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Strength to Connect (WP1)

Independent expert analysis/opinion provided by:

Dr. Yue Zhu, Prof. Tim Green, Dr. Yitong Li,
Department of Electrical and Electronic Engineering,
Imperial College London

NESO
National Energy System Operator

1. Contents

2. Introduction

Power system is transforming from a system dominated by synchronous generators to a system where inverter-based resources (IBRs) become dominant [1]. One consequence is that grid strength is decreasing in some regions in the GB system as thermal power plants with synchronous generators (SGs) are decommissioned in favour of IBRs in the drive to meet the UK's net-zero targets [2] .
Traditionally, short-circuit level (SCL), or short-circuit ratio (SCR) is the standard measure of grid strength for indicating the ability to connect a new device at a specific location. A large SCL indicates that a system can provide a large current into a short-circuit (or fault) and carries an implication that the system is able to hold the system voltage close of nominal value in the face of load changes and has a low series source impedance. Typically, the short-circuit current (SC) contribution (also known as fault current contribution) of an SG can reach 5-7 p.u. [3] because of their low impedance and ability to withstand currents well above normal for short periods without a large and damaging temperature increase. However, for IBR, especially for grid-following (GFL) IBR, the SC contribution is normally quite low due to its tight constraints on over-current in order to protect its IGBTs. For example, for a type 4 wind turbine generator, its SC contribution is around 1 p.u. [4]. Such difference dramatically drives the system strength lower. It is a common sense that the system strength is inversely proportional to effective GFL IBR penetration seen at that location [5].

In addition to the poor fault current contribution, the control-defined behaviour of IBR can also introduce instabilities in the system voltage in response to large or small disturbance. Oscillations attributed to IBRs are reported worldwide and occur at a variety of frequencies [6]. Such oscillations could be caused by the poorly designed control algorithms of some IBRs, or the control interactions among several IBRs, which are quite different from what has been observed from a SG-dominated system. The occurrence of oscillations is more commonly observed in low strength systems but is not a directly attributable to low SCR but is related to the design of the IBR [7].

Figure 2-1 illustrates an IBR-dominated system, in which oscillations might be introduced by adding a single IBRs, and interactions might be found between IBRs at the common connection bus on the right-hand side and between IBRs and the entire network. The existing network contains a variety with some configured as GFL IBRs and others as grid-forming (GFM) IBRs, making the system complex.

There are four emerging concerns relevant to assessments of system strength in an IBR-dominated system:

- inadequate voltage regulation,
- increased recovery times from voltage dips,
- potential instability of GFL inverters, and
- mal-operation of protection.

Considering the challenges above, it is suggested that SCR is no longer a good all-purpose indicator of system strength and refined metrics are needed to address each of the potential concerns.

Work Package 1 of Strength to Connect Project aims to find the best measures to assess potential problems and define new metrics as replacements or refinements for SCR.

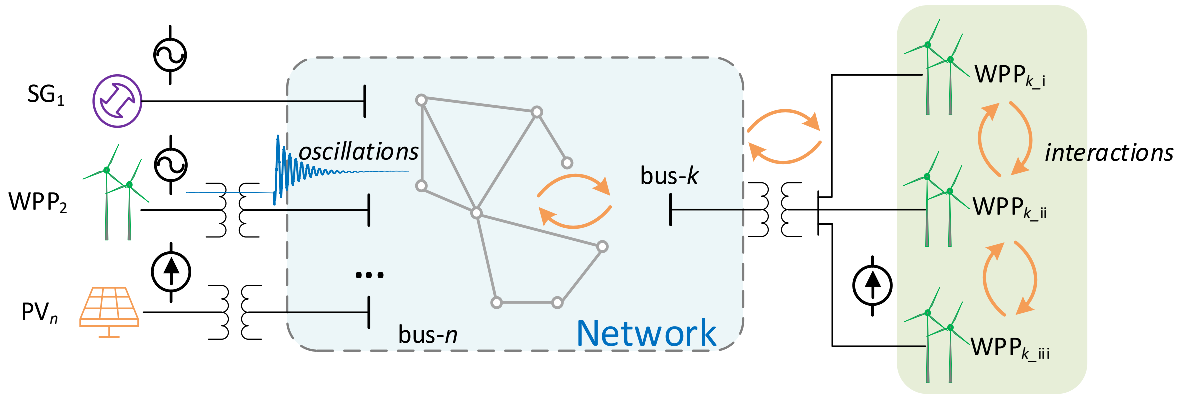

Figure 2-1 Power system is transforming to a IBR-dominated system, and instabilities have been introduced to the system due to the high penetration of IBRs.

3. System Strength Explanation

As a starting point, it is important to clarify the meaning of system strength. As stated by CIGRE report [8], the term 'system strength' has emerged to encompass a broad range of issues and their implications on power system operability. Explanations of system strength have been made by several system operators and organisations:

- *System strength is a characteristic of an electrical power system that relates to the size of the change in voltage following a fault or disturbance on the power system. --AEMC, 2017 [12]*
- *System strength is the ability of the power system to maintain and control the voltage waveform at any given location in the power system, both during steady state operation and following a disturbance. –AEMO, 2020 [5]*
- *System strength is the ability of power system equipment to operate in a stable manner and for the system as a whole to recover intact from major disturbances. ---CIGRE, 2021 [8]*

The above explanations basically align with the thinking in the Strength to Connect project. We also think the measures of system strength in IBR-dominated grids should also be distinguished from the way ‘system strength’ has been used traditionally. As we understand it, traditionally, ‘system strength’ is used, on the one hand, during connection studies to assess whether the system has enough ability to absorb the generation from the newly planned device, and on the other hand to assess how far a generator is from the limitation of power transfer. These issues are important for power flow management, and are captured well by SCR, which is the ratio of the maximum power the system can absorb and the nominal power of the new device. Nowadays, with high levels of penetration of IBRs, the term ‘system strength’ focuses more on the voltage stiffness at some specific locations: the degree of voltage change at that place subject to a certain perturbation in the system, as well as the length of recovery period after the perturbation. Compared with traditional use, the concept of ‘strength’ being discussed now has the following features:

- The perturbation could be a self-clearing short-circuit fault such as a lightening strike, or a small perturbation such as a small step-change of the load.
- The assessment includes not only the power transfer limitation, but also the dynamic behaviours of IBRs and interactions among IBRs in close proximity.

- The assessed voltage distortion includes not only a voltage dip during a fault (large-signal response), but also small voltage oscillations (small-signal response).

4. Short-Circuit Ratio (SCR)

a) Principle

Since SCR has been widely used for system strength assessment, it is important to review its concept and understand the principle.

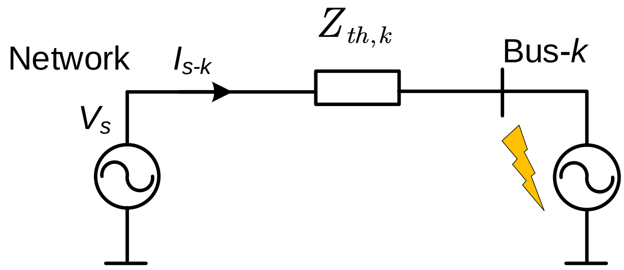

Figure 4-1 Fault level circuit representation.

When a system such as that in Figure 2-1 is viewed from a single bus, bus-k in this example, a linearisation can be made on the rest of the system to create an equivalent ideal voltage source in series with a Thevenin impedance, as shown in Figure 4-1. When a short-circuit happens at bus-k, i.e., bus-k is connected to the ground, the power flows from the system to bus-k is defined as the short-circuit capacity (SCC), or short-circuit level (SCL), and is expressed as

$$SCC_k = \frac{|V_S|^2}{|Z_{th,k}|}, \tag{1}$$

where $Z_{th,k}$ is the Thevenin impedance of the network seen from bus-k. SCR is then defined as the ratio between SCC and the nominal power of the device connected to bus-k, i.e.,

$$SCR_k = \frac{SCC_k}{P_k} \tag{2}$$

In a per unit system where the voltage is 1 p.u., SCR can be expressed in the following equation:

$$SCR_k = \frac{1}{|Z_{th,k,pu}| \cdot P_{k,pu}} \tag{3}$$

For the sake of brevity, the per unit symbol will be omitted from the following discussion. A global base power is also chosen depending on the scale of the system under consideration.

SCR refers to the ratio between the SCC (the maximum apparent power that the system can supply to this bus during a fault) and the rated power of the device connected to bus-*k*. An SCR greater than 1 indicates that the systems can supply more current into a short-circuit than the connecting generator supplies at full power. It also indicates that the Thevenin impedance of the network is less than the impedance base of the generator. Large values of SCR indicate a strong system with a low impedance relative to the connecting generator and an expectation of a small variation of voltage magnitude with changes in power flow from this bus. As experience has accumulated, the following judgements can be made based on the value of SCR:

- When SCR is larger than 5, the system is strong, and
- when SCR is smaller than 5 but larger than 3, the system is weak, and
- when SCR is smaller than 3 but larger than 1, the system is very weak, and
- SCR equalling as 1 is considered as the system boundary.

b) Understanding

There are two other ways to understand the meaning of SCR, from a view of power transfer and from a view of voltage stability.
If treating the device at bus-k as a voltage source (which can fix its angle) trying to deliver power to the rest of the system, as shown in Figure 4-2, it is apparent that when $\delta = 90°$, the source approximately reaches the maximum power it can deliver to the system which is determined by the Thevenin impedance as

$$P_{MAX,k} \approx \frac{1}{|Z_{th,k}|} \qquad 4)$$

Substituting 4) into 3) yields

$$SCR_k = \frac{P_{MAX,k}}{P_k} \qquad 5)$$

Equation 5) shows that SCR is the ratio between the maximum power the system can absorb and the nominal power of the device connected, thus refers to the margin of the power transfer at this bus.

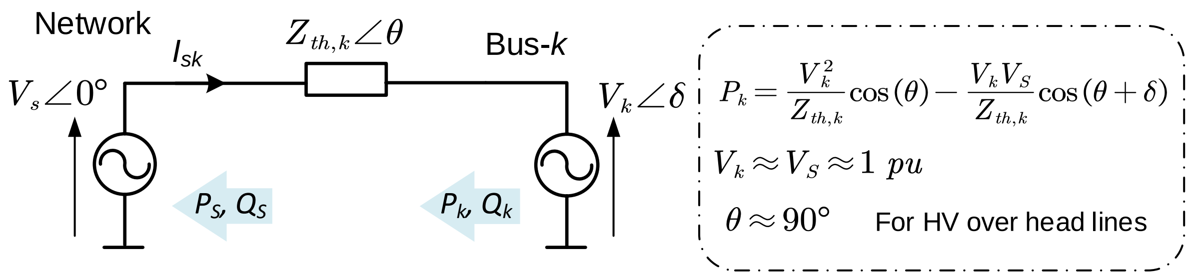

Figure 4-2 SCR understanding from a voltage source perspective.

Alternatively, SCR can be understood from a view that a negative load R_k, (a negative real part such that it sources current) with power of P_k connected at bus-k and for which the bus voltage must be maintained at 1, as shown in Figure 4-3. The magnitude of this impedance can then be expressed as

$$|Z_k| = \frac{1}{P_k} \tag{6)}$$

From circuit principles, it is known that when $|Z_k| < |Z_{th,k}|$, the voltage at bus-k terminal will collapse, as shown in Figure 4-4. As a result, the Thevenin impedance of the system sets the minimum magnitude of impedance that the negative load Z_k, can have to avoid voltage collapse i.e.,

$$|Z_{th,k}| = |Z_k|_{MIN} \tag{7)}$$

Substituting 6) and 7) into 3) yields

$$SCR = \frac{|Z_k|}{|Z_k|_{MIN}}, \tag{8)}$$

i.e., SCR is the ratio between the equivalent impedance of the device when delivering its nominal power and the minimum impedance the system is allowed to connect to maintain the voltage. Accordingly, we also have

$$SCR = \frac{|Y_k|_{MAX}}{|Y_k|}, \tag{9)}$$

which is the ratio between the maximum allowed admittance for maintaining voltage and the equivalent admittance when at the nominal power.

