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Assessing Short Circuit Levels as a Measure of System Strength in Future Grids with Uneven Distribution of Inertia and High Percentages of IBR

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***Abstract*—In power system analysis the system strength and suitability for connection of Inverter Based Resource (IBR) generation and disturbing loads is considered in terms of fault level and Short Circuit Ratio (SCR). This paper shows that with the increasing penetration of IBR and changes to the distribution of system inertia, such an approach overestimates system strength. This paper proposes an alternative approach using time domain Root Mean Square (RMS) / Electromagnetic Transient (EMT) simulation methods to analyse the system's ability to deliver energy over time in relation to small perturbations. This is demonstrated through the use of a test network, where uneven inertia distribution and increased fault levels due to IBR are shown to give misleading results.**

Keywords— EMT, Fault Level, Inertia, RMS and SCR.

I. Introduction

A. Introduction

In power system analysis, the network fault level is widely used as a measure of system strength and the ability to withstand disturbing loads and as a way of assessing the suitability for connecting Inverter Based Resources (IBR) generation and loads. This paper shows that with the increasing penetration of IBR generation and an uneven distribution of inertia, system strength represented by simple fault level calculation methods can be misleading. An alternative method of determining Relative System Strength (RSS) as a ratio of the ability of small signal disturbance to fault level, is proposed as a more robust method for assessing system strength.

Fault level calculation methods are well established through formal standards and procedures such as IEC 60909 [1] and IEEE C37.010 [2]. These remain popular and widely used analysis approaches, due to their computational speed and efficiency. In recent years, a number of researchers have considered modification to these standards to more accurately consider the impact of IBR on fault current methods [3], [4] & [5].

The use of Short Circuit Ratio (SCR) as a screening tool to identify potential problems for assessing connection of IBR generation to the network is widely adopted. The SCR being the ratio of the system strength in MVA_{SC} is compared to the proposed generation rating in MVA as shown in Equation (1). The use of SCR as a connection metric is widely accepted in literature and commercial practice. It is however recognised that there are potential shortfalls of such formal fault level analysis, and assessment using Root Mean Square (RMS) or Electromagnetic Transient (EMT) analysis methods is necessary [6], [7], [8], [9], [10] & [11].

The relevance of inertia in power systems is well understood, and has been studied extensively in both large and small networks [12] & [13]. More recent investigations have noted that an uneven distribution of inertia in a power system, can lead to localized variations of frequency in weak areas of the network during system disturbances, [14] & [15]. Formal fault calculation methods assume the upstream network source has a fixed frequency, and thus these methods will not fully consider weak and remote networks frequency response during disturbances.

B. Motivation & Contribution to Knowledge

The contribution of this paper is to show how the current consideration of fault level and SCR using simplified formal fault analysis methods such as IEC 60909 and IEEE C37.10 are leading to overestimation of actual system strength, for screening studies. The paper proposes that system strength should be considered as a ratio of available energy for small disturbing loads to fault level, using time domain techniques such as RMS, and EMT modelling.

II. Fault Level and System Strength

A. Fault Level Calculation Methods

Traditional fault level analysis performed with methods such as IEC 60909 and IEEE C37.10, are simple, robust, and widely used to determine maximum fault levels and system strength. These methods rely on various simplifications to determine the system impedance and fault contribution from generators to determine the fault levels. These methods generally work off the assumption of an idealised voltage source behind an equivalent impedance.

The simplifications used in formal fault level calculations allow the process to be carried out in a fast and computationally efficient method; are based on the underlying assumption that the contribution from IBRs is small compared to the overall network and is delivered instantaneously. These standards however, do not fully consider the fault contribution from IBR generator, leading to limitations and inaccuracies.

IEC 60909 assume that all IBRs are of a Grid Following (GFL) type, and does not consider Grid Forming Inverters (GFM). Whilst IEEE C37.010 neglects the contribution as small. GFM technology is often defined as a Virtual Synchronous Machine (VSM), which behaves in a similar manner to a synchronous machine, and can also provide so-called synthetic inertia, [16] [17]. It can therefore be seen that formal fault calculation standards contain a number of gaps, in relation to weak networks with a high percentage of IBRs.

