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Submissions in response to consolation paper on efficient reactive current access standards for inverter-based resources

I welcome this opportunity to make a submission to consolation paper on efficient reactive current access standards for inverter-based resources.

AEMC has recently made changes to the system strength framework in the National Electricity Rules (NER) [5, 7], which evolves the existing 'do no harm' obligation and coordinates the supply and demand sides of the system strength framework [4].

Under this framework, AEMO must specify revised system strength requirements for system strength nodes on the supply side in clause S5.1.14, include the minimum fault level which ensures the necessary levels of system strength for effective operation of network and generator protection equipment and the efficient level of system strength which ensures efficient levels of system strength for IBR connection and operation (hosting capacity and constraint alleviation).

On the demand side, new minimum access standards for relevant generators, loads and market network service providers (MNSPs) requires relevant plant to remain connected and operate stably at a short circuit ratio (SCR) of 3.0 for voltage phase angle shift limits less than 20 degrees at the connection point [5] in clause S5.2.5.15 and S5.2.5.16.

Clauses S5.2.5.5 has prescribed how reactive current should be injected and how active power should be recovered by IBRs at each stage of fault including entering fault, during fault and exiting fault.

However, the essence of system strength renovation is to provide a stable voltage waveform during steady state and following contingency. The main objective is voltage waveform stability not the amount of reactive current injection.

In this note, a mathematical model has been developed to identify and quantify some of problems associated with S5.2.5.5. Three problems have been illustrated as follows.

Firstly, the maximum active current which can be injected to grid during a sever fault is limited by power flow equation not by the equipment's inherent limitations. The physical law should be respected when prescribing the current injection.

Secondly, with appearance of the internal impedance, it is difficult to mean minimum reactive current capability standard specified at PCC especially for plant with high internal impedance. As an example, for moderate fault with a retained voltage of 0.65pu at PCC, it will require high Kfactor[1] of

[1] Reactive current injection from converter can be formulated as Iq =Min [Iqmax Kfactor *(Vth- Vt)].

4 and Vth of **0.95** pu) to meet reactive current injection requirement of MAS with reactive current injection commence at 0.9 pu even with an internal plant impedance of 0.2pu.

Finally, high reactive current injection and fast active power recovery following contingency will deteriorate voltage stability in a weak grid.

As a result, the MAS requirements prescribed in S5.2.5.5 might increase the need of the efficient level of system strength from supply side and deteriorate SCR / phase shift withstand capabilities of IBRs.

It is very important that the requirement in clauses S5.1.14, S5.2.5.5, S5.2.5.13, S5.2.5.15 and S5.2.5.16 are specified in a way that they are coordinated & supplemented to each other.

Since S5.2.5.15 and S5.2.5.16 will be enforced to ensure the SCR / phase shift withstand capabilities of IBRs, the minimum requirement of S5.2.5.5 can be removed to avoid contradiction among these clauses. In addition, IBRs' SCR withstand capability and phase shift capability should be examined in the FIA instead of efficient reactive current capability in order to achieve voltage waveform stability and the efficient level of system strength.

In the following sections, the problems with the present reactive current capability standard have been defined and quantitated using basic circuit principle with a simple two terminal system.

1. Background and Objective

Under a major amendment to Australia's National Electricity Rules in 2018, generators must provide capacitive reactive current injection up to the full thermal capacity of the equipment within 70 milliseconds of a sufficiently deep fault, and in proportion to the reduction in voltage for shallower faults. Further, reduction in the active-power component of current during a fault is permitted only in accordance with the equipment's inherent limitations and the provision of the required reactive current [2].

In [2], analytical approach has been applied to extend traditional P/V and Q/V stability analysis to performance networks under fault condition. In this note, the current injection rules prescribed by NER used in the converter-based generator (non-synchronous generator) have been further incorporated in the traditional P/V and Q/V stability analysis under specific fault conditions, namely, severe fault, normal fault, and shallow fault.

