21, rue d'Artois, F-75008 PARIS
http://www.cigre.org

CIGRE US National Committee
2021 Grid of the Future Symposium

Fault Level Measurement Techniques in Power Systems

B. BERRY, D. GHEORGHE
Reactive Technologies
United Kingdom

SUMMARY

In modern power systems, with high integration of distributed energy resources (DER), low fault level and system strength are becoming more common constraints. However, the worst-case scenario for low fault level is hard to predict and model accurately, therefore direct measurements could help mitigate this uncertainty.

This paper lists various methods for evaluating System Strength, including traditional methods (IEC60909, ANSI/IEEE C37) to determine the short circuit ratio, and measurement techniques that use Thevenin Equivalents. Traditionally, the Thevenin Equivalents (TE) method has been used to simplify circuits, no matter how complex, to an equivalent circuit with just a single voltage source and a single series impedance. It is a widely accepted and powerful tool used regularly in simulation models and also in the power system using high-speed measurements. The implementation of these techniques is not trivial, and misuse of the algorithm can lead to erroneous data. This paper will explore these applications as well as the techniques used to measure TE in the real power system. When used with diligence, these measurements can be very powerful, allowing for a less model-based approaches for power systems which are increasing in complexity. Measurements allow for the trustworthy use of models by providing means of model validation, model reduction and equivalencing.

This paper investigates how TE can be used for measuring Fault Level from near-nominal disturbances, the type of measurements required, suitability of PMU and synchronised instantaneous measurements considering their limited sampling rate and filtering.

KEYWORDS

System Strength, Short Circuit Ratio (SCR), Short Circuit Capacity, Short Circuit calculation, Fault Level, Thevenin Equivalent

brianb@reactive-technologies.com

INTRODUCTION

Traditionally, fault level and system strength were not areas of concern as they were straightforward to calculate, with the only embedded fault current contribution coming from rotating machines. Since the steep uptake of distributed energy resources (DER), grids have become increasingly complex not only because DER is connected through everchanging inverter technologies, but also because of the complex running arrangements of the grids and sometimes via automated control schemes (ANM or DERMS). In these circumstances, the standard methods, [1] and [2], of evaluating maximum and minimum fault level are no longer appropriate as they can lead to either inaccurate results or overly conservative estimates.

WHAT IS SYSTEM STRENGTH AND WHY IS IT IMPORTANT?

According to AEMO (Australian Energy Market Operator), System Strength is an inherent power system characteristic – it is a measure of its stability under all reasonably possible operating conditions. A key component of this relates to the size of the change in voltage following a fault or disturbance on the power system. 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 [3].

System strength is important for the maintenance of normal power system operation, for the power systems dynamic response during a disturbance, as well as for returning the power system to stable operating conditions. Adequate system strength is required to ensure:

- 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 CALCULATION TECHNIQUES

IEC 60909: Short-Circuit Current Calculation in Three-Phase A.C. Systems [1] provides the baseline for the manual calculation of short circuit currents in a three phase A.C. system. Further standards were derived from IEC 60909 such as the European Standard EN 60909 [4] and the Engineering Recommendation G74 [5] in the UK which, in addition, address the issue of fault contribution from electrical motors and the utilisation of pre-fault voltages based on load flow studies rather than applying “voltage C factors”. More recently (2016), the latest versions of IEC 60909 [1] include more complex DER models further increasing the accuracy of fault level calculations. Although these standards provide accurate fault level calculations, their main limitations are the accuracy and level of detail of the network model as well as the unrealistic

generation and demand levels considered. These factors together lead to overly conservative results which in turn could result in unnecessary investment.

In essence, the main source of error of the standardised method is the voltage C factor multiplier assumption, demonstrated in Table 1. The voltage is a key component of the fault level calculation and is affected by the following:

- Consumer load and operational data;
- Transformers' tap position;
- Variability of inverter connected generators fault contribution with their actual power output level;
- Voltage variations and actual load flow data.