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B. Short Circuit Ratio

SCR is used widely in many applications as a tool to estimate the system strength and suitability for potential connection of new generation as well as certain types of loads. SCR is generally defined as the ratio of the system short circuit strength (MVAsc) to the MVA rating of the proposed connection, as shown below in Equation (1).

$$SCR = \frac{MVA_{sc}}{MVA_{gen}} \tag{1}$$

The value of the SCR is often used as an identifier of a weak, system and where disturbances could potentially occur. Values of 3 < SCR < 5 are used to identify weak systems and a value of 3< SCR is used to identify a very weak system. The importance of SCR has multiple implications, and low SCR networks can be more susceptible to disturbances from fluctuations in the IBR output, and in the stability of the control systems such as the phase locked loops (PLL) .

Alternate methods have been considered for Equivalent Short Circuit Ratio (ESCR), Composite Short Circuit Ratio (CSCR) and Weighted Short Circuit Ratio (WSCR) [8] & [10]. The ESCR method utilises an adjustment factor for the fault level based on the magnitude of voltage disturbances on adjacent busbars *ij* as indicated below in Equation (2). The CSCR method, uses an approach of grouping all similar technologies in the same area, to a single equivalent machine as indicated in Equation (3). The WSCR method uses a simple weighting factor to the SCR value against the total connected IBR generation, as indicated in Equation (4). The methods are discussed in detail in [8].

$$ESCR = \frac{S_i}{P_{WFi} + \sum_j \left(WPIF_{ji} * P_{WFj}\right)} \tag{2}$$

$$CSCR = \frac{S_{MV}}{(WP1_{RAT} + WP2_{RAT} + WP3_{RAT})} \tag{3}$$

$$WSCR = \frac{Weighted\ S_{SCMVA}}{\sum_i^N P_{RMWi}} \tag{4}$$

C. Synchronous Machines Contribution

Synchronous machines are well-defined in classical theory, and the simplifications used in formal fault level methods are widely accepted, understood, and extensively discussed in the literature [12]. In formalised methods, such as IEC 60909, ENA G74 [18] and IEEE C37.010 the synchronous machine fault contribution is usually represented as a voltage source, behind a saturated sub-transient reactance (X"d) on the machine base along with a value of stator resistance or X/R ratio, which results in a worst case value at the connection point. When a time domain RMS or EMT fault study is carried out, the machine's dynamic response is considered, including the decay between sub-transient, transient, and steady-state conditions, as well as machine saturation effects. The difference in machine saturation levels and corresponding fault current contributions can be significant, depending on the connection type and fault location [18].

For small network disturbances, the machine's output is not dictated by its sub-transient reactance but instead by its transient reactance, synchronous reactance, voltage angle, and inertia [12]. This issue is well-understood and in industrial plants with large embedded generators, the machine transient reactance is a key parameter for the system performance during network disturbances such as a motor starting [19]. As formal fault level methods consider the machine sub-transient reactance, it can therefore be seen that the system strength for small network disturbance is fundamentally different to the maximum fault level used of equipment specification and is instead determined by parameters that are not considered in formal fault level calculation methods.

D. Inertia and Inertia Distribution

In recent studies, the distribution of inertia within the system, has been shown to be important, and can cause localised variations in network response. The overall system inertia can be calculated through the summation of all the system inertia in the network through the swing Equation (5). Researchers have developed various Inertia Distribution Index (IDI) approaches, to determine the relative strength of the system inertia in a localized region.

