Fault Level Measurement Techniques in Power Systems

CIGRE Grid of the Future 2021

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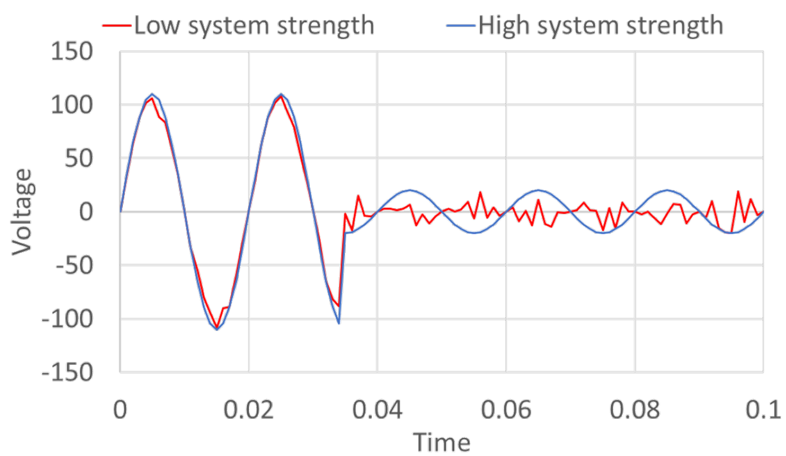
What is System Strength & why is it important?

What is it?

- Fault Level is one determinant of how well the power system can return to normal operation following a disturbance or fault, or to put it another way, **how quickly the power system voltage waveform can be restored to the consistent sine wave**



Why is it Important?

- stable operation of **Inverter Based Resources (IBR)**.
- network **voltage remains stable**, operates within a standard range during faults, switching and load disturbances.
- **protection** equipment operates correctly during disturbances.
- **Power quality is maintained**, i.e. harmonic and flicker limits are adhered to at all operating times.
- Support of the network voltage during faults and enable **rapid recovery after fault clearance**.
- Correct operation of generator control systems to support the system and **prevent undesired tripping**.
- **Avoiding commutation failure** of line commutated High Voltage Direct Current (HVDC) link

System strength keeps network voltage stable, but also increases risk of power flow through faults.

System strength is a network's resilience to voltage changes

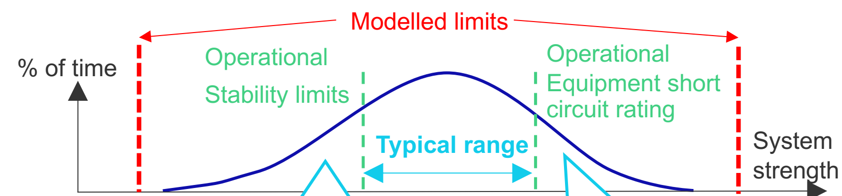
- A stable voltage waveform (amplitude and phase) is needed to meet safety specifications of power distribution equipment and grid-connected loads, and to connect non-synchronous generators, e.g., solar plants, to the grid
- Voltage deviates when disturbances take place, e.g., loads are switched on/off and/or faults occur
- System strength is needed to keep network voltage stable – the higher the system strength, the faster voltage returns back to original waveform
- Downside of high system strength are high fault currents – see right side

Increasing amounts of RE make system strength harder to estimate

- Synchronous generators, i.e. fossil fuel, nuclear & hydro plants, produce system strength as they provide voltage with the desired waveform
- Historically, most grids were in danger of too high system strengths as synchronous power plant capacities increased
- With increasing share of RE generation, which does not provide system strength as it follows grid voltage phase, too low system strength occurs
- System strength is a localised phenomenon - high levels of distributed generation complicate the traditional static modelling approach, leading to wrong values and planning assumptions

System strength defines power flow through short circuits

System strength is proportional to fault level, i.e. the power that would potentially flow through a fault or a short circuit:



System strength too low

- Safety issue in case of short circuit as protection devices do detect faults and do not operate
- Voltage stability issues
- Power quality issues (harmonics)

System Strength too high

- Fault level too high with risk of protection being underrated and not capable of interrupting fault currents