Table 1: Voltage C Factor

Nominal Voltage	Maximum Short Circuit Currents	Minimum Short Circuit Currents
Low Voltage 100 V – 1000 V -systems with a tolerance of 6% -systems with a tolerance of 10%	 1.05 1.10	 0.95 0.95
Medium Voltage > 1 kV – 35 kV	1.10	1.00
High Voltage > 35 kV	1.10	1.00

The voltage variations are typically handled in simulation by considering the worst and best case scenarios, i.e. maximum and minimum short circuit currents. However, in a modern power system with far more generation flexibility, these scenarios are not as easy to predict and the following assumptions are being challenged:

- Transmission fault infeed – these values are far more volatile with higher generation flexibility and IBR infeed
- Voltage support from IBR – this is difficult to model as it is highly dependent on the IBR controller tuning and setpoints. Many simulations assume this to be constant or do not consider this interaction. In the worst case, these are sometimes modelled as synchronous machines for simplicity, but this leads to highly conservative results.

To remedy these challenges, the complete short circuit method can be used where the load flow results for voltage are used in the short circuit calculations. This method becomes highly dependent on the state of the network which can create a large amount of study cases. In some cases, utilities will run short circuit calculations 'online' in their Energy Management Systems (EMS) to have the latest network status considered. This, of course, requires a highly accurate model and state estimation solution in the online system models.

System Strength in Planning studies

Fault level is carefully considered during planning and design of the power system or connection of new plant. For this, a metric known as Short Circuit Ratio (SCR) is traditionally used. This is the most basic metric to determine the relative strength of a power system. As shown in Equation 1, SCR is defined as the ratio between short circuit apparent power (SCMVA) from a 3-phase Line to Ground fault at a given location in the power system to the rating of the inverter-based resource connected to that location [6].

$$SCR_i = \frac{SCMVA_i}{P_{IBR_i}} \quad (1)$$

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.

During studies, an SCR of lower than 3 is considered weak and values over 5 are considered strong. This metric doesn't consider the interaction of the nearby IBR so several methods which consider the interaction of IBR nearby have been researched globally [7]. The Weighted SCR (WSCR) uses SCR at each interacting IBR but weights it by the nominal power over the square of the sum of all contributing IBR (Equation 2).

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

Where:

- $SCMVA_i$ is the 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.

It is noted that the WSCR cannot be compared to SCR and a weak connection is considered to be anything under 1.5. The weighted short circuit ratio has been used successfully for IBR connection studies in Texas [8], but it can be difficult to apply in practise as it challenging to define boundaries to a study area and to know which IBR to include in the calculation. Of course, including different IBR in the equation will lead to significantly varying results.

One suggested method of overcoming this is to use the 'inverter interaction level short circuit ratio' (IILSCR) [6, 9]. Here the power contribution from nearby IBR is determined using a weighted matrix that is determined from the power capacity of the IBR and the transmission lines between the bus of interest and the IBR (shown in Equation 3).

$$IILSCR_i = \frac{SCMVA_i}{P_{IBR_i} + \sum_{m=1, m\neq i}^N P_{IBR_{m-i}}} \quad (3)$$

Where:

- $SCMVA_i$ 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

Figure 1 shows the various acceptance ranges of the SCR, WSCR and IILSCR methodologies. It is noted that these are but a few of the methods available and the standard methodology has not been defined for global best practise. Each of these methods have advantages and disadvantages – choosing the right metric is a function of both accuracy, and ease of use.