An index value of dk can be determined for the generator [14] & [15]. The index value of dk can then be used to give an overall IDI value, by comparing it against the maximum value of dk on the system as shown in Equation (9). This returns an index value, where a high value indicates a busbar that either has a low concentration of inertia or is electrically distant from the COI, or both. The Centre of Inertia (COI) of the system is the weighted average of the network, which is used for calculation purposes, where the system is balanced.

$$\frac{df}{dt} = \frac{P_{in} - P_{out}}{2SH} f = \frac{\Delta P}{2I} f \tag{5}$$

$$\delta_{COI} = \frac{1}{H_T} \sum_{i=1}^{n} H_i \delta_i \tag{6}$$

$$f_{COI(t)} = \frac{\sum_{i=1}^{ng} H_i f_i}{\sum_{i=1}^{N} H_i} \tag{7}$$

$$d_k = \int_{t_0}^{T+t_o} \left(f_k(\tau) - f_{COI}(\tau)\right)^2 d\tau \tag{8}$$

$$IDI_k = \frac{d_k}{max\ d_k} \tag{9}$$

III. Fault Contribution of IBR

A. Grid Following Inverter (GFL) Response

Unlike synchronous machines, the fault output of GFL inverters is primarily determined by control system logic in the Fault Ride Through (FRT) control logic of the inverter and has a non-instantaneous response. The fault contribution of the GFL is triggered in specific circumstances, usually when the system voltage falls below a certain threshold. As noted earlier, there is little in the way of standard formulation in fault analysis standards, but ENA G74 [18] offers a formulation used, based on a k-factor, that is commonly used within FRT logic, as shown in Equations (10) and (11). Similar parameters are in use with generic WECC models as K_{qw} and T_{hld} parameters [20]. The output response of the IBR also depends

on the manufacturer's design and the ability of the IBR to provide sustained current without overheating.

$$\Delta I_{CDP} = K_j \Delta u_j \quad \text{:if } \Delta I \text{ is below the maximum current} \tag{10}$$

$$\Delta I_{CDP} = I_{maxj} \quad \text{: otherwise} \tag{11}$$

Therefore, the fault contribution of a GFL inverter depends on its design, control settings, and whether the system disturbance is significant enough to trigger an FRT response. Typical assumptions are that the IBR output will behave as a constant current source, that produces a fault current as a ratio of between 1.1-1.5 of I_N. which can be sustained for a small number of cycles [18] & [21]. In time domain RMS and EMT calculations, the analysis software can account, for the actual response of the IBR, considering if the magnitude of the disturbance is sufficient to trigger a response, and the magnitude and shape of the IBR output current.

B. Grid Forming Inverter (GFM) Response

GFM based resources are more complex than GFL technology, and have a different response characteristic during system disturbances and faults. A number of bodies have started to define outline performance requirements for GFM technology, but these are not fully established and implemented within fault analysis standards. In a similar manner to GFL, the output of the GFM to system disturbances is set and determined by the control logic. However, GFM behaves as a voltage-source, and can provide a synthetic response, similar to a traditional synchronous machine where the GFM is able to provide some level of support for system voltage disturbances [16] & [17].

As GFM technology is still considered to be in relatively early stages the control strategies and performances for behaviour during faults and small system disturbances varies between developers, and depends on the control strategies adopted, typically focusing on virtual synchronous machines. Currently, no formal methods exist to define the fault contribution from GFM-based technology. DIgSILENT Powerfactory, currently suggests that the most suitable method would be to consider the GFM as an equivalent synchronous machine, with a fault current contribution based on a nominal MVAsc and an X/R ratio [22].

IV. Alternative Formulation of System Strength

A. System Strength Considerations

The previous sections have detailed, how formal fault level methods make several simplifying assumptions during the calculation process. While these assumptions are suitable for calculating maximum fault levels used in selecting switchgear and equipment fault ratings, they are less appropriate for assessing small system disturbances. This is because they do not account for factors such as synchronous machine saturation, reduced and uneven system inertia, and the limited fault contribution from GFL technology. Additionally, there is currently no formal method for considering the behavior of GFM technology in short-circuit calculations, as no consensus exists within calculation standards.

In weak networks with high IBR penetration and low, or uneven inertia distribution, using formal fault level analysis methods to defined system strength may significantly overestimate system strength. This is particularly true when analyzing small signal disturbances, as the system's response to these is fundamentally different from its response during a full system fault.