Fault level in a modern power system can change hour to hour

System Strength Calculation techniques

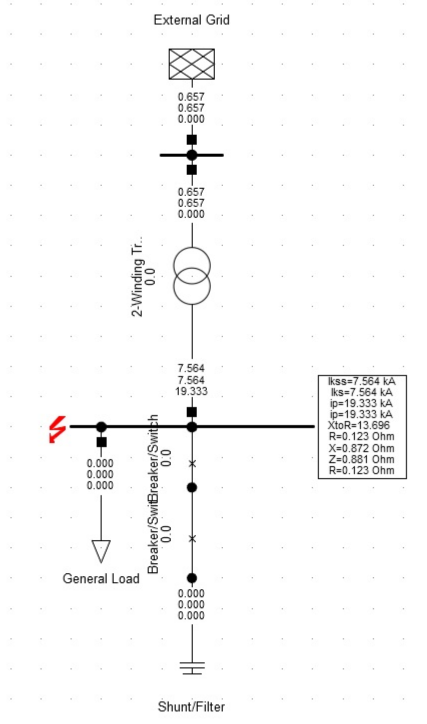
System Strength Modelling

Current standards

- IEC 60909: Short-Circuit Current Calculation in Three-Phase A.C. Systems
- European Standard EN 60909
- Engineering Recommendation G74 (in UK)

Typical modelling assumptions aim to calculate min/max fault level

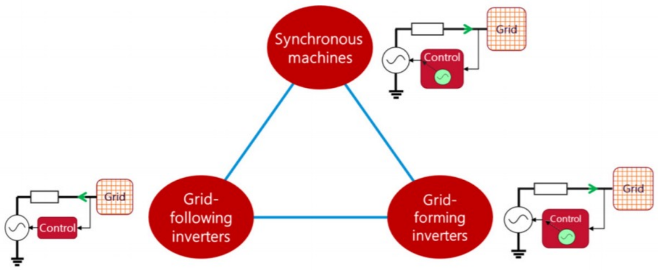
- Worst case consumer load and operational data;
- Either ignoring IBR fault contribution or modelling them as synchronous machine equivalents
- Worst case voltage and power flow scenarios.
- Worst case contingency scenarios



System strength factors and solutions

Factors Influencing System Strength:

- *IBR density*: concentration of IBRs in close proximity
- *Synchronous unit scarcity*: lack of synchronous machines
- *Network sparsity*: electrical remoteness



Source: System strength, B. Badrzadeh, Z. Emin, et al, CIGRE SCIENCE & ENGINEERING Volume No.20, February 2021, https://e-cigre.org/publication/cse020-cse-020

Possible solutions to improve system strength:

Grid forming inverters - force IBR to provide system strength and behave like conventional generation

Synchronous condensers – high cost solution to provide conventional system strength

Improved system modelling allowing the grid to be operated closer to its limits. EMT modelling of the grid including the existing grid following inverters with accurate PLL models.

Measure system strength to narrow down margins, validate modelling and enable grid control strategies.

Quantifying IBR Effect on Fault Level

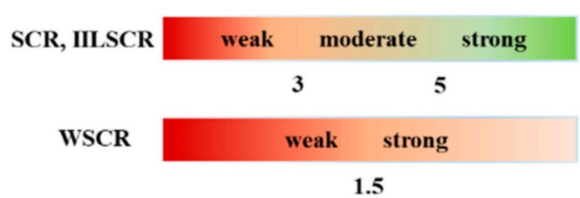
$$SCR_i = \frac{SCMVA_i}{P_{IBR_i}}$$

$$WSCR = \frac{\sum_i^N SCMVA_i * P_{IBR_i}}{\left(\sum_i^N P_{IBR_i}\right)^2}$$

$$IILSCR_i = \frac{SCMVA_i}{P_{IBR_i} + \sum_{m=1,m\neq i}^N P_{IBR_{m-i}}}$$

Where:

- SCR_i is the Short Circuit Ratio at the IBR connection bus
- $SCMVA_i$ is Short Circuit Capacity (Fault Level) at the point of interconnection (without the contribution from the IBR)
- P_{IBR_i} is the nominal power of the IBR being connected.
- $P_{IBR_{m-i}}$ is the inflowing power from nearby IBR



Source: D. Kim, H. Cho, B. Park and B. Lee, "Evaluating Influence of Inverter-based Resources on System Strength Considering Inverter Interaction Level," Sustainability, vol. 12, no. 8, 2020.