The analysis in section 2 and 3 in this note suggests

- Prescribing reactive current injection rule and active current injection rule should respect both equipment's inherent limitation and power flow equations in severe fault.
    - ✓ It is not possible to maintain the active component of current accordance with the equipment's inherent limitations and the provision of the required reactive current in a severe fault as there is limit on the maximum active power allowed transfer imposed by power flow.
- Meeting minimum assessment requirement at the connection point specified in S5.2.5.5 is still challenging for plants with a normal and large internal plant impedance and for plants connected to a weak grid.

1) The internal plant impedance (X in p.u.) between converter terminal and PCC will cause converter terminal voltage X p.u. higher than voltage at PCC with higher reactive current injection.
    - ✓ For a moderate fault at PCC, it will require high Kfactor[2], e.g., 4 or more, in the reactive current contribution formula of the converter to achieve of at least 2% of the maximum continuous current of the generating system for each 1% reduction of voltage at the connection point specified in MAS.
    - ✓ High reactive current injection in a moderate fault will result in Q spike when voltage rapidly recovers.
    - ✓ High reactive current injection during moderate fault and shallow fault can easily boost converter voltage too close to normal operating levels even when the fault at the connection point has not been cleared. This has the potential to cause instability due to hunting or retriggering of the LVRT control logic and furthermore could cause issues with the generating unit's ability to detect fault clearance locally by sensing the restoration of voltages [1].

[2] Reactive current injection from converter can be formulated as Iq =Min [Iqmax   Kfactor *(Vth- Vt)].

✓ The internal plant impedance X, e.g., 0.2pu up to 0.4 pu or more, makes it very difficult to coordinate fault entering voltage at IBR level and at PCC.

This problem becomes even worse in a larger internal plant impedance case.

2) High reactive current injection and fast active power recovery following contingency will deteriorate voltage stability in a weak grid because

✓ In a weak grid, a small amount reactive current injection will result in high voltage rise due to its voltage sensitivity. In almost all the projects connected to weak grid around world, the used k factor is rather small in order not to cause high voltage rise post fault.

✓ In a weak grid, if the active power increases rapidly and flow on larger impedance of the circuit, it will drive voltage down again and cause a further voltage dip. A small reactive current injection will drive IBRs voltage high to get out of fault again. The retriggering FRT has the potential to cause instability as well. Therefore, it is very important to achieve voltage stabilization first before injecting a significant amount of active power.

2. The Q-V characteristic for two terminal system

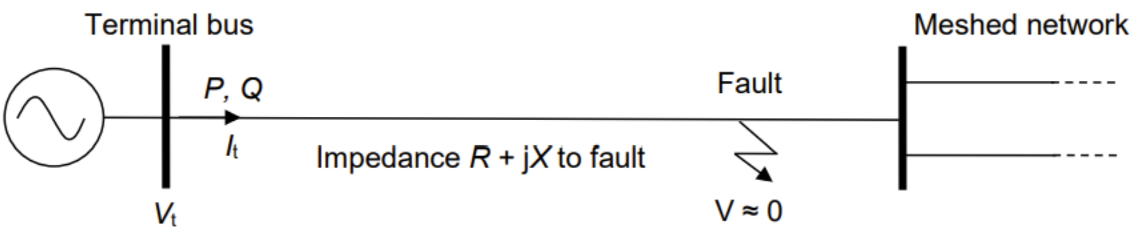

Figure 1 Hard short circuit located radially with respect to a generator.

The following formula relating the voltage magnitudes V1 and V2 at the two ends of a network section with series impedance R + jX appears in CIGRE TR-671 [3]:

$$V_1^4 - [2(RP + XQ) + V_2^2]V_1^2 + (R^2 + X^2)(P^2 + Q^2) = 0, \tag{1}$$

where P and Q are the active and reactive power injected at the V1 end.

In the present case V1 = Vt at the generator, V2 = VF at the fault point, and P, Q represent the active power and reactive power at terminal bus.

