# C4 – Power System Technical Performance

## PS 1 – Challenges and Advances in Power Quality (PQ) and Electromagnetic Compatibility (EMC)

## 10522_2022

# Theory and Application of Multi-Frequency Interaction Screening Method

Kaitlyn Babiarz, David Roop, Samantha Morello

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## Motivation

Stability challenges of the modern power system are changing, with power electronic penetration levels increasing as inverter-based resources (IBR) replace conventional generation. The reduction of short-circuit strength, increase of harmonic emission sources, and increased awareness of system and device complexity are deepening focus on power quality and multi-frequency (sub-synchronous and super-synchronous frequency) stability concerns. Screening methods to quantify electrical coupling between system nodes in a network can evaluate the potential for interaction between the active nature of power electronic converters and passive network elements. The harmonic multi-infeed interaction factor (HMIIF) is one such method for quantifying electrical coupling through the comparison of harmonic voltage among nodes.

## Methodology

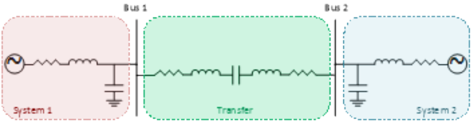
- Multi-infeed interaction factor is defined as the ratio of the change in voltage for two electrical nodes, given a small perturbation is applied at one node.
- Hamonic multi-infeed interaction factor (HMIIF) considers the system's electrical response across the entire frequency spectrum of interest, expanding on the previous MIIF method. TB 798 depicts HMIIF as the ratio of harmonic voltage for two electrical nodes within an interconnected system, as shown in the equation.

$$HMIIF = \frac{\Delta V_2(f)}{\Delta V_1(f)}$$

- Harmonic injection, in the form of sinusoidal perturbation, can be performed using either a harmonic current injection or a harmonic voltage injection.
- HMIIF can be evaluated with only the passive components of the electrical network, or with inclusion of active elements, such as power electronic converters and their control systems.

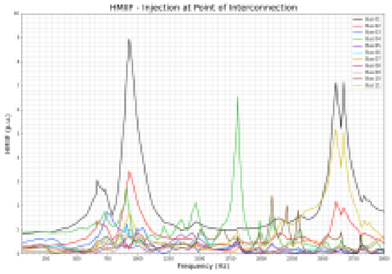
## System Overview

- Test system was developed to define criteria for interpreting HMIIF results, prior to applying the screening method in a large system.
- Shunt capacitors are modeled at each system to create parallel resonances at each bus, as well as, the series compensated line, defined as Transfer, to connect the two systems.




## HMIIF Applied to a Complex Network

- HMIIF calculation at 60 Hz was observed to be equivalent to the MIIF calculation.
- Beyond this range, HMIIF demonstrates tendencies that align with MIIF values. However, for HMIIF calculations for all nodes, frequency ranges exist where MIIF is not representative of the electrical coupling and subsequent harmonic amplification.
- MIIF provides indication of interaction potential between nodes in a system around fundamental frequency, whereas HMIIF provides the same indication of electrical coupling at fundamental frequency as well as throughout the frequency range of interest.




| Bus 01 | Bus 02 | Bus 03 | Bus 04 | Bus 05 | Bus 06 | Bus 07 | Bus 08 | Bus 09 | Bus 10 | Bus 11 |
|---|---|---|---|---|---|---|---|---|---|---|
| 0.84 | 0.33 | 0.48 | 0.87 | 0.21 | 0.17 | 0.07 | 0.18 | 0.07 | 0.23 | 0.18 |

## Conclusion

- HMIIF evaluated at fundamental frequency will represent the relative change in phasor magnitudes calculated by MIIF.
- HMIIF results derived from the harmonic injection method provide a direct relationship of the electrical coupling between system nodes in the sub-synchronous and super-synchronous frequency range.
- HMIIF provides insight into the potential for multi-frequency interaction of devices at different electrical nodes, as opposed to only considering driving point impedance for multi-frequency stability evaluation of a single converter.
- HMIIF magnitude represents total voltage amplification at a given frequency, resulting from resonant conditions between two nodes.
- MIIF is not representative of the electrical coupling and subsequent harmonic amplification in sub-synchronous and super-synchronous ranges, whereas HMIIF provides indication of electrical coupling throughout the frequency range of interest.

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## Theory

- Multi-infeed interaction factor (MIIF) is defined as the ratio of the change in voltage for two electrical nodes, given a small perturbation is applied at one node. The perturbation must be small enough to not influence the controls or the protection, but large enough to create a measurable difference.
- MIIF is an indication of electrical coupling between two different nodes, often evaluated at the fundamental frequency. An MIIF value of 0 indicates infinite separation between the two nodes, whereas a value of 1 indicates no separation.
- The criteria for interactions based on the MIIF products are defined as:
  - Low chance of interactions for products less than 15%.
  - Moderate chance of interactions for products between 15% and 40%.
  - High chance of interactions for products greater than 40%.
- MIIF is an indication of electrical coupling between two different nodes, often evaluated at the fundamental frequency. An MIIF value of 0 indicates infinite separation between the two nodes, whereas a value of 1 indicates no separation.
- Evaluating the relative magnitude change in phasor quantities provides a direct relationship of the electrical coupling between two nodes. If measured immediately following the perturbation, this quantifies the system's electrical response to the disturbance within the sub-transient timeframe, prior to influence of device control action.
- If this sinusoidal perturbation were to occur at non-fundamental frequencies, the system's sub-transient, small-signal electrical response to perturbations at that frequency can be evaluated. When the voltage phasor magnitude component at the frequency of disturbance is observed, then electrical coupling in the sub-synchronous and super-synchronous frequency range can be quantified.

$$HMIIF = \frac{\Delta V_2(f)}{\Delta V_1(f)}$$

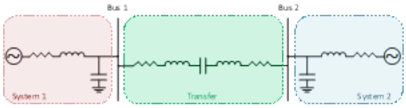
where:

  - V2 is the harmonic voltage at the remote bus of interest.
  - V1 is the harmonic voltage at the location of harmonic injection.