Challenges with Calculation Techniques

- **Dependence on an accurate model** including network impedance, generator loadings, voltage and IBR controller modelling.
- Requires a deep knowledge of the power system to **define interaction boundaries** in the case of WSCR metrics
- There can be **many combinations** of impedance in an interconnected network which can be difficult to pre-empt and study all edge cases.
- Online solutions in EMS require a **good state estimation** solution and thus high observability in the network. This is a known area of concern in Distribution networks.
- Dependence on voltage controller models for stability – these are dependent on the **IBR controller specifics** which require well controlled commissioning and information sharing processes for IBR.
- Studies can be **highly conservative** and can be **overly pessimistic or optimistic** depending on how these are configured.


System Strength
Measurement techniques
reactive
technologies

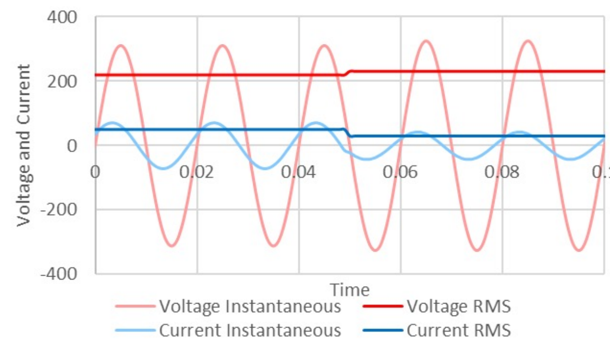
How can we measure System Strength?

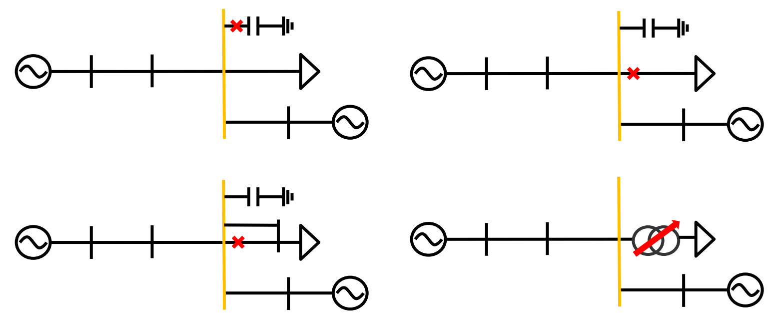
System Strength can be calculated during network events both large and small.

Fault impedance is determined from grid events on radial feeders with the Thevenin equivalents formula:

$$Z_{FL} = -\frac{\Delta\vec{V}}{\Delta\vec{I}} = -\frac{\vec{V}_{post} - \vec{V}_{pre}}{\vec{I}_{post} - \vec{I}_{pre}} \quad \text{[ohms]}$$