For a given voltage Vt, the reactive power can be uniquely determined.

$$Q_{1,2} = \frac{XV_t^2 \pm \sqrt{R^2V_t^4 + 2PRV_t^2 + Z^2V_F^2V_t^2 - Z^4P^2}}{Z^2} \tag{2}$$

Where R, X and Z are resistance, inductance and impedance between DER terminal and fault location. P, Q are active power and reactive power at terminal and S is apparent power with $S = \sqrt{P^2 + Q^2}$.

The equation has solution if

$$R^2V_t^4 + 2PRV_t^2 + Z^2V_F^2V_t^2 - Z^4P^2 \geq 0 \qquad (3)$$

The equation has no solution (voltage collapse occurs at the generator) if

$$R^2V_t^4 + 2PRV_t^2 + Z^2V_F^2V_t^2 - Z^4P^2 < 0 \qquad (4)$$

3. Problem definition and quantification for present reactive current capacity standard

3.1 Reactive Current Injection and Active Current Injection Rule

According to NER cl. S5.2.5.5(n)(1), to install a level of reactive power injection or absorption capability equal to at least 2% of the maximum continuous current of the generating system including all operating asynchronous generating units for each 1% change (reduction or increase) in voltage at the connection point above the under or over voltage range (see point 2 below)

According to NER cl. S5.2.5.5(o)(1), to commence their reactive current injection or absorption response when the connection point voltage is in an under-voltage range of between 80% and 90% of the normal voltage or an over-voltage range of between 110% and 120% of the normal voltage.

According to NER cl. S5.2.5.5(i)(1), despite the amount of reactive current injected or absorbed during voltage disturbances, and subject to thermal limitations and energy source availability, a generating system must make available at all times…… 'sufficient current to maintain rated apparent power of the generating system including all operating generating units (in the absence of a disturbance), for all connection point voltages above 115% (or otherwise, below the overvoltage range agreed…)' …...'the maximum continuous current of the generating system including all operating generating units for all connection point voltages below 85%' (or otherwise, below the undervoltage range agreed…)'.

The reactive current injection can be obtained with

Iq =Min [Iqmax Kfactor *(Vth- Vt)] (5)

Where Vth is the threshold voltage used for reactive current injection formula calculation and Vt is IBR terminal voltage.

The active current injection can be obtained with

Ip = min [Ip Sqrt(Imax^2-Iq^2)] (6)

With Ip=P./Vt where the terminal voltage can be obtained with

Vt= abs (Z * conj (Ip + j*Iq) +V_F) (7)

3.2 Definition of the Problem I

Problem I : The maximum active current which can be injected to grid during a sever fault is limited by power flow equation (3) not by the equipment's inherent limitations shown in Eq. (6).

Therefore, the requirement that reduction in the active-power component of current during a fault is permitted only in accordance with the equipment's inherent limitations and the provision of the required reactive current defined in S 5.2.5.5 clause I (2)[3] is not possible in theory.

This can be illustrated with example 1 and example 2. In example 1 & 2, for given R &X, 1 pu reactive current injection, with equipment maximum current of Imax of 1.1 pu, sweeping active power has been swept to identify the limiting factors for the maximum possible shipped active power & active current in a severe fault at PCC.

For given R &X and given reactive current injection Iq (which has been specified according to Eq. (5)), assuming a severe fault with the retained voltage V_F at the connection point, sweeping active power from 0 to 1 pu (which determines active current injection according to Eq. (6)), the IBR terminal voltage Vt can be calculated by Eq (7) and thus the IBR terminal reactive power can be uniquely determined by eq. (2) as a function of active current injected. The solution is available only if Eq. (3) is satisfied. The maximum active power/active current can be injected in the severe fault can be found by sweeping active power from 0.01 pu towards 1pu until eq (4) has been satisfied.

The variables used for these studies have been given as Table 1.