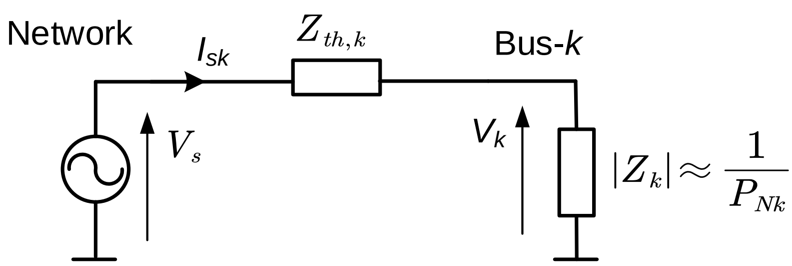

Figure 4-3 SCR understanding from a load perspective.

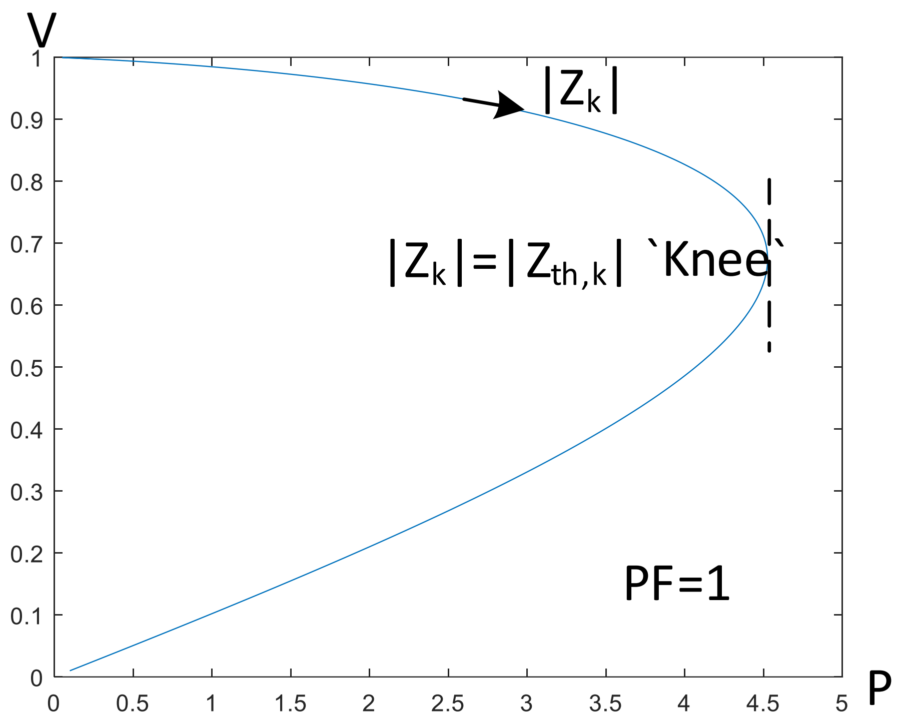

Figure 4-4 V-Z curve showing the voltage collapse when $|Z_k| < |Z_{th,k}|$.

c) Acquirement

After an understanding of SCR, it is crucial to know how SCR values can be acquired practically.

For simple circuit, e.g., a single machine that is going to connect to an infinite bus, the Thevenin impedance is directly equal as the line impedance. SCR can then be acquired from equation 3).

For a meshed network where there are multiple SGs, short-circuit analysis in power system simulation tools are often needed, such as PowerFactory. In such tools, the short-circuit current can be acquired at different locations, which combining with bus voltages (from power flow calculation) further gives the SCC. SCR can then be acquired from equation 2). There are different methods of short-circuit analysis, e.g., IEC 60909, IEC 61363 Method, and the complete method developed by PowerFactory [9]. The short-circuit analsyis considers a three-phase fault at the point of interaction (POI) and calculate the fault current during the fault. There are mainly three periods of short-circuit current: subtransient, transient, and steady-state, as shown in Figure 4-5. So far, it is not quite clear which period of short-circuit current is used for SCR calculation and few literature has discussed this issue, while

National Grid ESO currently applies the subtransient (initial) short-circuit current I_k'' for SCR calculation.

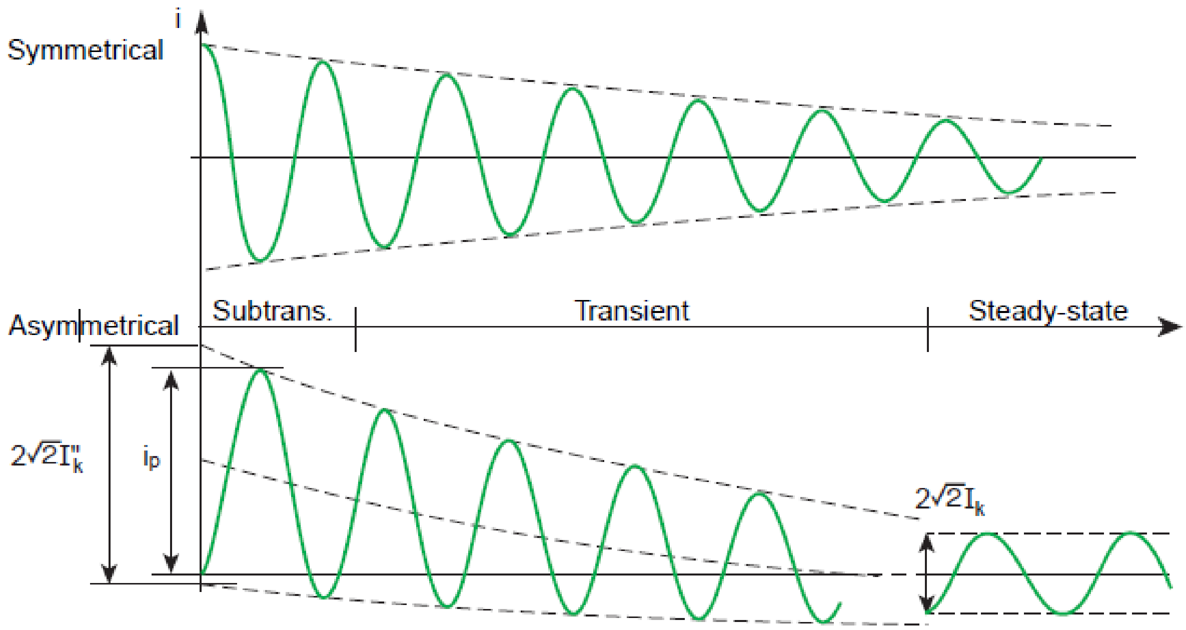

Figure 4-5 short-circuit currents near a generator (schematic diagram) [10].

Since I_k'' is taken for SCR calculation, the SGs in the system are typically modelled as X_d'' in series with an ideal voltage source, as shown in Figure 4-6. As a result, instead of treating them all as voltage sources, different ratings of SGs create different effect on system strength at other locations.

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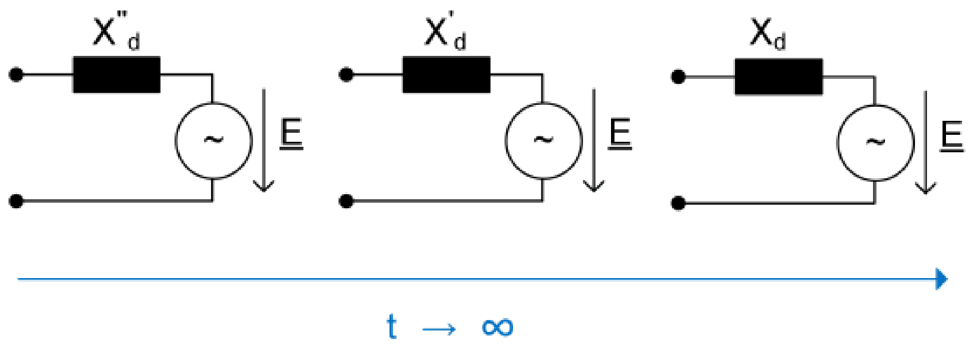


Figure 4-6 Single-phase equivalent circuit diagrams of a generator for short-circuit current calculations which include the modelling of the field attenuation [11].

Unlike SG which has a simple model to represent its subtransient period, there is currently not a generic IBR model for short-circuit analysis. Due to the absence of an appropriate model, IBRs are usually treated either as ideal current sources in their nominal power (with fault contribution of 1 p.u.) [16], or simply as disconnected (with fault contribution of 0) which is adopted by National Grid ESO. Such treatment may lead to a too optimistic prediction of system strength because as a general impression from system operators, grid-following IBRs do not contribute to system strength but, rather, have the overall effect of reducing it [13].

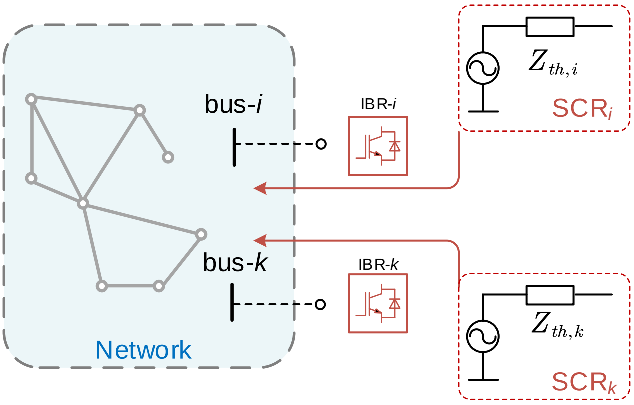
d) Discussions

The above understanding of SCR forms the basis of our consideration of system strength which is expressed as the ratio between a nominal value of system parameter (impedance, admittance, power) and its value it the limit of operation. The limit might be a static stability limit such as the knee, or bifurcation point, of the voltage curve and SCR=1 is the boundary of system stability. We also noticed that conventional short-circuit analysis methods lack proper models of IBRs so may lead to a too optimistic prediction. A further descale is needed on the SCR acquired from the short-circuit analysis.

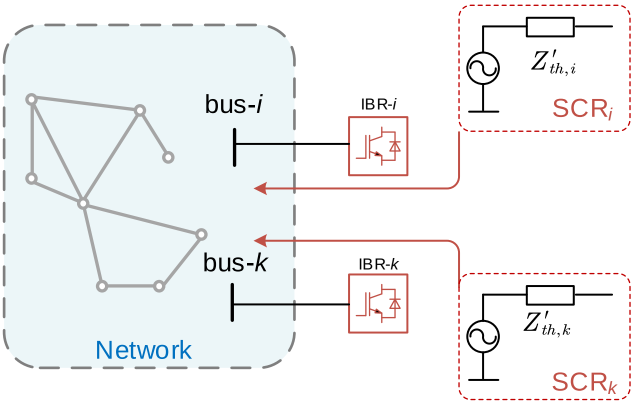
Another finding is that SCR may apply to cases where a device is 'going to connect', or 'already connected'. This clarification is brought up to serve two purpose: to assess the system strength at different locations and locate the 'weak point', and to assess the system potential for new device connection. Such separation makes no difference when only one POI is taken into consideration, but creates a distinct effect when SCR needs to be calculated at multiple POIs at the same time. For a meshed network, as illustrated in Figure 4-7 (a), when two IBRs are planned to connect to bus-i and bus-k, the SCR are calculated at these locations without the two new IBRs. Thevenin impedance $Z_{th,i}$ and $Z_{th,k}$ are then acquired which further gives the value of SCR at the two buses. However, once IBR-*i* and IBR-*k* are connected, as shown in Figure 4-7 (b), IBR-i can influence the Thevenin impedance at bus-k, i.e.,

$$Z'_{th,k} \neq Z_{th,k}, \qquad 10)$$

and vice versa. Consequently, the former assessment on SCR without including the two IBRs turns out to be inaccurate. Such effect is usually recognised as strength 'interaction' between IBRs, and cannot be described solely by conventional SCR. When IBRs are close with each other, the interaction can be strong. This shortcoming of SCR obstructs the strength assessment in a meshed network where devices interact with each other, which is common in IBR-dominated systems.