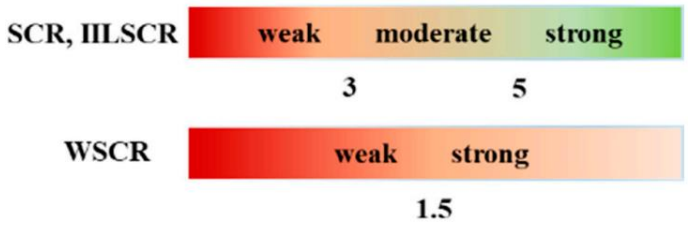

Figure 1: Graphical representation of what is considered an acceptable SCR, IILSCR or WSCR [6]

CHALLENGES WITH CALCULATION TECHNIQUES

Calculation techniques are required for future planning models but in the Operational environment are very conservative in either the high or low fault level calculation. Calculation methods are prone to the following considerations:

- 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.

When used diligently and carefully, models can be accurate and highly useful for mitigating power system instability. When used incorrectly, these hide the problems which are typically only discovered after a failure of plant or underperformance of the grid in practise.

SYSTEM STRENGTH MEASUREMENT TECHNIQUES

At a high level, the calculation of the fault level uses the concept of Thevenin Equivalents. Here, the source impedance is calculated from the small movement of voltage and current during an event on a radialised region of the network. The source impedance is calculated according to Equation 4 which is a ratio between the change in voltage over the change in current on the radial [9], [10], [11].

$$Z_{FL} = -\frac{\Delta\vec{V}}{\Delta\vec{I}} = -\frac{\vec{V}_{post} - \vec{V}_{pre}}{\vec{I}_{post} - \vec{I}_{pre}} \quad (4)$$

Where:

- Z_{FL} is the source impedance
- $\vec{V}_{pre}$ & $\vec{I}_{pre}$ are the pre-disturbance voltage and current phasor measurements respectively
- $\vec{V}_{post}$ & $\vec{I}_{post}$ are the pre-disturbance voltage and current phasor measurements respectively

The source impedance value is then used to calculate the fault level as per Equation 5.

$$S_{FL} = \frac{3 \times {V_{pre}}^2}{Z_{FL}} \quad [\text{MVA}] \quad (5)$$

Where:

- S_{FL} is the fault level in MVA
- Z_{FL} is the source impedance
- $\vec{V}_{pre}$ is the pre-disturbance voltage phasor

This concept is applied to near-nominal voltage events. Near-nominal here refers to small and fast sag/swell events in the range of 1% and lower. A simplified example of such an event is shown in Figure 2. Here a small increase in voltage is observed during a decrease in current which is typical of a small industrial load being disconnected from the grid. In this case the source impedance is easily calculated because the event is 'clean'; meaning it is free of noise; but in practise, the measurements will have noise that must be removed by the algorithm to calculate fault level accurately.

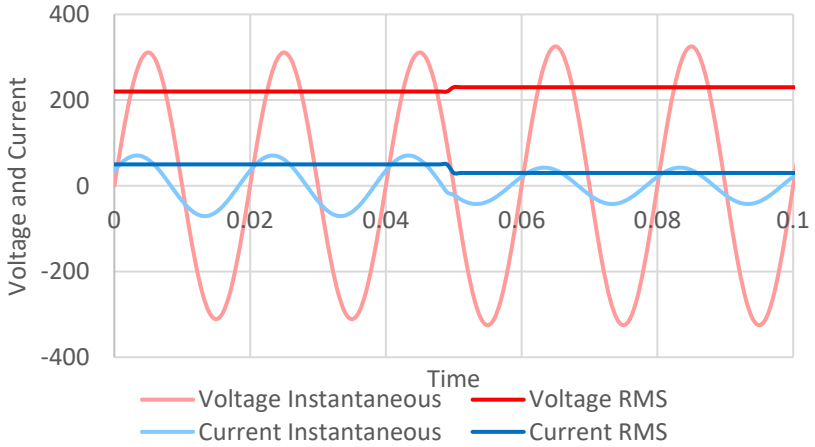

Figure 2: Simplified instantaneous and RMS voltages and currents during a near-nominal event

Figure 3 shows the event scenarios that can be used for the calculation of fault level. The fault level for the yellow-coloured bus is calculated for events shown by the red indicator. These are:

1. A reactive device switch event (top left)
2. A load step change event (top right)
3. A line switch event (bottom left)
4. A transformer step change event (bottom right)

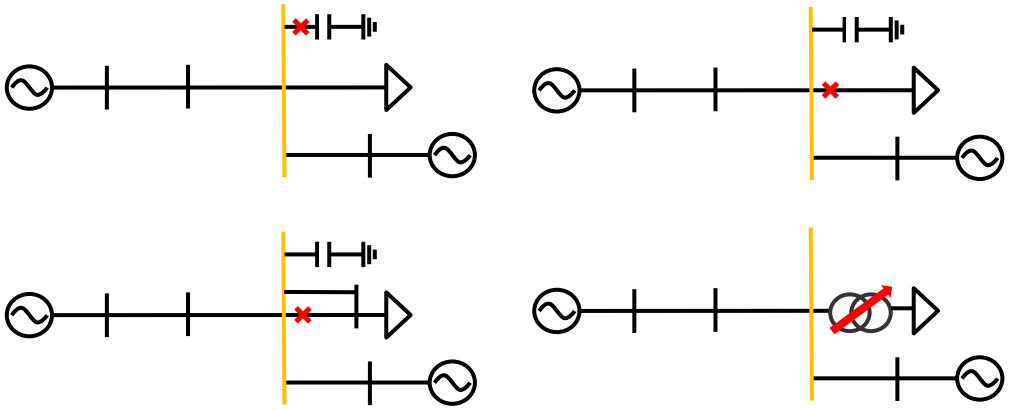

Figure 3: Examples of normal network events that could be used to calculate the fault level. (top left) shunt switching event, (top right) load step change, (bottom left) line switch event, (bottom right) transformer tapping event

In Figure 4, a real event from an 11 kV shunt capacitor switching event is shown. It is clear that it has noise and transients in the voltage and current measurements - the first challenge this presents is for the calculation of RMS values from the instantaneous waveforms. Some papers refer to the use of synchrophasor (PMU) measurements for this, but it is important to note that most M-class PMUs have 5-7 cycle filter windows (~100ms) to meet IEEE C37.118.1 2011/2014a standard compliance. This means that PMU-based results are likely possible for the measurement of the voltage recovery portion of an event (synchronous timeframe) but unlikely to yield accurate results in the subtransient and transient timeframes. Put in other words, PMUs are useful for the 'break' values of short circuit current but not accurate to measure the 'peak' values. Utilising instantaneous waveforms for this calculation is a better approach, as the RMS calculation can be tweaked to achieve the best results and can be used to potentially measure the peak current response on larger events.