Table 1. simulation parameters used in the example 1

	X (pu)	**X/R**	V_F (pu)	Iq (pu)	P (pu)	Imax (pu)	Ip_max (pu)	**Pmax satisfied Eq.(4)**
Value	0.2	**10**	0.04	1	0.01:0.01:1	1.1	0.46	**Ipmax**
Value	0.2	**5**	0.04	1	0.01:0.01:1	1.1	0.46	**Ipmax**

Figure .2 shows Q-Vt curve and Ip-Vt curve for a severe fault with V_F of 0.04 pu with 1 pu reactive current injection as a function of active current injection for different X/R ratios. The maximum allowed active powers during sever fault are 0.11pu in the X/R of 5 case and 0.08 pu in the X/R of 10 case. The maximum active current injected are 0.425 pu in the X/R of 5 case and 0.322 pu in the X/R of 10 case which are both **less than the equipment's inherent limitations of 0.46 pu.**

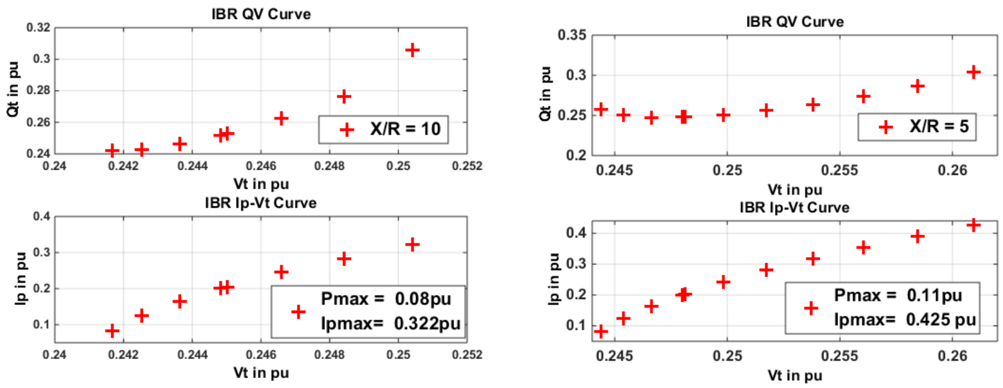

Figure .2 Q-Vt curve and Ip- Vt curve for a severe fault with V_F of 0.04 pu with 1 pu reactive current injection as a function of active current injection **for different X/R ratio**s

[3] NER ver181 pg693-694.

i) Subject to paragraph (h), despite the amount of reactive current injected or absorbed during *voltage* disturbances, and subject to thermal limitations and energy source availability, a *generating system* must make available at all times:

2) the maximum continuous current of the generating system including all operating generating units (in the absence of a disturbance) for all connection point voltages below 85% (or otherwise, below the undervoltage range agreed in accordance with subparagraph (g)(1)),

Table 2. simulation parameters used in the example 2

	X (pu)	X/R	**VF (pu)**	Iq (pu)	P (pu)	Imax (pu)	Ip_max (pu)	**Pmax satisfied Eq.(4)**
Value	0.2	10	**0.00**	1	0.01:0.01:1	1.1	0.46	**Pmax, Ipmax**
Value	0.2	10	**0.04**	1	0.01:0.01:1	1.1	0.46	**Pmax, Ipmax**
Value	0.2	10	**0.2**	1	0.01:0.01:1	1.1	0.46	**Pmax, Ipmax**