B. Time Domain Fault Current Analysis

An alternative to formal fault analysis standards is to use time-domain RMS or EMT analysis methods. These methods provide a more detailed assessment of the system at a specific location and can quantify the fault contribution of individual components based on specific events and disturbances. While these methods are technically robust, the analysis still uses the underlying assumption of a fault on the network, and therefore provides a measure of strength that would be different to a small signal disturbance, as the fault contribution from IBR responses may not be triggered due to the small value of the disturbance.

C. Energy Transfer

This paper, proposes that an alternative metric for assessing system strength is to consider the ability of the system to deliver energy to a disturbing load over a specific time period. The principle of this approach is that during a small signal disturbance the energy available in the system has a fundamentally different characteristic to those present during a fault. The response of the network is non-linear and determined primarily by the available energy from rotating machines, and the presence of IBR has limited input to system strength for small disturbances. Where IBR is able to contribute to a small signal disturbance the response is not instantaneous, and has a delay along with a time to respond.

It is therefore proposed that the real system strength to small system disturbances SYS_{STRSS} could be expressed in terms of actual energy MW_{SS} delivered over a given time period, from t1 to t2, in response to a small disturbing load. The disturbing load should be selected as a percentage of the nominal short circuit level, given through a formal calculation method. Initially this is assumed as 10% of the nominal MVA_{SC}.

The system strength for a fault can be expressed in a similar manner for an equivalent 3-phase fault at the connection point, over the same period. For ease of calculation the fault value is assumed to be constant, as per the formal method calculations. The relative system strength (RSS), can then be expressed as a ratio of SYS_{STRSS} to the fault system strength SYS_{STRSC}. The Relative Short Circuit Ratio (RSCR), is then expressed as the nominal SCR adjusted by the RSS. Formally this is shown, as indicated in Equation (12) through (15).

$$SYS_{STRSS} = \int_{t1}^{t2} MW_{ss}\, dt \tag{12}$$

$$SYS_{STRSC} = \int_{t1}^{t2} MVA_{sc}\, dt \tag{13}$$

$$RSS = \frac{SYS_{STRSS}}{SYS_{STRSC}} \tag{14}$$

$$RSCR = \frac{MVA_{Sc} * RSS}{MVA_{gen}} * 10 \tag{15}$$

V. Case Study

A. Network Model

To demonstrate the importance of both the type of fault contribution and the localized impact of inertia in the system as a measure of system strength for small system disturbances a simple test network, based on the Single Machine Infinite Bus (SMIB), used by Kundur [12] was setup in DIgSILENT PowerFactory, as shown in Fig. 1. PowerFactory was chosen as it has functionality for both formal short circuit analysis and time based RMS / EMT simulations. RMS analysis was used as this computationally simpler and faster to carry out.

The model is based on two identical synchronous machines, each rated at 350 MVA with an unsaturated X"d of 20%, inertia constant of H=5.0 set with a simple AC1A AVR and GGOV1 governor. An IBR is connected to Bus 1 and modelled with a WECC REEC_C electrical control model, with the IEC 60909 fault contribution of 1.5 pu during system disturbances and 1.0pu during steady state conditions. The generators are connected to a load busbar via a 50 km, cable length of 3x1c500mm^2 Cu cable, which is provided with two static loads to damp any transients and limit power flow down the line, a perturbation load is connected to Bus 2.

