance on (often complex) special protection schemes
  - Trying to squeeze more out of given infrastructure but as history shows these introduce a point of failure
- Common mode failure risks of changing generation and demand backgrounds highlighted
  - Multiple converter control systems responding in tandem to a certain system condition
  - Coherent operation of e.g. EV charging to price or time signals (opportunities as well as risk)
- Extreme weather
  - Higher probability of line or generation outages
    - More outages in close succession; N-k conditions likely before system re-secured
  - System operated defensively given warning of impending extreme weather
    - Some interviewees judged extreme weather to not necessarily mean higher likelihood of collapse
- Insights from event review: action of generator or network protection key to cascade propagation