(a)



(b)

Figure 4-7 Strength evaluation for multiple POI: (a) devices at bus-i and bus-k need to be disconnected for SCR calculation. (b) Once the devices are connected, IBR-i can influence the Thevenin impedance at bus-k, and vice versa.

5. Other Strength Metrics

To address the issue that the interaction among IBRs are not properly concerned in SCR, several new metrics of system strength have been proposed in recent years and they will be reviewed in this section. Many of these were developed with wind power plants (WPPs) in mind and discussed in those terms originally but WPP are merely an example of IBR.

e) Composite Short-Circuit Ratio (CSCR)

CSCR was proposed by NERC & GE Energy Consulting in 2015 [14]. It considers the case where several WPP are going to connect to the same high-voltage (HV) bus in the system, as shown in Figure 5-1(a). Since each WPP is connected to bus-k via a different line impedance or transformer impedance, their nominal power cannot be simply added directly to create a single aggregate device. An assumption is made that a common bus is created and all WPPs of interest are tied together at that common bus and then the SCR is found from an equivalent circuit as shown in Figure 5-1(b). As a result,

$$CSCR = \frac{1}{(Z_{th,k} + Z_{kc})P_k}, \tag{11}$$

where

$$Z_{kc} = Z_{k1} \parallel Z_{k2} \parallel Z_{k3} = \frac{1}{\frac{1}{Z_{k1}} + \frac{1}{Z_{k2}} + \frac{1}{Z_{k3}}}, P_k = P_1 + P_2 + P_3.$$

CSCR is an aggregated metric representing the strength at bus-k where a group of WPPs is going to connect.

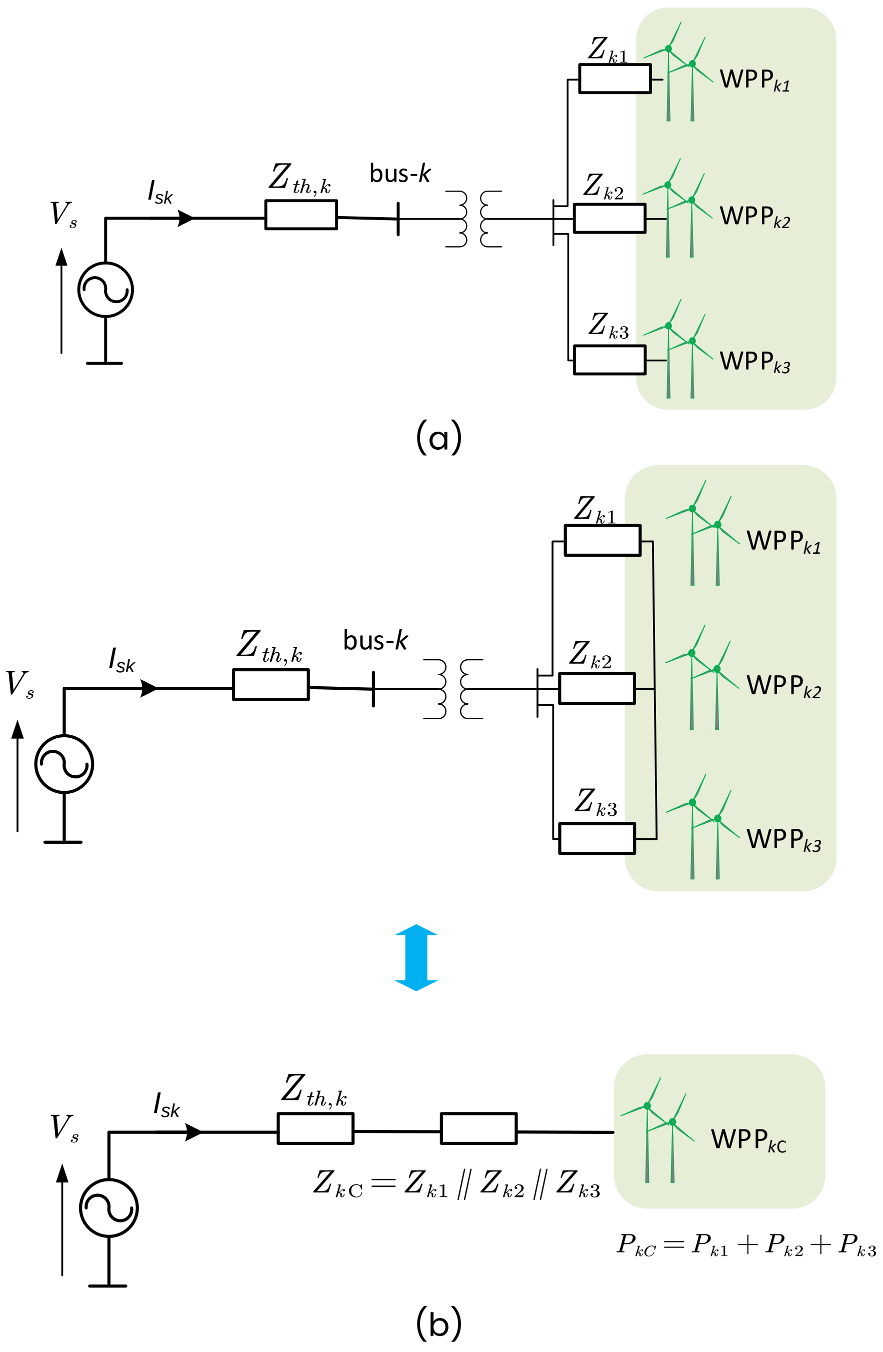


Figure 5-1 CSCR illustration: (a) original connection, (b) equivalent circuit

f) Weighted Short-Circuit Ratio (WSCR)

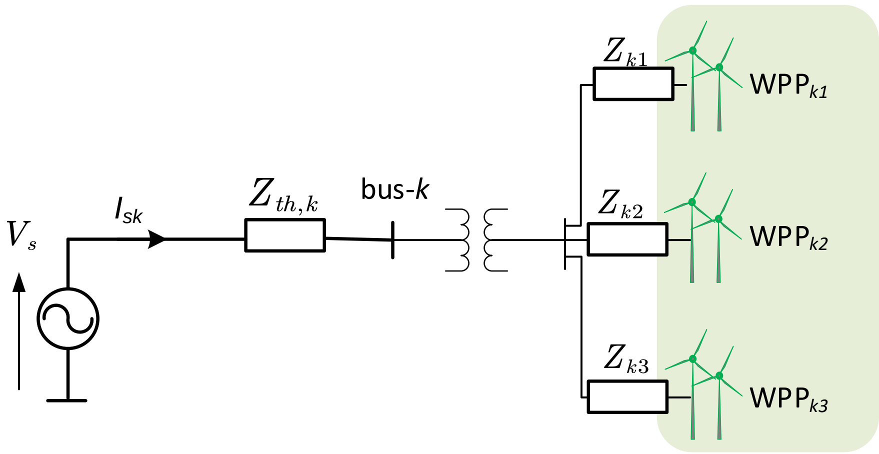
WSCR was proposed by ERCOT in 2014 [15]. The scenario is similar to CSCR, i.e., several WPPs are going to connect to the same bus. Short circuit capacity of each WPP, SCC_{ki}, is assessed separately and then the WSCR is then formed by weighting the values according to the power of the WPP:

$$WSCR = \frac{\sum SCC_{ki} \times P_i}{(\sum P_i)^2} \qquad 12)$$

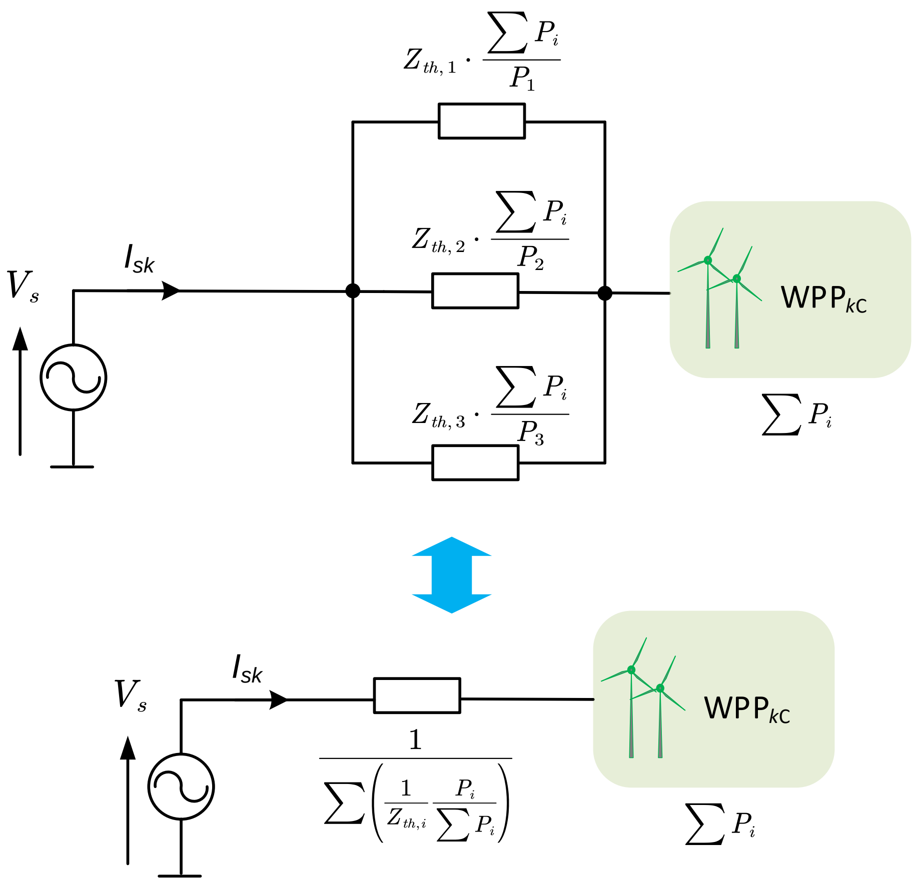
Detailed explanation of thinking behind WSCR was not provided in the original study. As we understand it, WSCR aims to form an equivalent single device to connect to bus-k. A weighted average is carried on the Thevenin impedance based on the corresponding nominal power, as shown in Figure 5-2.

As with CSCR, WSCR is an aggregated metric representing the strength at bus-k

where a group of WPPs is going to connect.