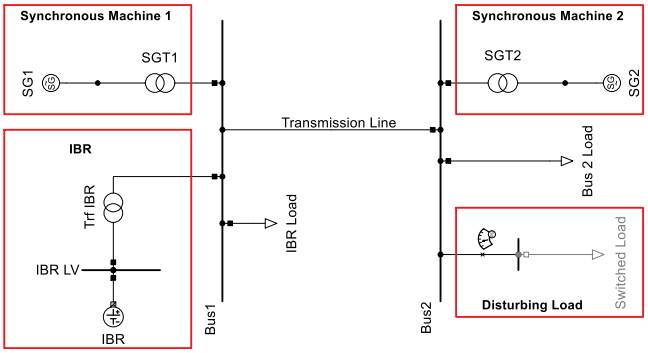


Fig. 1. Network Model – Modified SMIB

B. Scenario 1- Changing Inertia Distribution

In Scenario 1, the IBR is left out of service, and the machine inertia of SG2 is reduced progressively, with the inertia of SG1 increased by a corresponding value, in order to keep the overall system inertia the same; all other parameters remain constant. The fault level at the Load Bus is calculated using both IEC 60909 with a voltage factor of 1.0 and as an RMS positive sequence fault. A disturbing load based on 10% of the maximum RMS fault level (165MW at 0.95Pf lagging). The delivered energy is measured over a nominal time of 1s

The results of the simulations are shown in Table I, and Fig. 2. It can be seen that the fault level in IEC 60909 method and the RMS remain constant in all cases. Despite the system fault level remaining constant the reduced inertia in the Bus 2 area, increases the magnitude of voltage disturbance. The energy delivered over the time period, however indicates a decrease of power transfer as the local system inertia falls. The relative system strength measure also falls for Bus 2 where the lower inertia is available. Such a relationship would not be apparent if system strength is measured as a simple fault level issue.

TABLE I. Scenario 1 – Uneven Inertia Results

Inertia Bus 1	IEC 60909 Fault Level (MVAsc)	RMS Fault Level (MVAsc)	Max ΔV (%)	SYS_{STRSS} Δt=1s	RSS to IEC 60909
50%	1966.5	1644.6	5.74	165.3	8.4079%
60%	1966.5	1644.6	5.99	164.5	8.3672%
70%	1966.5	1644.6	6.36	164.2	8.3520%
80%	1966.5	1644.6	6.86	163.3	8.3062%
90%	1966.5	1644.6	7.50	163	8.2909%

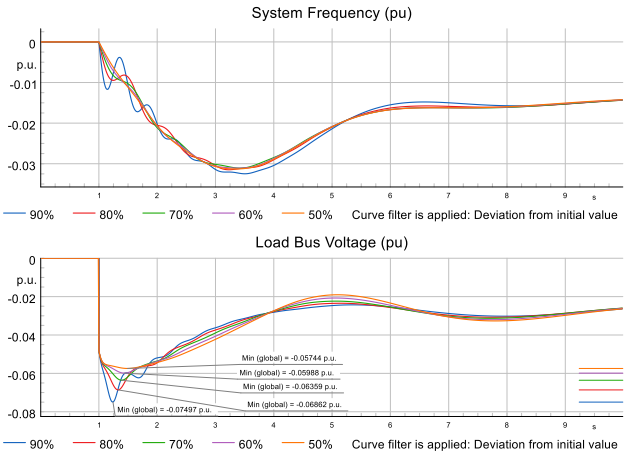


Fig. 2. Scenario 1 – Uneven Inertia: Switch Event Results

C. Scenario 2 – Increased Fault Level From IBR

In Scenario 2, the IBR is switched in service and its MW rating increased progressively to show an increased fault contribution. The synchronous machines are left with their default parameters and all other configurations are kept constant, and the IBR is left in a power-frequency control mode. The fault level at the Load Bus is calculated using both IEC 60909 with a voltage factor of 1.0, and as an RMS positive sequence fault. A disturbing load based on 10% of the maximum RMS fault level for the base case (165MW at 0.95Pf lagging). The delivered energy is measured over a nominal time of 1s.

The results of all the simulation are shown in Table II, and Fig. 3. It can be seen that the fault level in IEC 60909 method differ significantly as the IBR increases in size, whilst the RMS calculated fault level increases slightly. As expected, despite the apparent fault level rising in the system with the increasing IBR presence, the influence of the disturbing load on the system remains constant and the energy delivered from the network to the disturbing load also remains constant. It can therefore be seen that despite an apparent increase in system strength due to the fault level rising the increased fault level does not provide useful contribution to small disturbing loads.