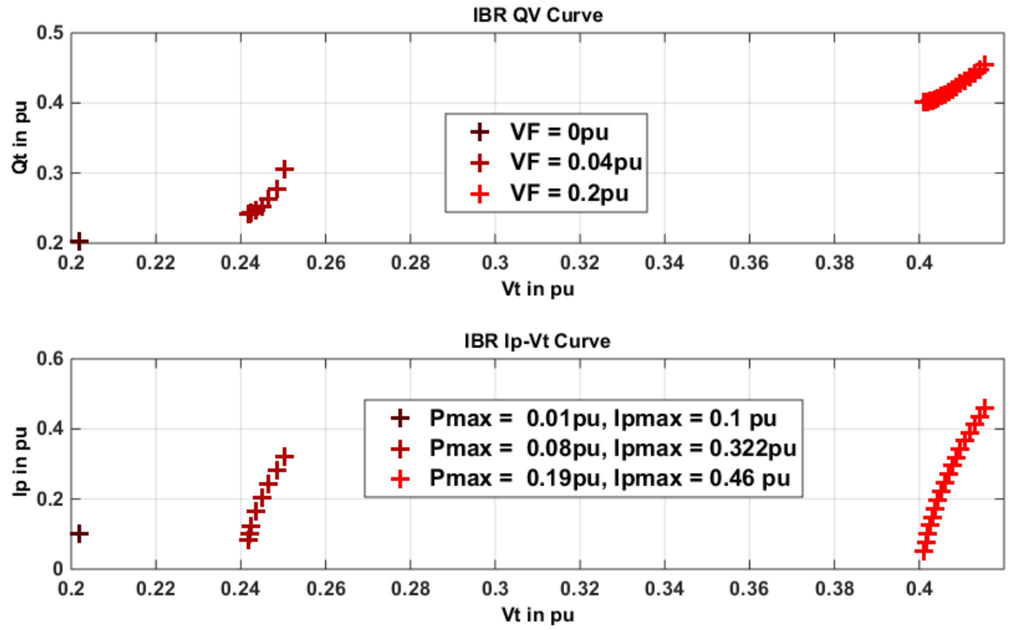

Figure .3 Q-Vt curve and Ip- Vt curve for a severe fault with V_F of 0.04 pu with 1 pu reactive current injection as a function of active current injection **for different retained voltages at PCC**

Figure .3 shows Q-Vt curve and Ip-Vt curve for a fault with different retained voltage V_F at PCC with 1 pu reactive current injection as a function of active current injection. The example again confirms that the possible active current injection in a severe fault is limited by power flow equation.

Conclusion:

- 1 pu reactive current injection (or more limited by converter thermal limit and injection rule defined in IBR) will boost voltage at IBR terminal to roughly X pu where X is internal impedance of plant for given X/R used.
- The active current and reactive current injection formula should be prescribed in a way that there is (are) a physical solution (solutions) available with respect to power flow Eq (1)-(3) for severe fault. Otherwise, there is no equilibrium which can be achieved for a severe fault. **This should be aware by both IBR OEMS and policy makers.**

3.3 Definition of the Problem II

Problem I I: The internal plant impedance (X in p.u.) between converter terminal and PCC will cause converter terminal voltage e.g., X p.u. higher than voltage at PCC especially with high capacitive reactive current injection.

- ✓ For a moderate fault at PCC, it will require **high Kfactor**[4] in the reactive current contribution formula of the converter to achieve of at least 2% of the maximum continuous current of the generating system for each 1% reduction of voltage at the connection point specified in MAS.

  This has been illustrated in Example 3. In example 3, for moderate fault with a retained voltage of 0.65pu at PCC, it will require high Kfactor[5] of 4 and Vth of 0.95 pu) to achieve 0.5 pu reactive current injection for MAS with reactive current injection commence at 0.9 pu.

- ✓ The internal plant impedance X, e.g., 0.2pu up to 0.4 pu or more, makes it very difficult to coordinate fault entering voltage at IBR level and at PCC.

  With Vth and Kfactor settings fulfilling MAS in a moderate fault, IBRs will see terminal voltage higher than 0.9 pu when retained voltage at PCC is 0.8 pu as seen in example 4. As a result, for a shallow fault at PCC, converter terminal voltage might not drop below LVRT threshold voltage and thus there is no reactive current injection from converter at all.

  This problem becomes even worse in a larger internal plant impedance case.

The NER prescribe that a generating system should be capable of supplying during the fault to assist the maintenance of power system voltages during the fault, capacitive reactive current… of at least 2% of the maximum continuous current of the generating system… for each 1% reduction of voltage at the connection point. Reactive current response is to commence when the voltage is in an under-voltage range of 80% to 90%.