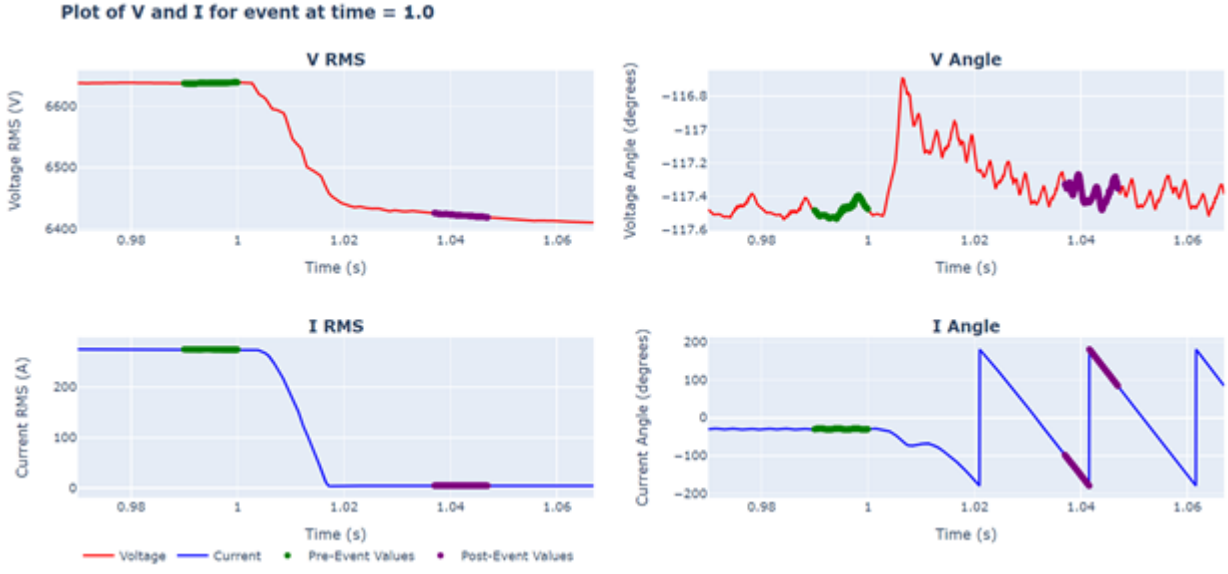

Figure 4: Example of a Thevenin Equivalent calculation of SCR from a shunt capacitor switching event.

The results from the capacitor switching can be seen in Table 2. It is observed that the TE method has difference of 12-19% but this is not necessarily attributed to error since the EMS models are prone to modelling error. As expected, the voltage measurement has a significant influence on the fault current.

Table 2: Results of Thevenin Equivalent method vs an EMS calculation

	Thevenin Equivalent			EMS calculation
Event	**Vpre [kV]**	**Z [Ohms]**	**Isc [kA]**	**Isc [kA]**
Switch in	11.401	0.751	7.74	6.90
Switch out	11.538	0.774	8.23	6.90

For further validation, the event was mimicked in Digsilent PowerFactory to determine a true reference for which to compare results. The simulated system, shown in Figure 5, is a simple infinite bus with a finite fault level specified, a load and shunt capacitor. The results can be observed in Table 3 with errors of less than 10%.

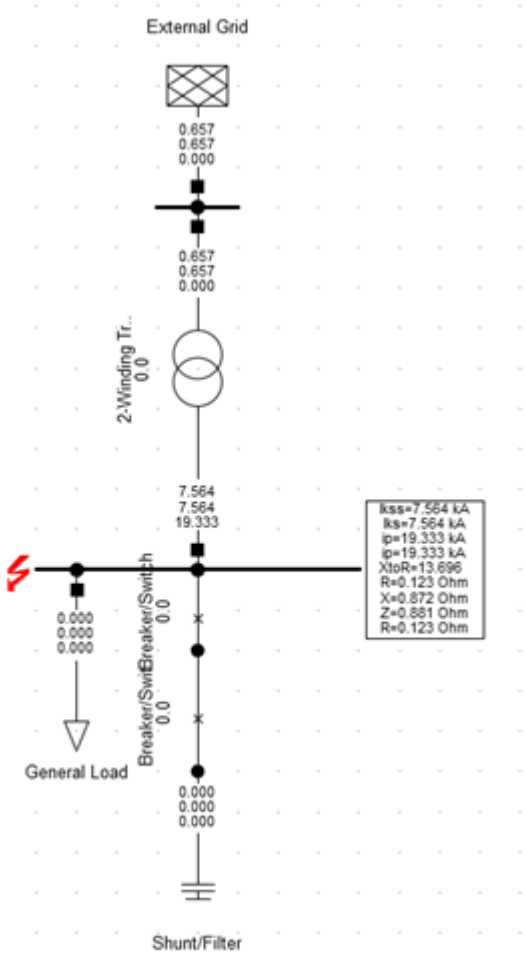

Figure 5: Simplified system used to simulate a capacitor switching event

Table 3: Results comparison of Thevenin Equivalent vs simulation

		Digsilent		Script		Error
Event	**Vpre [kV]**	**Z [Ohms]**	**Ik'' [kA]**	**Z [Ohms]**	**Ik'' [kA]**	**%**
Switch in	11.401	0.828	7.972	0.751	7.74	**-2.9%**
Switch out	11.538	0.881	7.564	0.774	8.23	**8.8%**