TABLE II. Scenario 2 Results

IBR Size (MW)	IEC 60909 Fault Level (MVAsc)	RMS Fault Level (MVAsc)	Max ΔV (%)	SYS_{STRSS} Δt=1s	RSS to IEC 60909
0	1967	1644.6	5.76	165.3	8.4037%
50	2014	1652.0	5.76	165.3	8.2075%
100	2061	1658.1	5.76	165.3	8.0204%
150	2108	1664.2	5.76	165.3	7.8416%
200	2156	1670.1	5.76	165.3	7.6670%

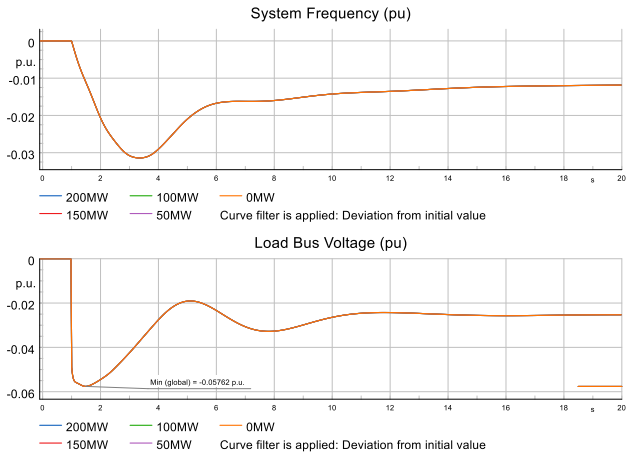


Fig. 3. Scenario 2 – IBR Fault Level: Switch Event Results

D. SCR vs RSCR Comparison

To demonstrate the effectiveness of the RSCR method, an assessment of the suitability of a 350 MW IBR connection is considered at Bus 2 of the test network, for the 2 scenarios considered. The results are shown in Table III, where it can be seen that in all cases the IEC60909 method significantly overestimates the SCR and indicated that an SCR of >5 is achieved in all cases indicating a reasonably strong network. The RMS method gives much better accuracy but does not capture all of the dynamics, whilst the RSCR method adjusts for localized reduced inertia and filters out non-useful fault contribution of nearby IBRs.

TABLE III. SCR vs RSCR

Scenario	IEC60909 Fault Level MVAsc	RMS Fault Level MVAsc	SCR vs IEC	SCR vs RMS	RSCR vs IEC
50% Inertia	1967	1645	5.62	4.70	4.72
60% Inertia	1967	1645	5.62	4.70	4.70
70% Inertia	1967	1645	5.62	4.70	4.69
80% Inertia	1967	1645	5.62	4.70	4.67
90% Inertia	1967	1645	5.62	4.70	4.66
0 MW Bus1	1967	1645	5.62	4.70	4.72
50MW Bus1	2014	1652	5.75	4.72	4.72
100MW Bus1	2061	1658	5.89	4.74	4.72
150MW Bus1	2108	1664	6.02	4.75	4.72
200MW Bus1	2156	1670	6.16	4.77	4.72

VI. Conclusions & Further Work

This paper has demonstrated that the use of formal short circuit calculation methods have significant limitations as an indication of system strength. An alternative measure of system strength was developed based on a ratio of small signal disturbances strength, to traditional fault level strength. Through the use of a simple test network, it was demonstrated that as the inertia is displaced away from a busbar, the ability to transfer energy to the disturbing load becomes reduced; and that while IBR can provide fault contribution to a network it is limited by the IBR control logic. In isolated small network, or weak areas of the network with low inertia and high IBR penetration, such as rural or remote areas, these effects can become significant and traditional SCR approaches can lead to an overestimation of the system strength.

Future research would be to consider larger systems, higher penetrations of IBR, and more complex representations of IBR with both GFL and GFM technology. Additional developments would be to consider different time windows for evaluation and using EMT models for greater accuracy.

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