According to this requirement, it requires full reactive current injection for minimum detVpcc of 0.25pu (corresponding to VF of 0.65pu) with assumption that reactive current response is to commence when the voltage is 90%. As turbine see much higher voltage with 20% internal plant impedance, it needs a very high Kfactor and Vth to obtain 0.5 pu reactive current with high terminal voltage.

Iq =Min [Iqmax Kfactor *(Vth- Vt)]

With Kfactor =4 and Vth=0.95, it is possible to inject 0.5 pu reactive current with terminal voltage above 0.75pu.

The variables used for the study show in Figure.3 have been given as below.

Table 3. simulation parameters used in the example 3

	X (pu)	X/R	V_F (pu)	Iq (pu)	Imax (pu)	Ip_max (pu)	P (pu)
Value	0.2	5	0.65	1	1.1	0.46	0.01:0.01:1

[4] Reactive current injection from converter can be formulated as Iq =Min [Iqmax Kfactor *(Vth- Vt)].
[5] Reactive current injection from converter can be formulated as Iq =Min [Iqmax Kfactor *(Vth- Vt)].

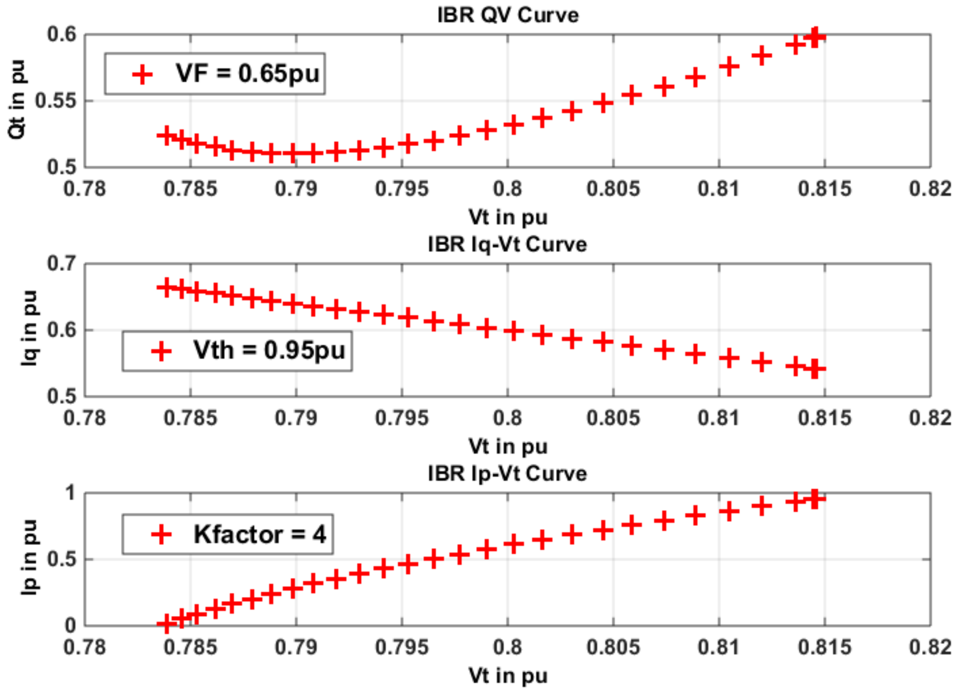

Figure .4 Q-Vt curve and Ip & Iq- Vt curve for a shallow fault with VF of 0.65 pu with Kfactor of 4 and Vth of 0.95 pu for reactive current injection as a function of active power injection

