IMPERIAL

“Voltage Source Behind an Impedance” (VSBI) Characteristic as a Service

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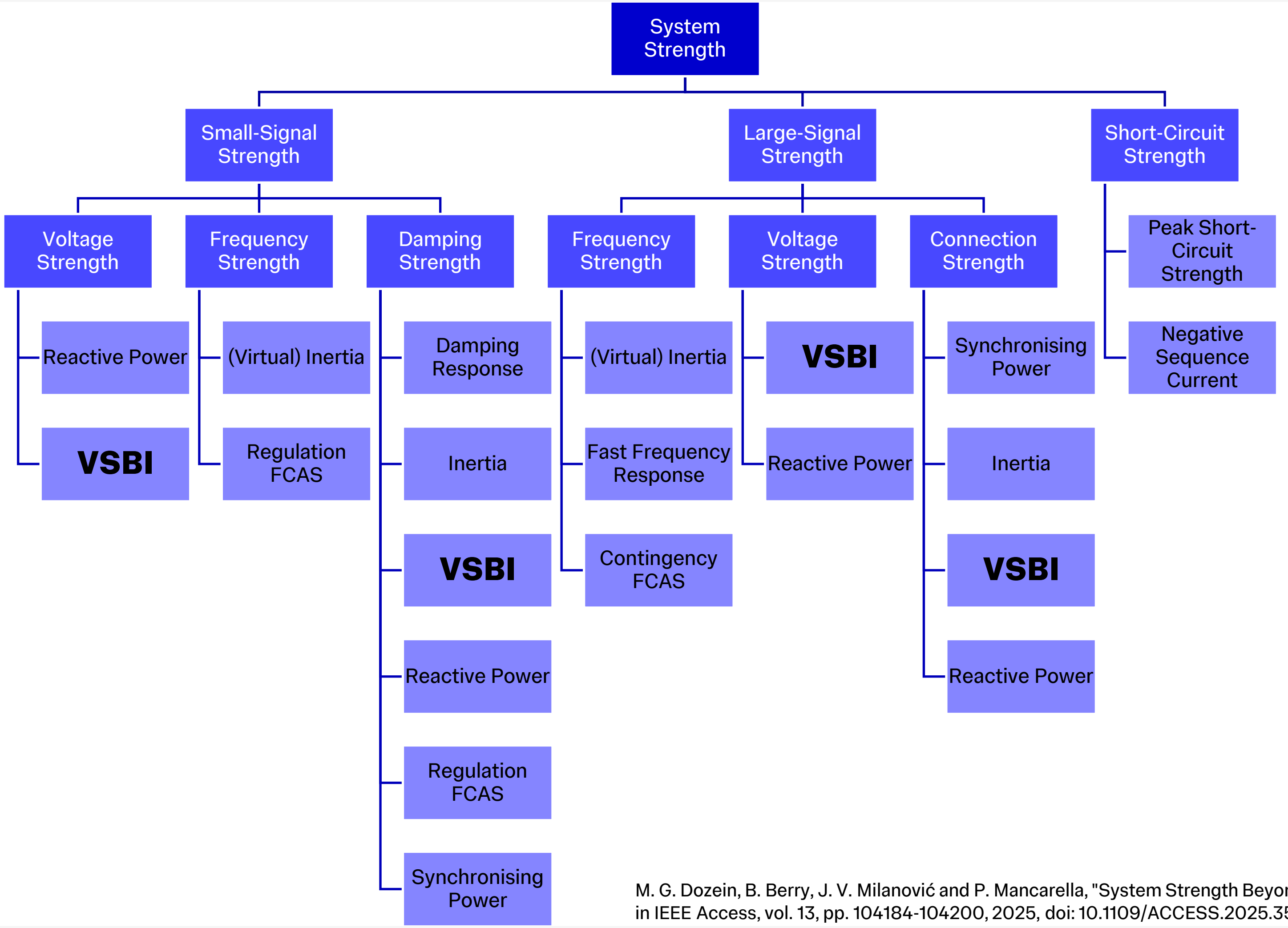
New System Strength Classification

Voltage source behind an impedance (VSBI) characteristics - an upcoming need.