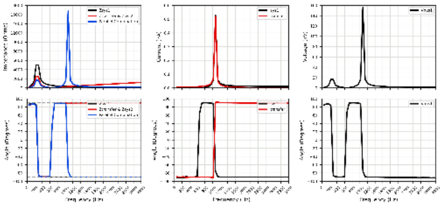
- The harmonic injection, in the form of sinusoidal perturbation, can be performed using either a harmonic current or voltage injection. The voltage induced by the harmonic injection is measured at each node in the system. These harmonic voltage values are used to calculate the HMIIF.

## System Overview & Methodology

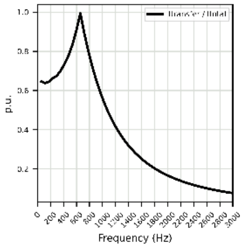
- Test system was developed to define criteria for interpreting HMIIF results, prior to applying the screening method in a large system.
- Shunt capacitors are modeled at each system to create parallel resonances at each bus, as well as, the series compensated line, defined as Transfer, to connect the two systems.



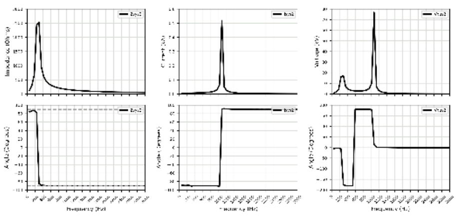

Bus 1



- Ratio of current flowing through Transfer ($I_{transfer}$) to the sum of total current flowing into System 1 and into Transfer ($I_{total}$).
- Maximum current flow to the remote system occurs at the minimum of the parallel impedance, where the total impedance of Transfer and System 2 is small and is the dominating influence of the low parallel impedance, which occurs at 660 Hz.




Bus 2



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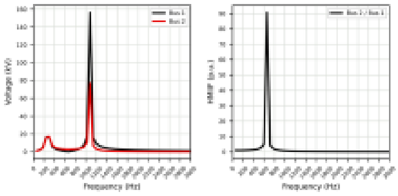
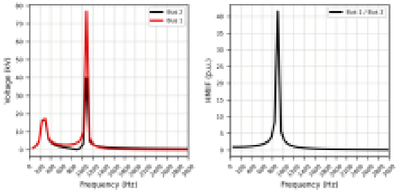
## Observations

- Evaluating the impedance characteristic of each bus individually, it would be natural to infer that the greatest magnitude of HMIIF would occur at frequencies with greater magnitudes of current or voltage, which is not the case.
- When the series resonance, or minimum impedance, occurs for the combined impedance of Transfer and System 2 at 660 Hz, the harmonic current that is injected at Bus 1 experiences a low-impedance path and flows through Transfer towards System 2. When this current arrives at System 2, the impedance is non-zero, therefore resulting in a harmonic voltage at 660 Hz.

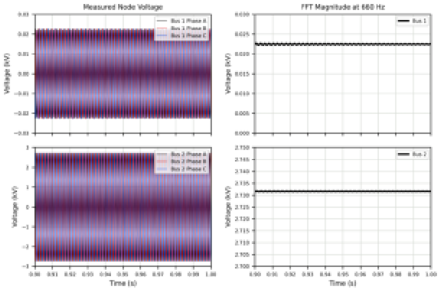



- When the harmonic voltage is instead injected at Bus 2, the peak value for the HMIIF occurs at 900 Hz rather than 660 Hz. Additionally, the HMIIF magnitude with an injection at Bus 2 is approximately half of the HMIIF magnitude with an injection at Bus 1.
- Relative characteristic between electrical paths for harmonic current flow, as opposed to the impedance characteristic of a single electrical node, determine the voltage amplification for a remote node.

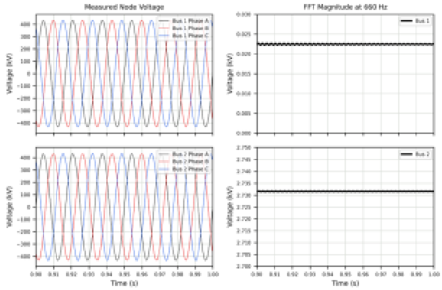



- Harmonic injection source can either be a current injection or a voltage injection. Both injection types will yield the same HMIIF values.
- Source characteristic will change the absolute magnitude of harmonic voltage distortion or harmonic current flow; however, the relative amplification of such values remains the same.
- HMIIF is valid for evaluation of electrical coupling in passive networks, or with the inclusion of Norton or Thevenin equivalent emission sources representing active network elements, such as power electronic converters.

- Same voltage amplification is observed in a system with or without fundamental frequency sources.




- When performing HMIIF in a system with fundamental frequency components, care must be taken to remove this background component, so that only the relative impact of the harmonic injection is considered.




## Conclusion

- Definition of boundary conditions for system under study will impact validity of HMIIF results.
- Accuracy of frequency-dependent system representation will impact the usability of HMIIF.
- Relative impedance characteristics between electrical paths for harmonic current flow, as opposed to the impedance characteristic of any single electrical node, determine the harmonic voltage amplification among nodes.
- HMIIF results are consistent whether the source of harmonic emissions exhibits Norton or Thevenin equivalent characteristic properties.
- HMIIF results are consistent whether evaluated in time-domain or frequency-domain, where the system representation is the same, i.e., representative of the small-signal electrical response within the frequency range of interest.