$$S_{FL} = \frac{3 \times {V_{pre}}^2}{Z_{FL}} \qquad \text{[MVA]}$$

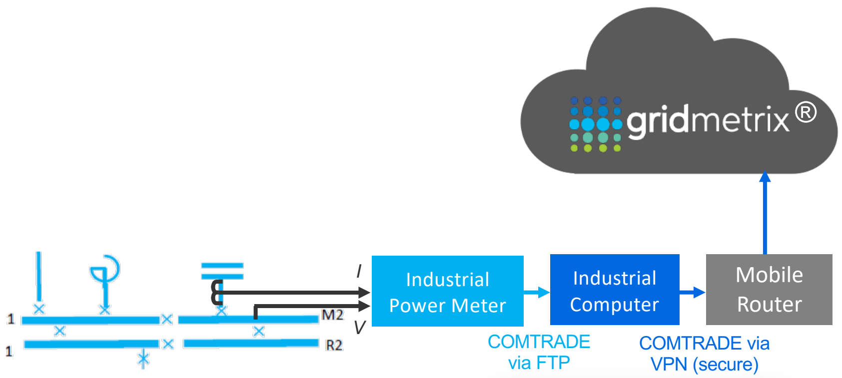




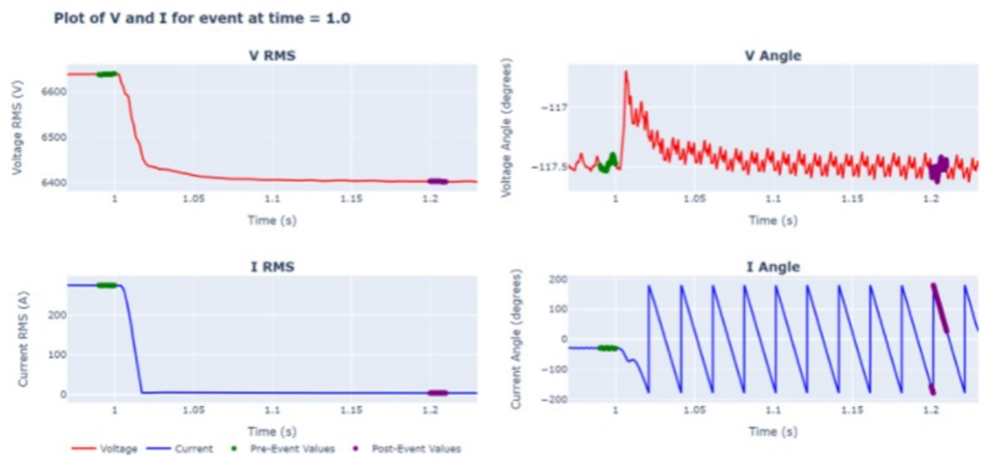
Passive measurements: recorded as they occur naturally in the grid from sudden changes in load, faults and transformer tap changes.

Active measurements: generated by inducing small voltage fluctuations (<0.2%)

Real world example



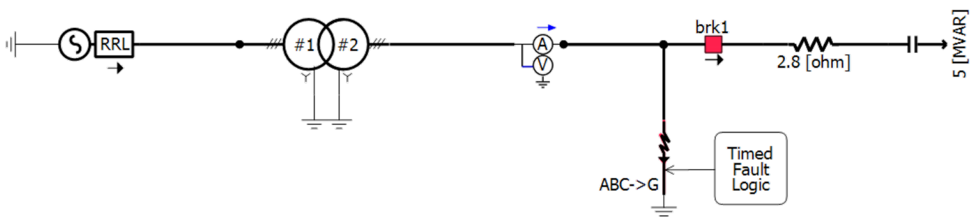
- 11 kV busbar
- Shunt capacitor

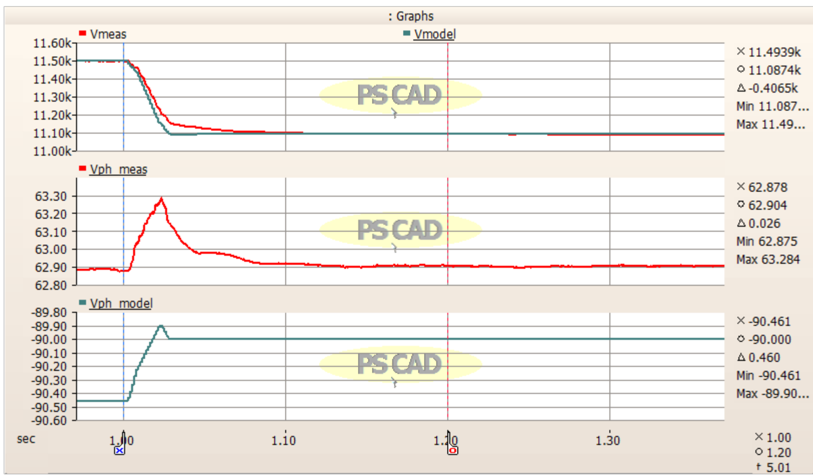


	Thevenin Equivalent			EMS calculation	Error
Event	Vpre [kV]	Z [Ohms]	Isc [kA]	Isc [kA]	%
Switch in	11.422	0.829	7.955	6.90	15.29
Switch out	11.497	0.849	7.819	6.90	13.32

Which one is wrong?