M. G. Dozein, B. Berry, J. V. Milanović and P. Mancarella, "System Strength Beyond Fault Level," in IEEE Access, vol. 13, pp. 104184-104200, 2025, doi: 10.1109/ACCESS.2025.3572432.

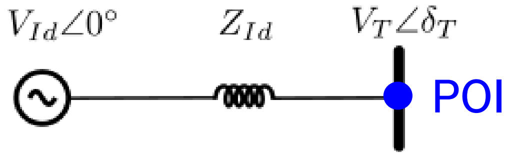
GFM Definitions around the World

Supply: GFMs are expected to demonstrate VSBI characteristics

COUNTRY	GFM DEFINITION
NERC [1] (USA)	“The primary objective of GFM control for BPS-connected IBRs is to maintain an internal voltage phasor that is constant or nearly constant in the sub-transient to transient time frame”
FINGRID [2] (FINLAND)	“GFM shall provide autonomous, near-instantaneous frequency and voltage support by maintaining a nearly constant internal voltage phasor in the sub-transient time frame”
UNIFI [3] (USA)	“GFM IBR controls to maintain an internal voltage phasor that is constant or nearly constant in the sub-transient to transient time frame”
AEMO [4] (AUSTRALIA)	“A GFM inverter maintains a constant internal voltage phasor in a short time frame, with magnitude and frequency set locally by the inverter, thereby allowing immediate response to a change in the external grid”
NESO [5] (GB)	“Any Plant and Apparatus whose supplied Active Power is directly proportional to the difference between the magnitude and phase of its Internal Voltage Source and the magnitude and phase of voltage at the Grid Entry Point or User System Entry Point and the sine of the Load Angle”
ENTSO-E / ACER [6] (EUROPE)	“Within its current and energy limits, the GFM PPM shall be capable of behaving at the terminals of the individual unit(s) as **a voltage source behind an internal impedance (thevenin source)** during normal operating conditions and upon inception of a network disturbance”
MISO [7] (USA)	GFM IBR shall provide autonomous, near-instantaneous frequency and voltage support by maintaining a nearly constant internal voltage phasor in the sub-transient time frame, within the inverter’s current limits and the resource’s energy limitations

VSBI Characteristics of a Device

- The ability of a device to behave like an ideal voltage source (IDVS) behind an impedance in the sub-transient time frame.



  - Ability to maintain a constant voltage at the point of interconnection (POI).

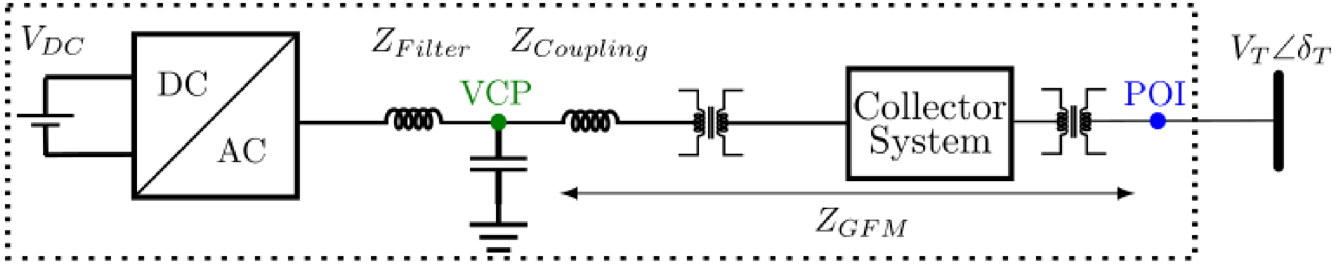
  - In case of a voltage phase angle jump, the device should exchange appropriate amount of active power or current with the grid.

  - In case of a voltage magnitude jump, the device should exchange appropriate amount of reactive power or current with the grid.