(a)



(b)

Figure 5-2 WSCR equivalent circuit: (a) original circuit. (b) Weighted average on the original circuit based on the rating of each WPP.

g) Equivalent Circuit-Based Short-Circuit Ratio (ESCR)

ESCR was proposed by CIGRE in 2016 [16]. The ESCR approach makes use of the observed voltage change at the POI of one WPP bus for a voltage change at the POI of another WPP, as an approximate indicator of the interactions between the WPPs. An interaction factor is defined as

$$IF_{ik} = \frac{\Delta V_i}{\Delta V_k} = \frac{Z_{ik}}{Z_{kk}}, \qquad 13)$$

where Z_{kk} is the self-impedance at bus-i and Z_{ik} is the transfer-impedance between bus-i and bus-k. ESCR is then defined in the following way:

$$ESCR_k = \frac{SCC_k}{P_k + \sum_{i \neq k} IF_{ik} \times P_i} \qquad 14)$$

It worth noting that in such an equivalent circuit representation, Z_{kk} is also the Thevenin impedance of bus-k, i.e., $Z_{th,k} = Z_{kk}$. Therefore, we have

$$SCC_k = \frac{1}{Z_{kk}} \tag{15)}$$

Combining 13), 14) and 15) yields

$$ESCR_k = \frac{1}{\sum P_i Z_{ik}} \tag{16)}$$

An illustration of ESCR expressed in the similar format as the other metrics discussed so far is shown in Figure 5-3, where three WPPS are going to connect to bus-1,2,3 which are in close electrical proximity. Strength of bus-3 is then assessed by including the influence from bus-1 and bus-2. In such a case, WPP1 and WPP2 are transferred as an equivalent source at bus-3 through the interaction factor defined in 13).

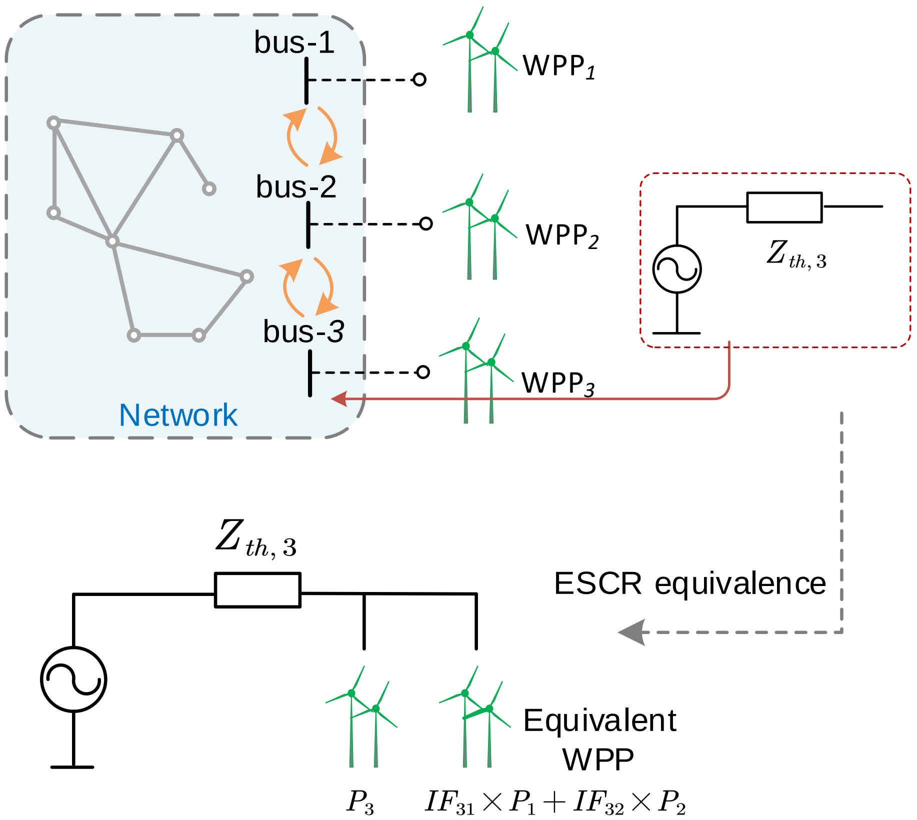


Figure 5-3 ESCR equivalent circuit representation

Compared with traditional SCR which considers only a single WPP, ESCR includes the influence from other WPPs in close electrical proximity. From 14) it is clear that the value of ESCR is smaller than the original SCR, i.e., strength would be lower if there are interactions among close-by WPPs. Compared with CSCR and WSCR, ESCR indicates the strength at an individual POI instead of combining WPP at several POIs and creating an aggregated index. However, it should be noted that ESCR only applies to the specific situation where the WPPS taken into consideration are far from the rest of the grid so the interaction between the newly connected WPPs and the rest of the grid should is excluded. Otherwise, in a case where a WPP is close to a large-scale SG (whose nominal power is quite large, SC contribution is large) and system is strong, ESCR of this WPP would be close to zero according to 16), which gives a false indication of system strength. This means that ESCR, same as SCR, cannot be applied for strength assessment across the entire grid.

h) Grid Strength Impedance Metric (GSIM)

Further to metrics discussed so far, which all derive from the original short-circuit perspective, there are also new studies that attempt to define system strength for a small-signal analysis perspective. One such approach is GSIM as proposed by University of Strathclyde in 2023 [17]. GSIM is found from a frequency domain impedance in *dq* components

$$\begin{bmatrix} GSIM_q(s) \\ GSIM_d(s) \end{bmatrix} = \lambda\left(Y_{sys}(s)\right) \odot \lambda(\mathrm{Z_b}(s)),$$
$$GSIM(s) = \sqrt{\left(\frac{GSIM_q(s)^2 + GSIM_d(s)^2}{2}\right)}, \quad 17)$$

Where $\lambda(\cdot)$ refers to eigenvalue calculation, $\odot$ denotes the element-wise multiplication, $Y_{sys}(s)$ is the frequency-domain admittance of the rest of the system seen from point of connection, $Z_b(s)$ is base impedance given as

$$Z_b(s) = \begin{bmatrix} R_b + sL_b & \omega_b L_b \\ -\omega_b L_b & R_b + sL_b \end{bmatrix}. \quad 18)$$

The fact that GSIM considers strength in the frequency domain, i.e., strength is frequency dependent, is an important departure from other metrics. In the study of GSIM, the IBR at its nominal operating point is modelled as a resistor in series with an inductor, so its impedance across the frequency spectrum is represented by $Z_b(s)$. If only the positive sequence impedance is considered, 17) can be reduced to

$$\mathrm{GSIM(s)} = \frac{Z_b(s)}{Z_{sys}(s)}, \quad 19)$$

where $Z_{sys}(s)$ is the Thevenin impedance of the system in frequency domain. It is clear that 19) has the same format as 8), showing that at in a *dq* frame, when GSIM is evaluated at $s = 0\,Hz$, $GSIM = SCR$. Compared with SCR, GSIM includes the dynamic characteristics of the system at all frequencies so can describe the oscillatory behaviour in the sub- and super-synchronous ranges. However, the IBR itself is simply modelled as an R-L branch, so the interaction between the normally quite sophisticated control-loops of the IBR and the rest of the system is not included. Meanwhile, it is not clear how to compare GSIM from different operating points or conditions since it is a spectrum not a single number. In the original publication, values of GSIM at 75 Hz, 125 Hz and 175 Hz are picked for comparison but without a reason being given.

i) Grid Strength Impedance Metric (GSIM)

In [18], a so-called generalised short circuit ratio (gSCR) is proposed as a global small-signal system strength indicator for the entire system, rather than a localised parameter as traditional SCR. This method quantifies the system small-signal stability margin by linking SCR with the system oscillatory modes so is able to address the SSO behavior. This procedure is achieved by representing the system characteristic equation with terms of 'SCR', i.e., solving the equation

$$SCR^2 + a(s) \cdot SCR + b(s) = 0 \qquad 20)$$

Such method can be easily applied in a single-bus system, but the extention of gSCR from a single-infeed system to a multi-infeed system relies on an assumption that all IBRs in the system must have the same control strategy and control parameters, which is unachievable in most cases as IBRs are designed by different vendors.

6. Classification of System Strength Metrics

To address the issue that SCR, and the variants of it that have emerged, are not good overall indicators for all aspects of system strength, we have classified system strength into two perspectives: small-signal system strength and large-signal system strength, as set out in Table 1. It is a natural separation considering the system strength explanation introduced in Section **Error! Reference source not found.**. (An extension of the table to accommodate system strength metrics for protection studies is envisaged at a later point in the project).

Small-signal system strength considers the behaviour of system voltage in response to small perturbations around the operation point which is an aspect of the general topic of small-signal systems analysis. It is a linear systems analysis so can express strength across the frequency domain but is applies only to linearisation around given operating points. The expected use of a small-signal system strength metric is to address the potential instability and oscillations caused by the complex dynamics of inverters and small-signal interactions among inverters. Existing studies that adopt a frequency domain or small-signal approached include GSIM introduced in section 5 and small-signal generalized short-circuit ratio (gSCR) proposed in [18]. That said, other variants of SCR such as ESCR have been used as indicators of onset of oscillatory behaviour of IBR. Later in this report, a new metric, named impedance margin ratio (IMR), will be proposed.

The large-signal system strength concerns recovery of a bus voltage following large disturbances such as a local short-circuit fault or a deep voltage dip caused by a remote fault. Such analysis is carried out at the system fundamental frequency. The measures are extensions of conventional SCR but consider the situations in which multiple IBRs are connected in close electrical proximity. The expected use of large-signal system strength metrics are to address the issues of recovery time from voltage dips and inadequate voltage regulation. The same metrics may also prove useful for low fault current and mal operation of protection but that is not addressed in this report. Existing studies that use system frequency analysis and are essentially large-signal methods include CSCR, WSCR and ESCR as introduced in Section 0. Later in this report, a new metric, named type-dependent short-circuit ratio (TDSCR) will be introduced.

Table 1 Classifications of two new strength metrics

	Metrics for Small-signal System Strength	Metrics for Large-signal System Strength
Features	• Small perturbations around an operation point • Frequency-domain analysis • Linear system stability analysis	• Large perturbations like faults • Fundamental frequency analysis, 50 Hz in the UK • Extension of SCR
Intended Indications	• Potential poorly damped oscillations and potential instability caused by inverters, and • small-signal interactions among inverters	• Excessive recovery time from voltage dips, • inadequate voltage regulation, • low fault current. • (mal operation of protection)
Existing Studies	• Grid strength impedance metric (GSIM) [University of Strathclyde] • Small-signal generalized short-circuit ratio (gSCR) [Zhejiang University] • Impedance Margin Ratio (IMR)	• Composite short-circuit ratio (CSCR) • Weighted short-circuit ratio (WSCR) • Equivalent Circuit-Based short-circuit ratio (ESCR) • Type-dependent short-circuit ratio (TDSCR)

1. Small-signal System Strength

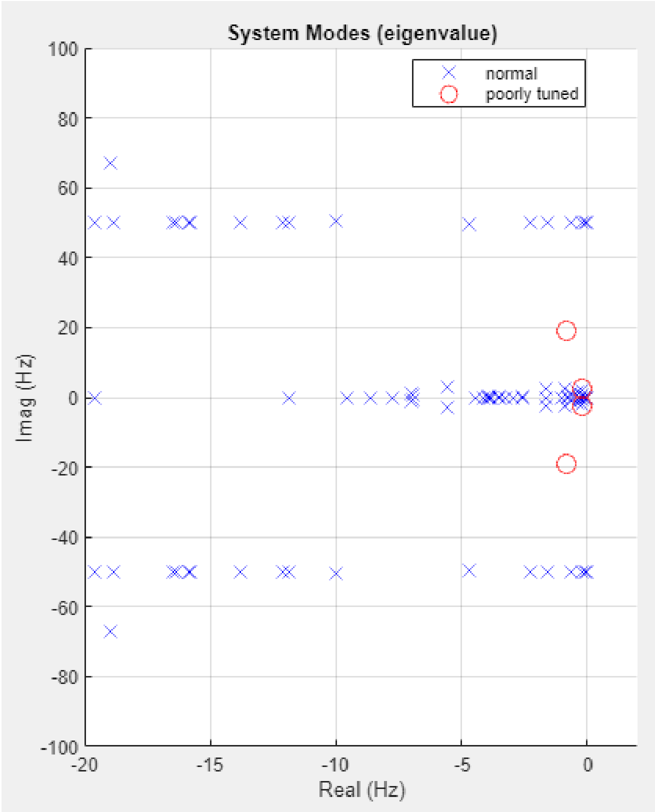
a) Background

Conventionally, small-signal analysis for power systems makes use of state-space models. For stability analysis, the eigenvalues, λ, of the state-space matrix **A** can be assessed. The criteria for system being stable is that there are no right-half-plane (RHP) eigenvalues, i.e. all eigenvalues should have a negative real part. For a physical system, λ would either be a real number, or a pair of conjugate complex values. When λ is conjugate complex, i.e., $\lambda = \sigma \pm j\omega$, it refers to an oscillatory mode in the system, where σ refers to the damping of the mode (the time that oscillations take to be dampened) and ω is the oscillation frequency, as shown in Figure 1-1(a). When there are modes with a small damping factor in the system, one expects to see oscillations in the system following a small disturbances such as small step change of the load, as shown in Figure 1-1(b). When there are modes on the RHP, one expects to see a self-excited oscillations, as shown in Figure 1-1(c).