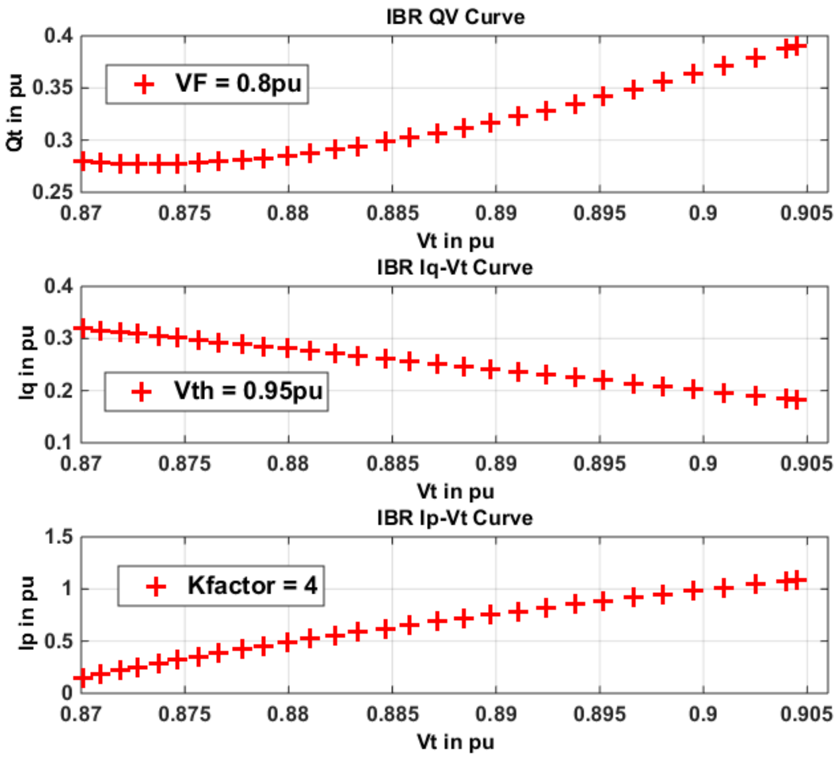

Figure .5 Q-Vt curve and Ip & Iq- Vt curve for a shallow fault with VF of 0.8 pu with Kfactor of 4 and Vth of 0.9 5pu for reactive current injection as a function of active power injection

Table 4. simulation parameters used in the example 4

	X (pu)	X/R	V_F (pu)	Iq (pu)	Imax (pu)	Ip_max (pu)	Ip (pu)
Value	0.2	5	0.8	1	1.1	0.46	0.01:0.01:1

Conclusion:

- ✓ With appearance of the internal impedance, it is difficult to mean minimum reactive current capability standard specified at PCC especially for plant with high internal impedance.

3.4 Definition of the Problem III

Problem III: it is not possible to inject high reactive current and have a fast active power recovery following contingency for below reasons.

- ✓ High reactive current injection is not possible in a weak grid due to the voltage sensitivities. In a weak grid, a small amount reactive current injection will result in high voltage rise due to its Q-V characteristic. In almost all the projects connected to weak grid around world, the used k factor is small in order not to cause high voltage rise post fault.
- ✓ Fast active power recovery following contingency is not possible in a weak grid because if the active power increases rapidly and flow on larger impedance of the circuit, it will drive voltage down again and cause a further voltage dip. IBR will inject a large amount of reactive current injection to drive IBRs voltage high and thus out of fault again. The retriggering FRT has the potential to cause instability as well.

4. Reference

[1] NATIONAL ELECTRICITY RULE CHANGE PROPOSAL, Reactive current response to disturbances (clause S5.2.5.5), GE International Inc, Gold wind Australia, Siemens Gamesa Renewable Energy and Vestas Australia

[2] Generator Fault Current Injection: Are system operators asking for the right thing? A. Morton, Lloyd's Register Australia.

[3] Cigre 671 Connection of wind farms to weak AC networks

[4] System strength final determination, pg94.

[5] National Electricity Amendment (Efficient management of system strength on the power system) Rule 2021 No. 11

[6] Dr. Bo Yin, Dr. Hongtao Ma, Najlae Yazghi, Bjoern Andresen, IEEE PES 2013, Operation of full-converter wind turbines in low SCR applications

[7] Bo Yin, Submissions in response to Amendments to AEMO instruments for Efficient Management of System Strength Rule Issues Paper April 2022