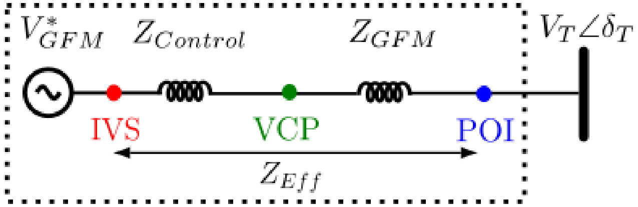
GFM's VSBI Characteristics

- A Synchronous Machine (SM) behaves like an ideal voltage source (E") behind reactance (X") in sub-transient time frame.

- GFM's equivalent circuit:



- Internal Voltage Source - IVS
- Voltage Control Point - VCP
- Point of Interconnection - POI



- However, unlike for a SM, V^*_{GFM} is not an ideal voltage source in the sub-transient time frame.

GFM's Compliance & Testing for VSBI Characteristics
Existing Time Domain Requirements

- ❑ **ISOs:** Assess active/reactive power response to voltage magnitude (MJ) & phase (PJ) jump at the grid voltage.

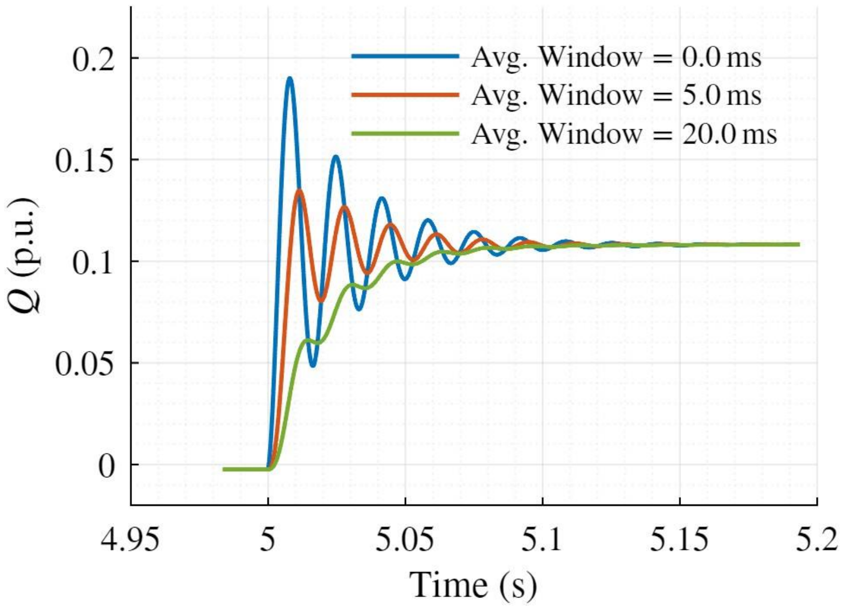
- ❑ Test Setup: GFM connected to the Thevenin grid equivalent with SCR=3 & X/R ratio = 6.

ISO	Peak Value	Rise Time	Decay Time
AEMO / MISO	P ≥ 0.2 p.u./10° PJ	≤ 15 ms	–
ERCOT	P ≥ 0.2 p.u./10° PJ Q ≥ 0.03 p.u./3% MJ	≤ 16.6 ms	ΔP ≥ 0 VL ≤ 50 ms ΔQ ≥ 0 VL ≤ 100 ms
ENTSO-E	I-Active = 50–70% I-RMS	≤ 10 ms	t-decay = 0.016 s ± 33%

GFM's Compliance & Testing for VSBI Characteristics

Assessing VSBI characteristics in the time-domain has some major drawbacks

- ❑ Dependent on testing setup (e.g. SCR, X/R, etc).
- ❑ As requirements are at few-ms time-frame, heavily dependent on measurement device's resolution, accuracy, and length of the sliding window for the moving average filter.



- ❑ Can not quantify or compare VSBI strength.

VSBI Characteristics in Frequency Domain

- Device should have similar admittance spectra (in the dq domain) to an ideal voltage source (IDVS) behind an impedance.