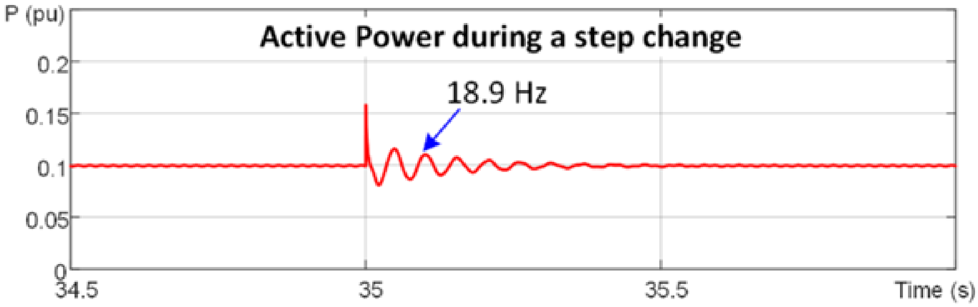
Recent studies have shown that λ can be acquired from system impedance model or system admittance model, namely $Z^{sys}(s)$ and $Y^{sys}(s)$, in addition to acquisition from a state-space model. When obtained from an impedance/admittance model, λ is a pole of the s-domain transfer function, and a corresponding 'peak' will be apparent in the spectrum and that peak represents that mode [19], as depicted in Figure 1-1(d). Due to the fact that oscillations are related to modes, the following conclusions can be drawn for system small-signal system strength assessment:

- Small-signal system strength should be assessed at the oscillatory frequency ω, and
- the damping of the mode σ directly reflects the strength.

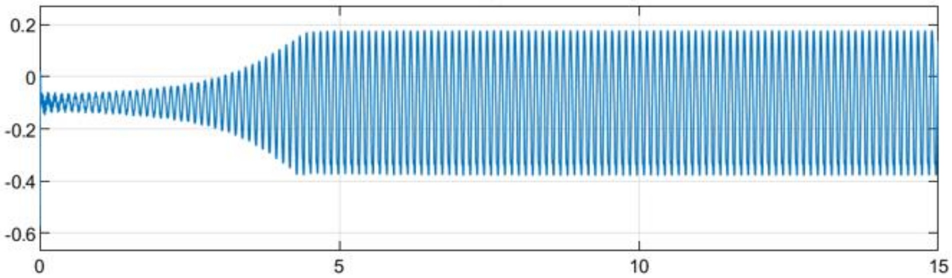
In general, the mode λ is a global small-signal system strength indicator; global in the sense that it is a property of the whole system such as the IBR in combination with everything else in the grid. When the mode is away from imaginary axis, the system is strong. Nevertheless, a localized metric is needed to describe the strength at different locations, which will be described in the next subsection.


System Modes (eigenvalue)
normal
poorly tuned
Imag (Hz)
Real (Hz)
100
80
60
40
20
0
-20
-40
-60
-80
-100
-20
-15
-10
-5
0

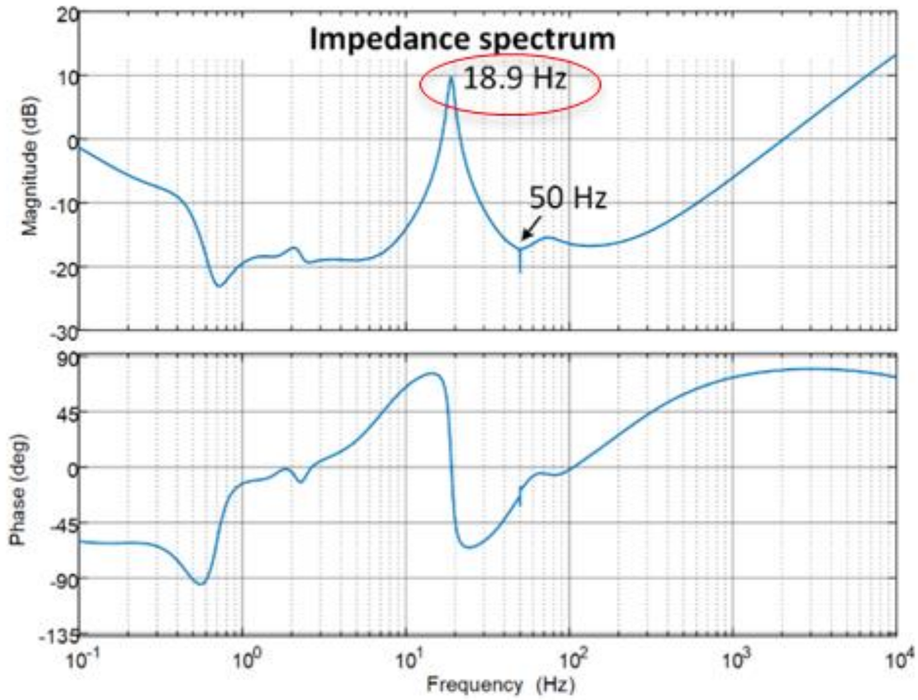
(a)


P (pu)
Active Power during a step change
18.9 Hz
0.2
0.15
0.1
0.05
0
34.5
35
35.5
Time (s)

(b)


0.2
0
-0.2
-0.4
-0.6
0
5
10
15

(c)



(d)

Figure 1-1 Oscillation mode explanations: (a) eigenvalue plot (pole map) of the system. (b) Step response of active power output when a mode with a small damping factor. (c) Self-excited oscillation when there is a RHP pole. (d) Impedance spectrum, showing a peak of 18.9 Hz which matches the eigenvalue.

b) Review of Whole-system Admittance Model

Since the metric introduced later is derived based on the previous study on the whole-system admittance model Y^{sys}, its concept is briefly reviewed here.

Whole-system admittance model is essentially a frequency-domain admittance matrix to describe the dynamic characteristic of the entire system. It chooses the small-signal voltage $\tilde{v}$ at each POI as the input, equivalent to adding a virtual small voltage perturbation, and the small-signal current Δi as the output, as shown in Figure 1-2.

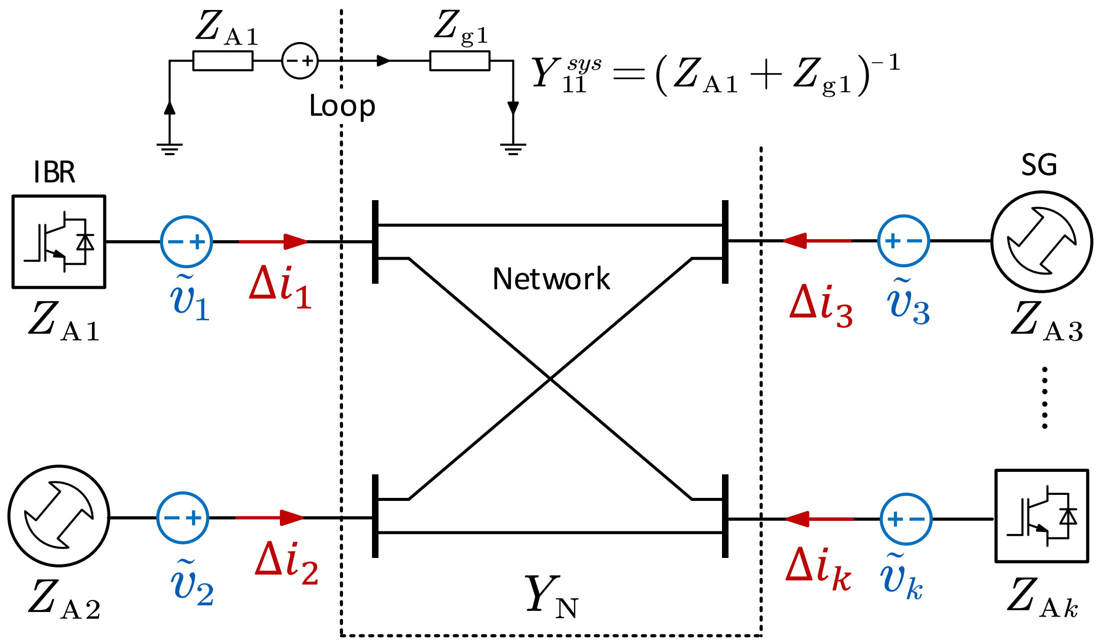


Figure 1-2 Virtual small-signal voltage injection at each node to form Y^{sys}

Y^{sys} is then defined as the transfer function from the input to the output, i.e.,

$$Y^{sys} \cdot v = \Delta i \qquad 21)$$

It is noted that a diagonal element of Y^{sys}, such as Y_{11}^{sys}, is essentially the combined admittance of the local IBR impedance and the grid impedance seen from bus-1 in a series connection, i.e.,

$$Y_{11}^{sys} = (Z_{A1} + Z_{g1})^{-1} \qquad 22)$$

It is further proved that through a feedback arrangement as shown in Figure 1-3, Y^{sys} can be derived as

$$Y^{sys} = (I + Y_N Z_A)^{-1} Y_N \qquad 23)$$

where Y_N is the conventional nodal admittance matrix consisting of admittance of branches but extended in frequency domain, Z_A is a diagonal impedance matrix where the diagonal entries are the impedances of apparatus at each POI, and I is the identity matrix. The elements of Y^{sys} are all transfer functions sharing a common set of poles which are also identical to the eigenvalues of the state-space model, i.e., the criteria that the system maintains stable is that there is no RHP poles for each of the element in Y^{sys}. It is also worth mentioning that the elements of Y^{sys} can be monitored through on-line admittance measurement.