Further to this simplified model, a larger model representing a 132 kV to 33 kV and 11 kV Grid Supply Point was in the UK was modelled. Here multiple days of loading scenarios reflecting both heavy loading (winter) and light loading (summer) were simulated. Disturbances were sporadically created to enable the calculation of 'passive' Thevenin Equivalent calculations over the full time period. Figure 6 show the results from these simulations. It is noted that the solid blue line represents the simulated results (true fault level) whilst the dots represent the Thevenin Equivalent calculated every time there is a near-nominal disturbance. It is important to note that the simulated results use the complete method and very accurately represent the system state – typical simulated results would be on the extremities (i.e. minimum and maximum) of the fault level trend rather than following the load. Table 4 summarises these results – here the mean absolute percentage error is typically around 5% but does increase to 15.75 % in the case of the 33 kV busbar. Whilst these results are not definitive, it shows that fairly accurate results can be achieved, and the method does not require a power system model. This could be a powerful means for validating models. Especially if quantified with many disturbances over time.

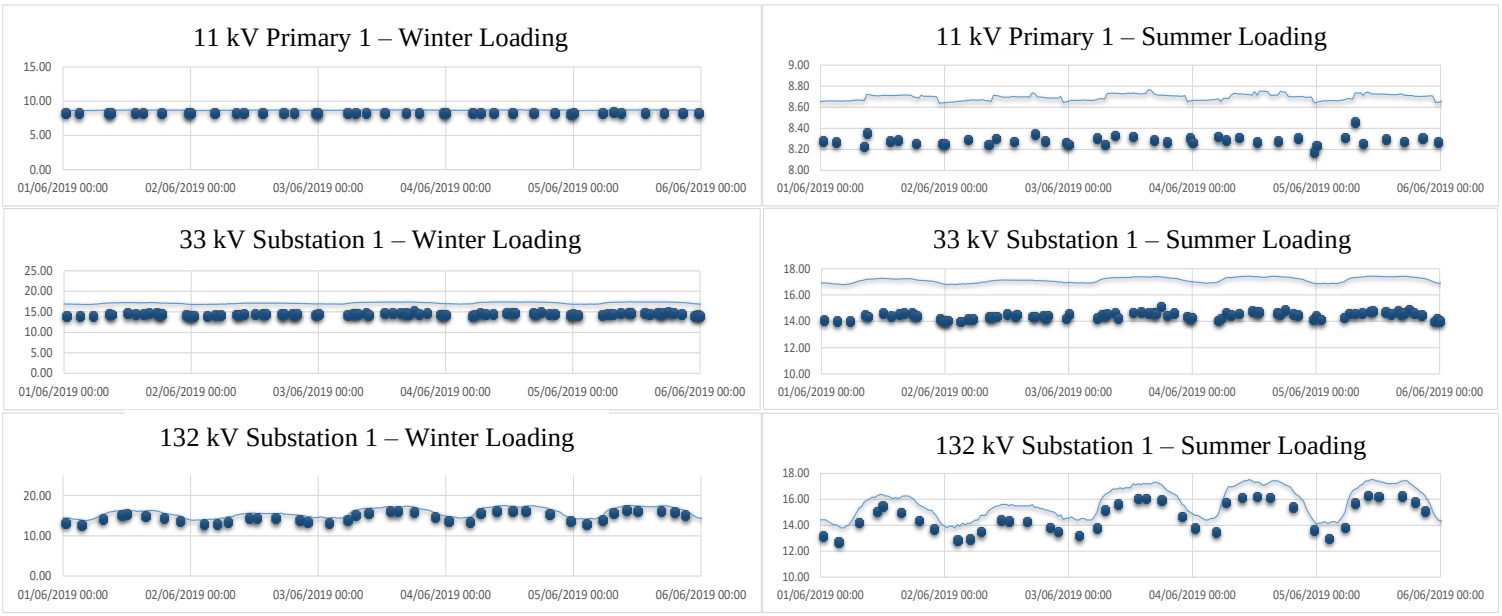

Figure 6: Thevenin Equivalent results compared to modelled results from the complete method.