- Focus on coupling terms:
  - $\boldsymbol{Y_{qd}/Y_{dq}}$ → Reactive/Active power response to a voltage magnitude/phase perturbation.

$$-\begin{bmatrix} I_d(s) \\ I_q(s) \end{bmatrix} = \begin{bmatrix} Y_{dd}(s) & Y_{dq}(s) \\ Y_{qd}(s) & Y_{qq}(s) \end{bmatrix} \begin{bmatrix} V_d(s) \\ V_q(s) \end{bmatrix} \qquad \ldots(1)$$

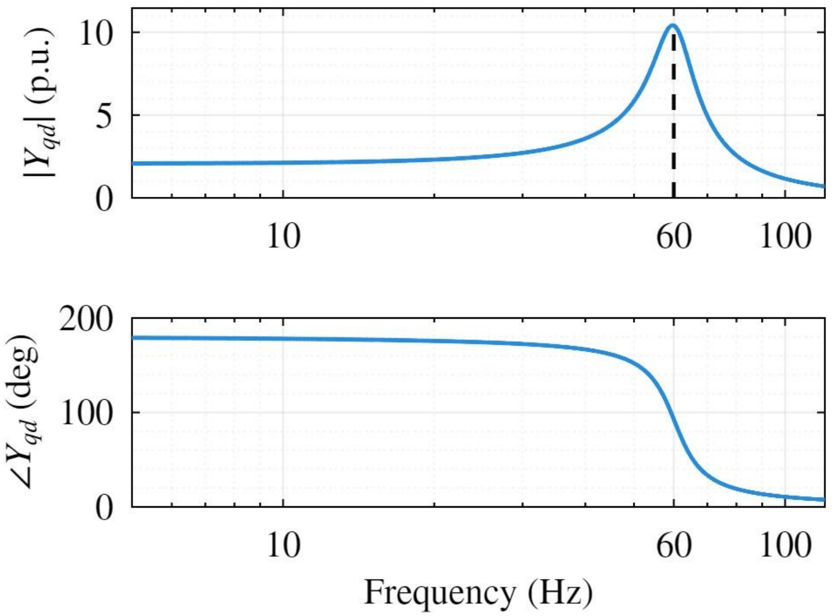
VSBI Characteristics in Frequency Domain

Ideal voltage source (IDVS) behind an impedance:

- For an Ideal voltage source behind an impedance:

$$Y_{Id}(s) = \frac{1}{(R_{Id} + sL_{Id})^2 + (\omega_1 L_{Id})^2} \begin{bmatrix} R_{Id} + sL_{Id} & \omega_1 L_{Id} \\ -\omega_1 L_{Id} & R_{Id} + sL_{Id} \end{bmatrix} \quad \ldots(2)$$

- Poles at $s = -\frac{R_{Id}}{L_{Id}} \pm j\omega_1$
- $\omega_d = \omega_1$
- $\left|Y_{qd}(0)\right| = \frac{\omega_1 L}{R^2 + (\omega_1 L)^2}$
- $\angle 180°$ → oppose voltage magnitude changes.