Simulated Equivalent





	PSCAD			Script		Error
Event	Vpre [kV]	Z [Ohms]	Ik'' [kA]	Z [Ohms]	Ik'' [kA]	%
Switch in	11.422	0.884	7.462	0.829	7.955	6.60
Switch out	11.497	0.916	7.243	0.849	7.819	7.96

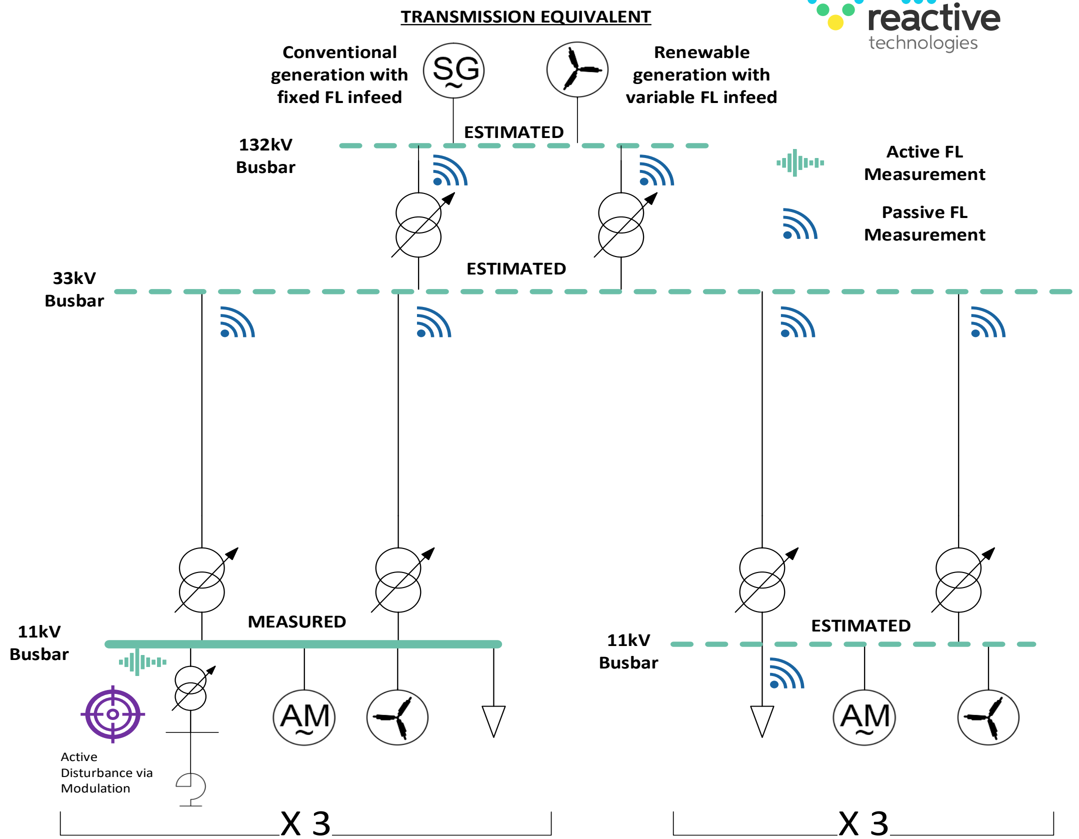
Simulated Network

Typical distribution grid supply point including
- inverter connected generation
- motors

Transmission equivalent
- Includes synchronous and renewable infeeds
- This was varied to reflect grid dynamics

Time-series EMT simulations
- Instantaneous voltage and currents recorded throughout the grid