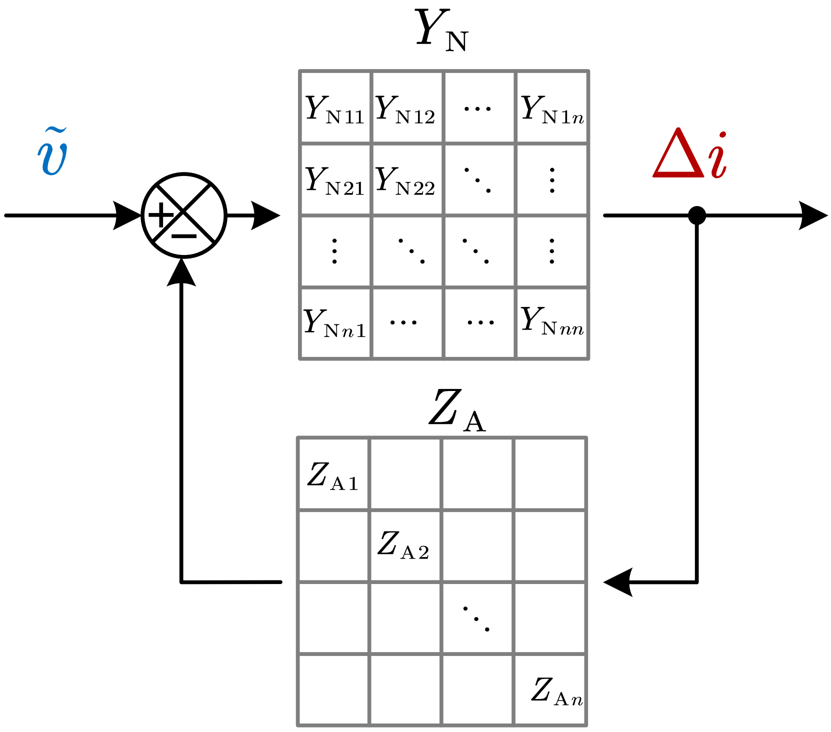


Figure 1-3 Close-loop of nodal admittance matrix and apparatus impedance matrix to form Y^{sys}.

c) Impedance Margin Ratio (IMR)

Although state-space modelling is a powerful tool for stability analysis, such models can be difficult to apply in practice if IBRs are present because the differential equations describing the controllers of IBRs are not generally openly available due to commercial confidentiality of the control implementation. On the other hand, an impedance model, which is naturally a black-box model describing only the relationship between the terminal voltage and current, is considered useful for small-signal analysis in a system with IBRs presented. In this subsection, the concept of *impedance margin ratio* (IMR) is proposed as a small-signal system strength metric based on impedance models.

Consider a small change added on the impedance of an IBR connected at bus-k, i.e., ΔZ_{Ak}. It will lead to a variation of the system eigenvalue $\Delta\lambda$. It has been proved in [20] that the value of $\Delta\lambda$ can be calculated as

$$\Delta\lambda = \langle -\mathrm{Res}_{\lambda}^{*} Y_{kk}^{sys},\ \Delta Z_{Ak}(\lambda) \rangle, \qquad 24)$$

where Y_{kk}^{sys} is the k-th diagonal element of the whole-system admittance model $\mathrm{Y}^{\mathrm{sys}}$, $\mathrm{Res}_{\lambda}^{*} Y_{kk}^{sys}$ refers to the conjugate transpose of the residues of Y_{kk}^{sys}

in *d*-*q* frame (a 2×2 matrix), $Z_{\mathrm{A}k}(\lambda)$ is the impedance of the IBR (classed here apparatus to distinguish it from the network) which is connected at bus-*k*, and the angle bracket refers to the Frobenius inner product. Although Equation 24) is maybe intimidating mathematically, it can be processed readily in software scripts in Matlab and it gives us the relationship between the change of a local IBR impedance and the corresponding variation of the system oscillatory mode. When a strong relationship is found, it is more likely that λ will vary widely for relatively small changes in the apparatus impedance and it is more likely that the mode will move to the right-half plane and become unstable as a result. Such a strong relationship means that the system is '*weak'* at this location because the change at this location may lead to system instability.

To maintain stability, λ must be kept in the left-half plane, such that $\Delta\lambda$ has a limitation of

$$|\Delta\lambda|_{MAX} = |\sigma| \qquad 25)$$

where σ is the real-part of λ. (This is a conservative limitation since a larger change might be allowed if it were known to be in a safe direction, but the direction is not considered known here). The change of impedance at $s = \lambda$ has a limitation of $|\Delta Z_{Ak}(\lambda)|_{MAX}$, which is the margin of impedance variation. Combining 24) and 25), impedance margin ratio is then defined as

$$\textbf{Impedance Margin Ratio (IMR)} \equiv \frac{|\Delta \mathrm{Z}_{Ak}(\lambda)|_{MAX}}{|Z_{Ak}(\lambda)|} = \frac{|\sigma|}{\left\|-\mathrm{Res}_{\lambda}^{*} Y_{kk}^{sys}\right\| \cdot \|Z_{\mathrm{A}k}(\lambda)\|} \qquad 26)$$

which is the ratio between the margin of impedance variation and the magnitude of the original impedance. With this definition of IMR, we can state the following properties:

- A large IMR means the mode is relatively insensitive to the connected apparatus, i.e., system is strong at this POI.
- A small IMR means the system is prone to modes moving and possibly becoming unstable when the IBR at that location is varied, i.e., system is weak at this POI.
- IMR is based on small-signal analysis, hence is only valid in a small range around an operation point.
- When several oscillatory modes are observed, IMR relevant to each mode can be calculated and the strength determined by the minimum IMR.

Figure 1-4 illustrates the principle of IMR. The blue arrow represents the original impedance vector at $s = \lambda$, the red arrow represents the perturbed impedance $Z'_{Ak}(\lambda) = Z_{Ak}(\lambda) + \Delta Z_{Ak}(\lambda)$, and the red meshed circle area is the allowable range of the impedance variation, i.e., the impedance variation margin. IMR is then defined as the ratio between the radius of the red meshed circle and the magnitude of the blue arrow.

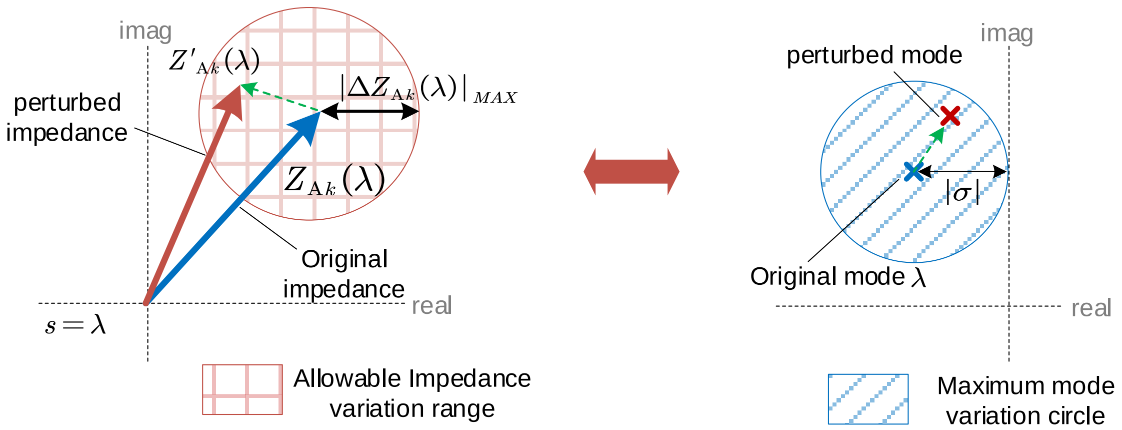


Figure 1-4 IMR illustration on complex plane, at $s = \lambda$. The change of local apparatus impedance will lead to a change of mode λ, while the maximum mode variation circle (blue shaded circle) then determines the range of allowable impedance variation (red shaded circle).

d) Case Study

A modified IEEE-14 bus system[21], shown in Figure 1-5, is employed here to prove the effectiveness of IMR. Three badly tuned GFL inverters are connected at bus 11, 12 and 13.

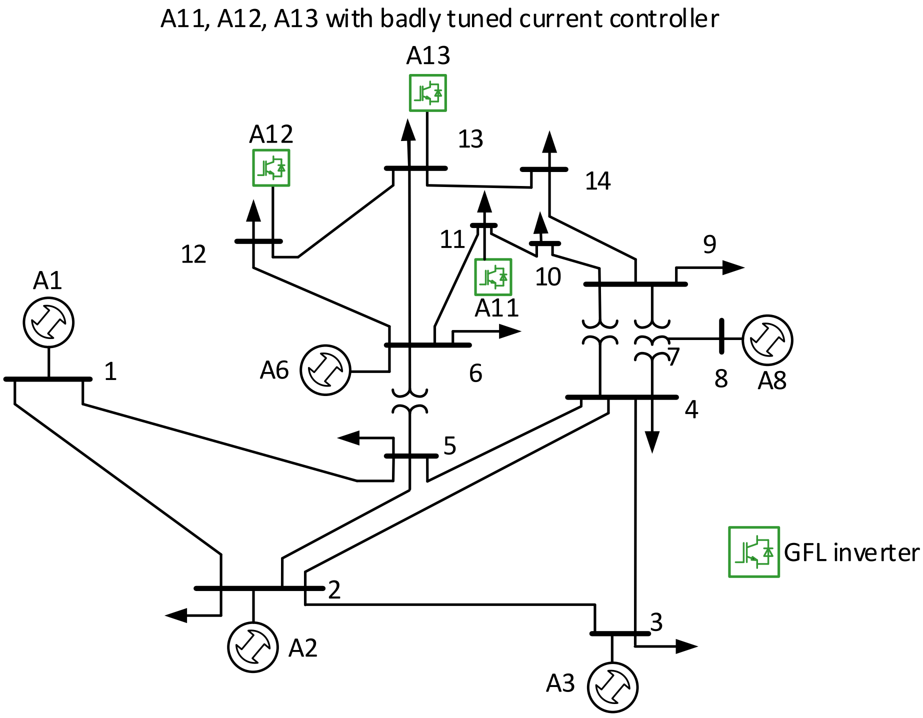


Figure 1-5 Modified IEEE-14 bus system

The impedance spectra acquired from buses with the GFL and other apparatus connected are shown in Figure 1-6. A significant peak appears at 18.87 Hz, indicating that there is a 18.87 Hz oscillatory mode. The mode λ and the residues of it can be obtained via several routes depending on what information is available and including vector fitting of spectra data, from a transfer function or from a state-space model. In this case study, since the analytical model is available, the mode can be acquired as

$$\lambda = -0.1362 + 3.0033j\ rad/s$$

The residues of Y_{kk}^{sys} were also acquired but the values are not shown here for the sake of brevity.