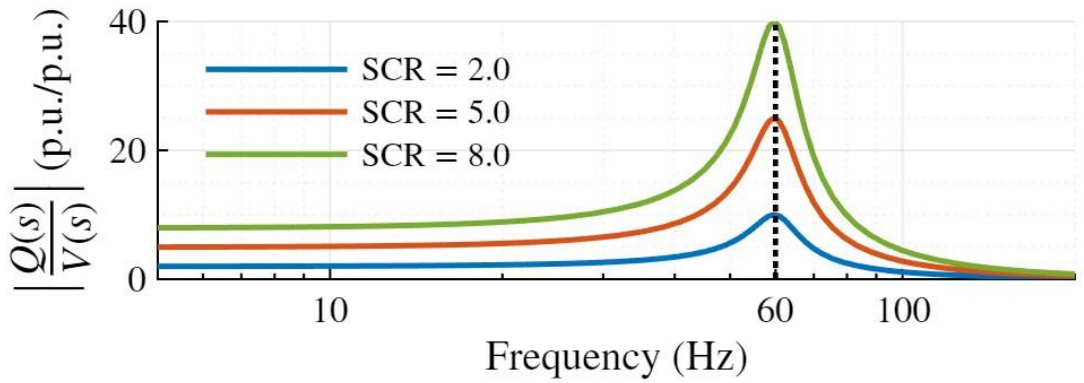


VSBI Characteristics in Frequency Domain

Admittance Spectra vs Small-Signal Jacobian Matrix

- The terms for small-signal Jacobian Matrix are linear functions of terms from dq admittance matrix.
- Jacobian terms P-θ/Q-V are analogous to Y_{dq}/Y_{qd} terms:

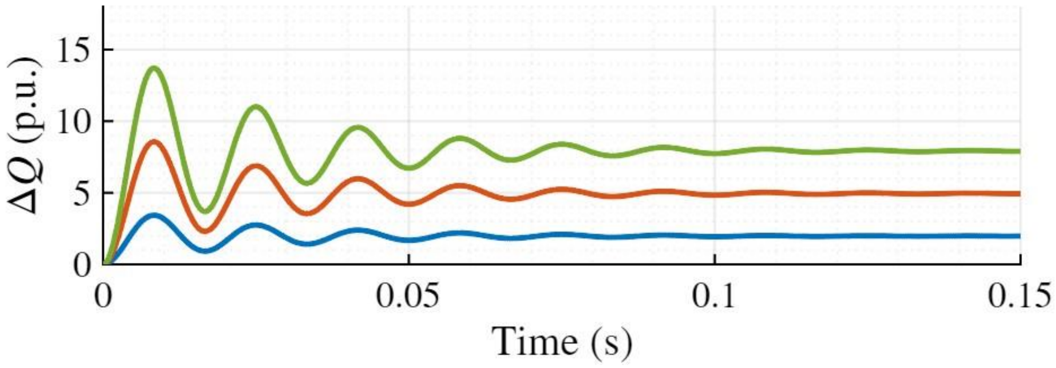
$$\begin{bmatrix} P(s) \\ Q(s) \end{bmatrix} = \begin{bmatrix} \frac{P_0}{V_1} - \frac{3}{2}V_1 Y_{dd}(s) & -Q_0 - \frac{3}{2}V_1^2 Y_{dq}(s) \\ \frac{Q_0}{V_1} + \frac{3}{2}V_1 Y_{qd}(s) & P_0 + \frac{3}{2}V_1^2 Y_{qq}(s) \end{bmatrix} \begin{bmatrix} V_m(s) \\ \theta(s) \end{bmatrix} \quad ...(3)$$



- For an Ideal voltage source behind an impedance:

$$\left.\frac{Q(s)}{V_m(s)}\right|_{\theta(s)=0} = \frac{Q_0}{V_1} - \frac{3}{2}V_1 \cdot \frac{\omega_1 L}{(R+sL)^2 + (\omega_1 L)^2} \quad ...(4)$$