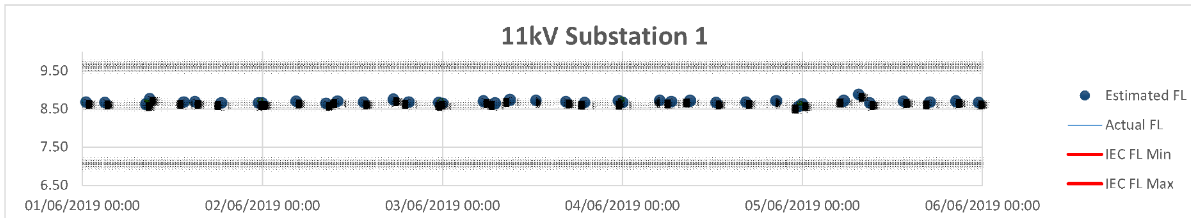
Typical Fault level calculations in parallel for validation

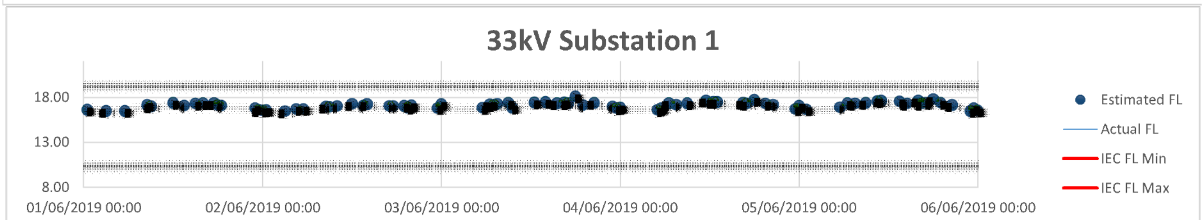


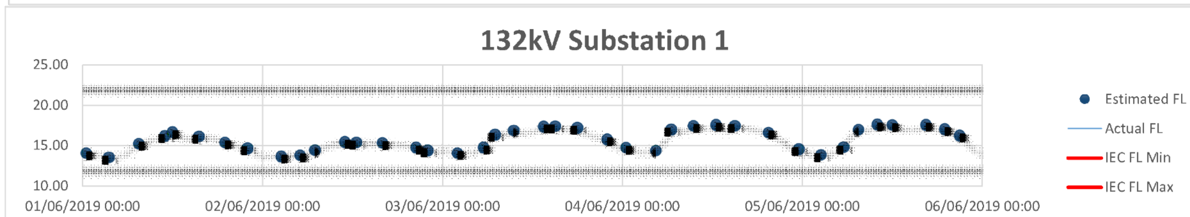
Studies and Results

Measured vs calculated fault level over time at different voltage levels

Substation	Voltage	Passive Error	
		MAX	MAPE
132 kV Substation 1	132	2.51%	1.02%
33 kV Substation 1	33	2.73%	0.87%
11 kV Substation 1	11	3.63%	0.86%
11 kV Substation 2	11	1.26%	0.31%
11 kV Substation 3	11	2.28%	0.56%
11 kV Substation 4	11	7.28%	1.27%
11 kV Substation 5	11	1.61%	0.41%







Challenges with Measurement Techniques

- The use of near-nominal disturbances assumes the system behaves similarly during fault events, but **controllers and saturation will reduce fault current during faults**.
  - This does not mean the results are useless but must be used with caution as the fault current during events could be lower.
- The **calculation of RMS values can be tricky** and lead to varying results in the subtransient and transient periods.
  - For **SCR and voltage stability studies the synchronous impedance is sufficient** but for **protection studies the subtransient and transient values are required**.
- The **selection of the samples for use within the equation is not trivial** and leads to errors in the results. Again, this largely relates to the timing aspect of the results.
  - If the synchronous period is required, these can relatively easily be obtained even with weaker RMS computation (such as with the use of synchrophasors).

Conclusions

- Calculation techniques
  - Limited and based on assumption.
  - Models must be validated for both low and high fault level constraints
  - IBR dynamics difficult to capture
  - Accurate simulation cases, load and generation modelling is critical
- Measurement techniques
  - Accuracy within <10% (can be improved)
  - Using more measurements statistically increases accuracy significantly (<2%)
  - Timing and sample selection greatly affects results
  - Synchronous time periods is more accurate (required for voltage stability)
  - Could bridge the gap operationally between now and when complete models are available

Thank You