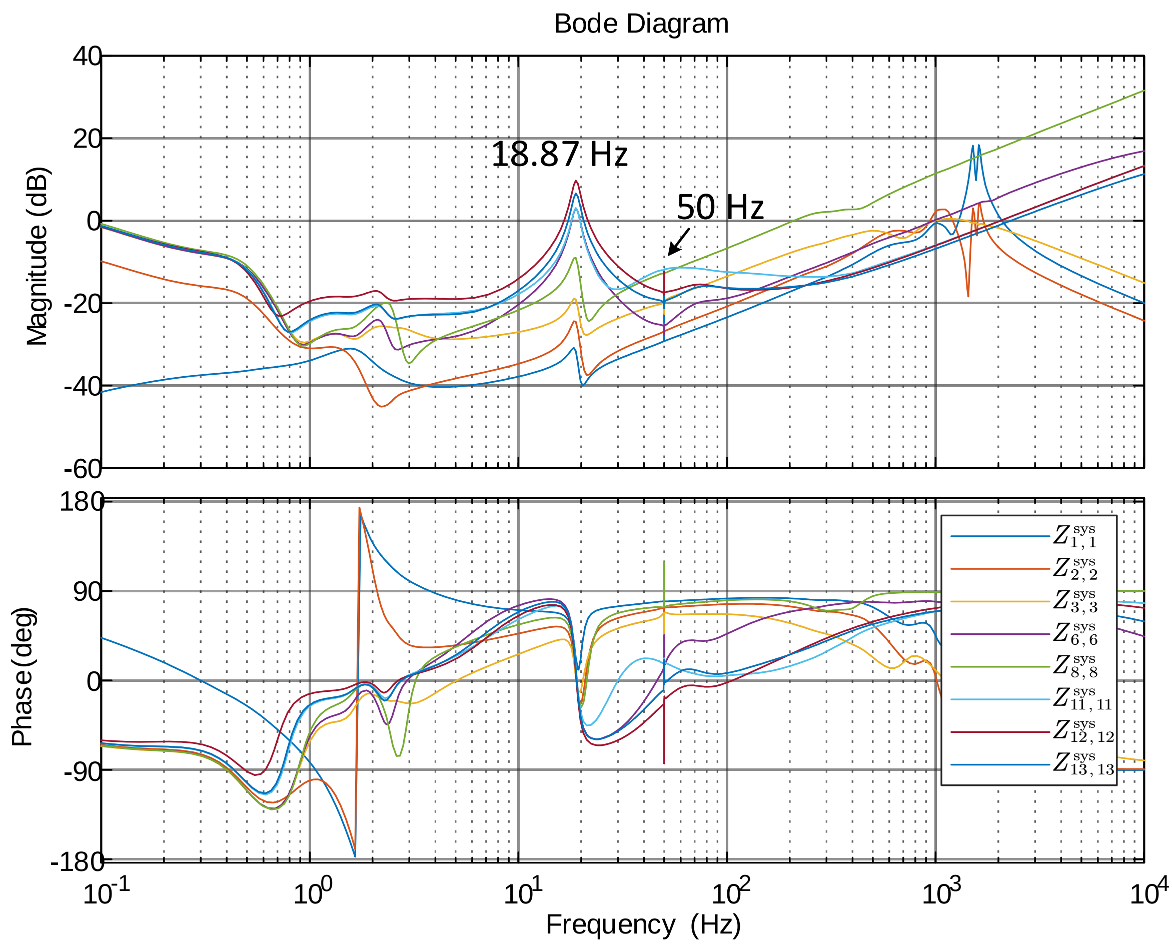


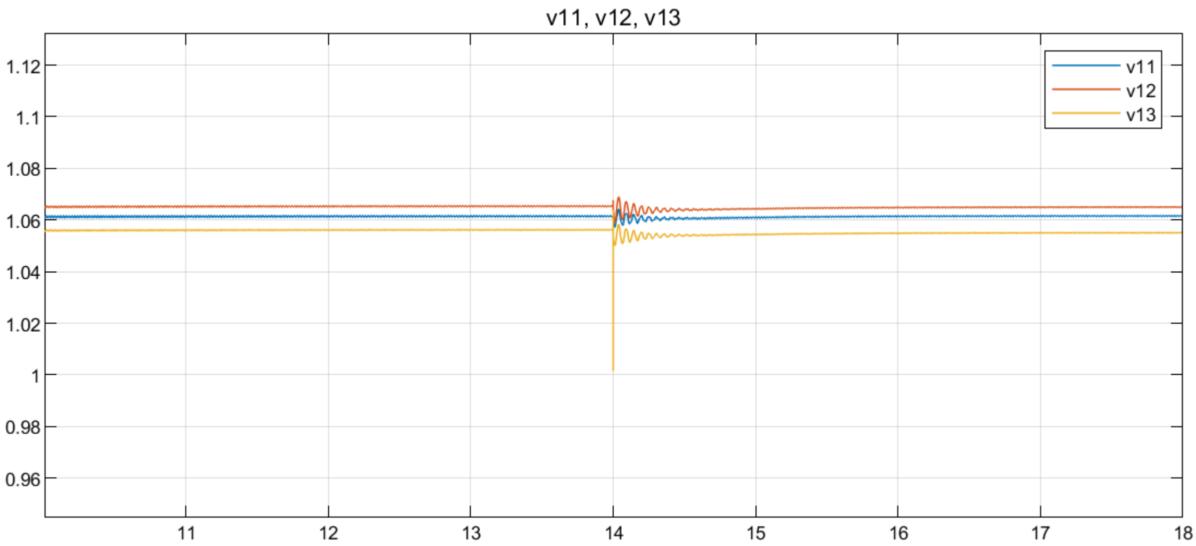
Figure 1-6 Impedance spectra acquired at different buses

IMR values for various buses are shown in Table 2. Note that the IMR cannot be computed at buses where no apparatus is connected (or planned to be connected) and so is show as not available, N/A. It is obvious that the IMR at bus 12 and 13 are relatively low, below 0.5, meaning that the system is 'weak' at these buses and can be vulnerable to perturbations introduced at these locations.

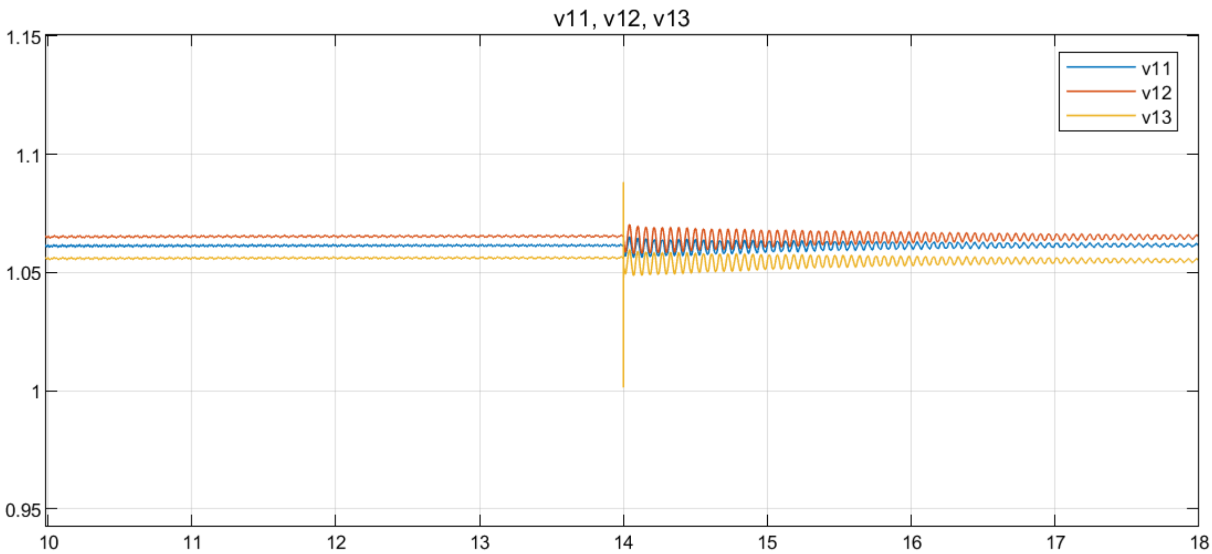
Table 2 IMR values of the modified IEEE-14 bus system

Bus	IMR (18.87 Hz)	Bus	IMR (18.87 Hz)
1	1.7608	8	1.9104
2	2.1955	9	N/A
3	4.8340	10	N/A
4	N/A	11	0.3490
5	N/A	12	0.0845
6	0.3842	13	0.1688
7	N/A	14	N/A

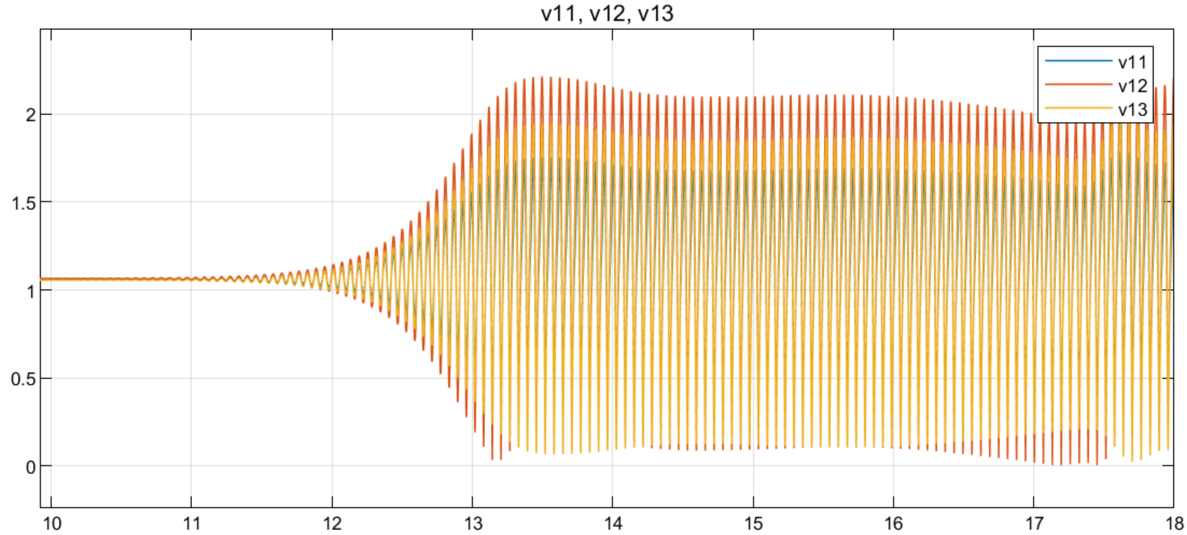
Time-domain simulations were performed to validate the effectiveness of IMR. The voltage waveforms (in per unit) are shown in Figure 1-7. Figure 1-7(a) shows the baseline case where at t = 14 s, a 20% step change is introduced on the load at bus-13. Small oscillations at around 18.9 Hz prove that there is a 18.9 Hz mode existing in the system. Figure 1-7(b) shows a case where the rated power of IBR-13 is increased by 50% at t = 10 s and then the same 20% load step change applied at t = 14 s. Larger amplitude oscillations and a longer damping period can be observed. Figure 1-7(c) shows a case where the rated power of IBR-12 is increased by 50% at t = 10 s with the step change in load at t = 14 s. It can be seen that the system becomes unstable and starts to oscillate. The above results align with the indications from IMR results, showing that IMR can be successfully used as a metric for system strength with regard to small-signal stability.


v11, v12, v13
v11
v12
v13
1.12
1.1
1.08
1.06
1.04
1.02
1
0.98
0.96
11
12
13
14
15
16
17
18

(a)


v11, v12, v13
v11
v12
v13
1.15
1.1
1.05
1
0.95
10
11
12
13
14
15
16
17
18

(b)



(c)

Figure 1-7 Time-domain simulation of the 14 bus system: voltage at bus 11, 12 and 13. At t=14 s, a 20% step change is introduced on the load at bus-13: (a) baseline, (b) at t=10 s, the rated power of IBR-13 is increased by 50%, equivalently as connecting more wind

2. Large-signal System Strength

Note: this part of contents still needs further completion and verification. It will be further completed in WP2.