Table 4: Results from the Thevenin Equivalent wide scale simulation

Substation	Voltage	Passive Error	
		MAX	MAPE
132 kV Substation 1	132	8.39%	6.91%
33 kV Substation 1	33	17.53%	15.75%
11 kV Substation 1	11	7.72%	4.45%
11 kV Substation 2	11	5.46%	4.30 %
11 kV Substation 3	11	5.50%	4.48%
11 kV Substation 4	11	10.14%	3.32%
11 kV Substation 5	11	5.49%	4.62%

CHALLENGES WITH MEASUREMENT TECHNIQUES

The results shown above are encouraging as are those presented in the referenced papers. However, the methodology is not without its challenges. The following considerations must be taken into account when using Thevenin Equivalent measurements of fault level.

- 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).

CONCLUSION

System strength and fault level are important metrics for determining the voltage stability of the power system, particularly when inverter-based resources are dominant and can interfere with each other. There are several calculation methodologies available, each with certain trade-offs – in particular the trade-off is typically between ease of use and accuracy. The best practice for fault level and short circuit ratio calculations is not yet standardised globally. Regardless of the standardisation, many utilities have much work to bring their power system models (both offline and online) up to a standard that will yield consistent and trustworthy results. As such, measurement methodologies could provide a good steppingstone to help fill the gap and validate the accuracy of models whilst the these are brought up to a higher accuracy standard. The Thevenin Equivalent methodology shows promise but must be used with care, particularly if being utilised for fault studies. In the case of voltage stability, this presents a useful means of validating existing models. These measurements could already be available in power systems by making disturbance recorders more sensitive and storing the data in a low-cost data storage environment (like the Cloud).

BIBLIOGRAPHY

[1] "IEC 60909 Short-circuit currents in three-phase a.c. systems - Part 0: Calculation of currents," 2016.

[2] ANSI/IEEE Std. C37.010-1979, Application guide for AC high-voltage circuit breakers rated on a symmetrical basis..

[3] AEMO Operational Analysis and Engineering, "System Strength Requirements Methodology - System Strength Requirements & Fault Level Shortfalls," 2018.

[4] BS EN 60909-0 Short-circuit currents in three-phase a.c. systems. Calculation of currents, 2016.

[5] Engineering Recommendation G74, 1992.

[6] 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.

[7] North American Electric Reliability Corporation, “Integrating Inverter Based Resources into Low Short Circuit Strength Systems - Reliability Guideline,” Atlanta, 2017.

[8] J. Matevosyan, “ERCOT’s Experience Integrating High Shares of IBR,” 6 June 2021. [Online]. Available: https://www.wingrid.org/wp-content/uploads/2021/08/13-Julia-Matevosyan-ERCOT-Integrating-high-shares-of-IBR.pdf. [Accessed 30 August 2021].

[9] M. Jamei, A. Scaglione, C. Roberts, A. McEachern, E. Stewart, S. Peisert and C. McParland, “Online Thevenin Parameter Tracking Using Synchrophasor Data,” IEEE, 2017.

[10] E. S. Ibrahim, “Experimental Measurements of Fault Level For Sceco West, Kingdom of Saudi Arabia,” JKAU: Eng Sci. vol15 no. 1, Jeddah, 2004.

[11] S. Polster, “Thevenin Impedance for voltage stability - Estimation of the Thevenin Impedance in Power Transmission Systems,” Institut für Elektrische Anlagen Technische Universität Graz, Graz, 2016.