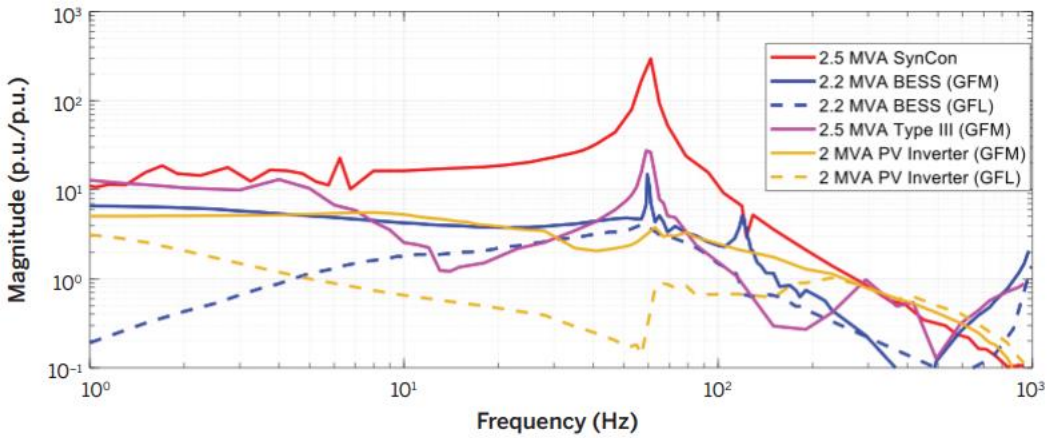
$$\left.\frac{P(s)}{\theta(s)}\right|_{V_m(s)=0} = -Q_0 - \frac{3}{2}V_1^2 \cdot \frac{\omega_1 L}{(R+sL)^2 + (\omega_1 L)^2} \quad ...(5)$$



GFM's Compliance for VSBI Characteristics
Existing Frequency Domain Specifications

- P-θ & Q-V Spectra Magnitude:
  - Should be nearly constant in the frequncy range of about 4-40 Hz.
  - Should be minimum 0.5 p.u./p.u. between 4- 40 Hz.

- P-θ & Q-V Spectra Phase:
  - Should be within ±60° error band of ±180° in frequncy range of about 4-40 Hz.

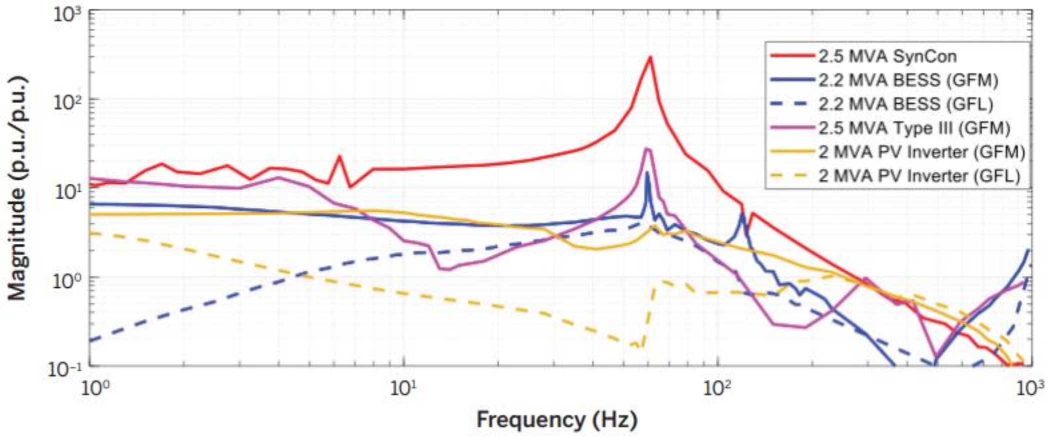


Examples of Magnitude of Q/V Frequency Spectra for different resources [Source: ESIG]

GFM’s Compliance for VSBI Characteristics

Drawbacks with Existing Frequency Domain Specifications

- No explicit definition of “nearly constant".
- A minimum P-θ & Q-V spectra magnitude at low frequencies may exclude GFMs (with faster droops) with good VSBI strength.
- Can not quantify or compare VSBI strength.



Examples of Magnitude of Q/V Frequency Spectra for different resources [Source: ESIG]

Design of Voltage Source Behind an Impedance (VSBI) as a Service

Open Questions?

- How to quantify and compare VSBI strength – another system strength metric?
- **Need:**
  - How to define & quantify the need for VSBI strength at each node?
- **Supply**:
  - How much VSBI strength should be mandated from GFMs (Compliance)?
  - Can we differentiate between various devices (GFLs vs GFMs) based on VSBI strength?
- What are the ideal characterstics for cross-coupling terms – {Q-θ ; P-V}?

References

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Thank You.

VSBI Characteristics
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