Although CSCR, WSCR and ESCR are proposed to address the shortcomings of SCR as a system strength metric in an IBR dominated system, all these methods treat all IBRs as current sources with fault current contribution of 1 p.u. when using equivalent circuit method. In practice, a grid-forming (GFM) inverter can fix the voltage and angle of the POI and is usually considered as a positive role which can increase the system strength [13]. In such a case, the GFM inverters should be treated as voltage sources. In some cases when GFM is equipped with fast fault current injection function, it may also mode-change into current mode during fault, and should be considered as current sources. And for GFM with energy storage, such as a GFM in a battery energy storage system (BESS), it may be capable of outputting current of 2~3 p.u. [22]. Such differences are important when considering system strength under large disturbances. To address this issue, a new metric which considers the different types of IBR (voltage type or current type) is proposed.

a) Equivalent Circuit Analysis for Strength Assessment

We first start from the equivalent circuit method applied in the ESCR method. When considering a group of WPPs where they are all considered as current types, the equation applied is shown below:

$$\begin{bmatrix} Z_{11} & Z_{12} & \cdots & & \\ Z_{21} & \ddots & & & \\ \vdots & & Z_{kk} & & \\ & & & \ddots & \\ & & & & Z_{nn} \end{bmatrix} \begin{bmatrix} I_1 \\ \vdots \\ I_k \\ \vdots \\ I_n \end{bmatrix} = \begin{bmatrix} V_1 \\ \vdots \\ V_k \\ \vdots \\ V_n \end{bmatrix} \quad 27)$$

The diagonal element of the Z matrix is the Thevenin impedance of each bus connected with IBR. This value can be acquired from fault current analysis if using a simulation tool. For example, by disconnecting all IBRs, if the short-circuit capacity at bus k is SCC_k, the Thevenin impedance Z_{kk} can then be calculated from equation 1). The off-diagonal element of Z matrix is the mutual impedance between two buses. They can be acquired from impedance scan around the system base frequency, as applied by National Grid ESO. Alternatively, they can be calculated from whole-system impedance model Z^{sys} introduced in [19]. Essentially, Z^{sys} can be calculated as

$$Z^{sys} = (Y_N + Y_A)^{-1} \qquad 28)$$

where Y_N is the conventional nodal admittance matrix used for power flow calculation, and Y_A is the apparatus admittance matrix, which is a diagonal matrix will each element representing the apparatus connected at the corresponding bus. There are two differences between the Z matrix discussed here and Z^{sys} in [19]: 1) it is not on frequency domain but just at the base frequency. 2) All IBRs are treated as disconnected for analysis. Consequently, Y_A is then written as

$$Y_A = \begin{matrix} Y_{A1} & & & \\ & \ddots & & \\ & & 0 & \\ & & & \ddots \end{matrix} \begin{matrix} \left.\vphantom{\begin{matrix} a \\ b \end{matrix}}\right\} SG \\ \left.\vphantom{\begin{matrix} a \\ b \end{matrix}}\right\} IBR \end{matrix} \qquad 29)$$

For SG, $Y_{A1} = 1/x''_d$, an approximation applied in Section 4, while for IBR the admittance is 0, equivalently as open-circuit since they are treated disconnected initially. By applying 28) Z^{sys} can then be acquired and the off-diagonal elements of Z can is mapped with those elements in Z^{sys}. In fact, the diagonal element of Z^{sys} corresponding to buses with IBR also equal the diagonal elements in Z matrix.

Nevertheless, it is obvious from 27) that all IBRs are treated as a current source, and are considered a fault current contribution of 1 p.u. for those variations of SCR.

b) Type-dependent Short-circuit Ratio

To overcome the above difficulty, a type-dependent short-circuit ratio (TDSCR) is proposed that can accommodate current-type sources and voltage-type source that switch mode to current-type under some disturbances. The first modification is to change the nodal admittance matrix into a hybrid matrix by swapping the input and output of the sources that are current type. To do so, the nodal equations and matrix $\boldsymbol{Y}$ are first sorted according to the source type by gathering the voltage-type sources together and placing their variables at begin of vectors with the variables of current-type source following, as shown in Figure 2-1. The nodal admittance matrix is accordingly partitioned into four parts: $\boldsymbol{Z}_{P11}, \boldsymbol{Z}_{P12}, \boldsymbol{Z}_{P21}, \boldsymbol{Z}_{P22}$.

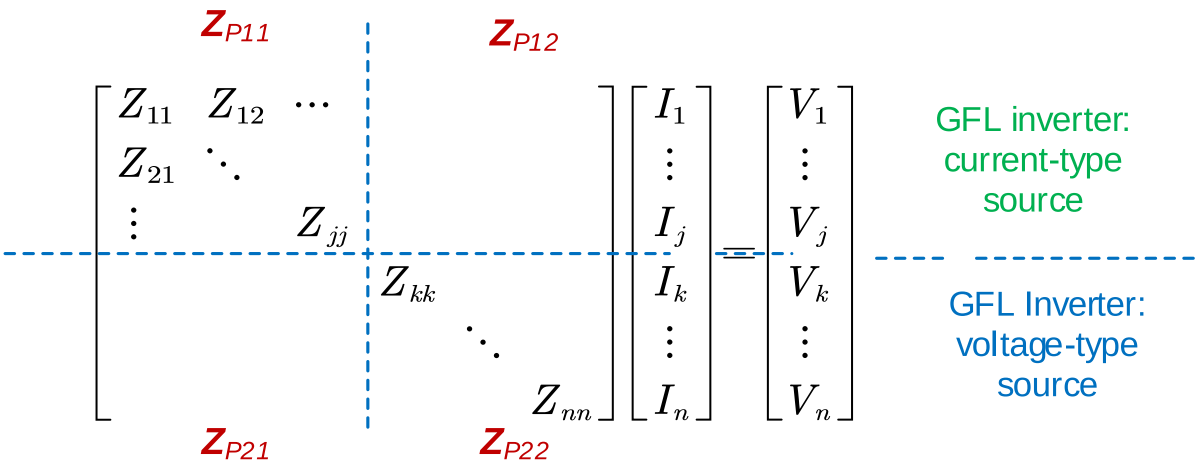


Figure 2-1 Impedance matrix sorting for hybrid matrix

Error! Reference source not found. can then be modified as follows

$$\begin{bmatrix}\boldsymbol{Z}_{P11} & \boldsymbol{Z}_{P12}\\ \boldsymbol{Z}_{P21} & \boldsymbol{Z}_{P22}\end{bmatrix}\begin{bmatrix}i_a\\ i_b\end{bmatrix}=\begin{bmatrix}v_a\\ v_b\end{bmatrix} \qquad 30)$$

v_b and i_b can then be swapped and 30) then becomes

$$\begin{bmatrix}\boldsymbol{Z}_{P11}-\boldsymbol{Z}_{P12}Z_{P22}^{-1}\boldsymbol{Z}_{P21} & \boldsymbol{Z}_{P12}\boldsymbol{Z}_{P22}^{-1}\\ -\boldsymbol{Z}_{P22}^{-1}\boldsymbol{Z}_{P21} & \boldsymbol{Z}_{P22}^{-1}\end{bmatrix}\begin{bmatrix}i_a\\ v_b\end{bmatrix}=\begin{bmatrix}v_a\\ i_b\end{bmatrix}, \qquad 31)$$

From which the hybrid matrix $\boldsymbol{H}$ is defined as

$$\boldsymbol{H}=\begin{bmatrix}\boldsymbol{Z}_{P11}-\boldsymbol{Z}_{P12}Z_{P22}^{-1}\boldsymbol{Z}_{P21} & \boldsymbol{Z}_{P12}\boldsymbol{Z}_{P22}^{-1}\\ -\boldsymbol{Z}_{P22}^{-1}\boldsymbol{Z}_{P21} & \boldsymbol{Z}_{P22}^{-1}\end{bmatrix}. \qquad 32)$$

As a result, the meshed network with GFL inverters is described as

$$\begin{bmatrix}H_{11} & H_{12} & \cdots & & & \\ H_{21} & \ddots & & & & \\ \vdots & & H_{jj} & & & \\ & & & H_{kk} & & \\ & & & & \ddots & \\ & & & & & H_{nn}\end{bmatrix}\begin{bmatrix}I_1\\ \vdots\\ I_j\\ V_k\\ \vdots\\ V_n\end{bmatrix}=\begin{bmatrix}V_1\\ \vdots\\ V_j\\ I_k\\ \vdots\\ I_n\end{bmatrix} \qquad 33)$$

From 33), the Thevenin impedance can then be acquired as

$$Z_{th,k}=\begin{cases}H_{kk}, & current-type\ source\\ \dfrac{1}{H_{kk}}, & voltage-type\ source\end{cases} \qquad 34)$$

Combining 3) and 34) yields a type-dependent short-circuit ratio (TDSCR)

$$TDSCR=\begin{cases}\dfrac{1}{|H_{kk}|P_{Nk}}, & current\text{-}type\ source\\ \dfrac{|H_{kk}|}{P_{Nk}}, & voltage\text{-}type\ source\end{cases} \qquad 35)$$

The TDSCR defined in 35) treats voltage-type source and current-type source differently, offering a more reasonable strength metric for systems with IBR present. In a case where a GFM inverter mode-changes into current-type source during a fault due to its self-protection, it can be modified to a current-type source for the TDSCR calculation.

To further include the interactions of IBRs in close proximity, the concept of ESCR could be borrowed here to shape a type-dependent equivalent circuit-based short-circuit ratio (TDESCR). This is to be investigated in WP2, including case studies on it.

3. Conclusions

This report summarises the explorations of system strength metrics undertaken in WP1 of the "Strength to Connect" NIA project. The following work has been accomplished:

(1) The concept of system strength has been reviewed and a distinction drawn between small-signal system strength and large-signal system strength.

(2) The traditional metric of SCR as well as new metrics including CSCR, WSCR, ESCR, GSIM were reviewed in terms of their definitions and analysed to establish their pros and cons.

(3) Since existing metrics capture only local interactions between IBR, or, in the case of GSIM are system-wide but do not include the dynamics of the connecting IBR, a proposal has been made for a new metric to indicated strength in terms of avoidance oscillatory behaviours and small-signal instability. It is described as small-signal system strength metric and named Impedance Margin Ratio (IMR). It is a whole-system assessment that accounts for the dynamics of apparatus at all nodes, local and remote to the node in question. A modified IEEE-14 bus system was employed to demonstrate the effectiveness of IMR in indicating onset of small-signal instability and instances of poor mode damping.

(4) To address large-signal system strength, which is the ability of a system to recover well from large disturbance such as a short-circuit fault at a given node, a new metric name type-dependent short-circuit ratio (TDSCR) was proposed. It extends the principles of SCR to account properly for the current-source nature of some IBR in system, GFL IBR in particular, and to account for the voltage source nature of GFM IBR even if their traditional fault current capability is limited. A 4-bus example system was employed to illustrate the effectiveness of TDSCR in recognising the contribution of IBR to large-signal system strength.

There are also several points that warrant further exploration:

(1) The TDSCR is a variant of, an expected improvement on, SCR but it does not consider the interactions among adjacent IBRs during large disturbances. To include the interactions, the principles of ESCR could be adapted but the types of the interreacting IBRs will need to be considered, i.e., different combinations of voltage-type and current-type sources in electrical proximity. Such an extension of TDSCR will be an item of further work within "Strength to Connect".

(2) Further, TDSCR treats IBR as an ideal source (voltage to current) with an associated impedance but omits the internal control design of the IBR. The influence of PLL, droop controller and other control loops should be included to study the interactions among IBRs in large-signal conditions in a more accurate way.

(3) The situation that the limited fault current IBR (low fault-current system strength) may lead to mal-operation of protection and failure to properly clear faults has not yet been discussed. This needs to be included in future work.

In addition to progressing the further work identified here, the "Strength to Connect" team will now progress to WP2 in which the services which IBR can provide to the system to increase the strength will be investigated.

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National Energy System Operator
Faraday House
Warwick Technology Park
Gallows Hill
Warwick
CV34 6DA

[insert email address]

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