Impact of Induction Motor Loads in System Loadability Margins and Damping of Inter-Area Modes

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Paper Outline

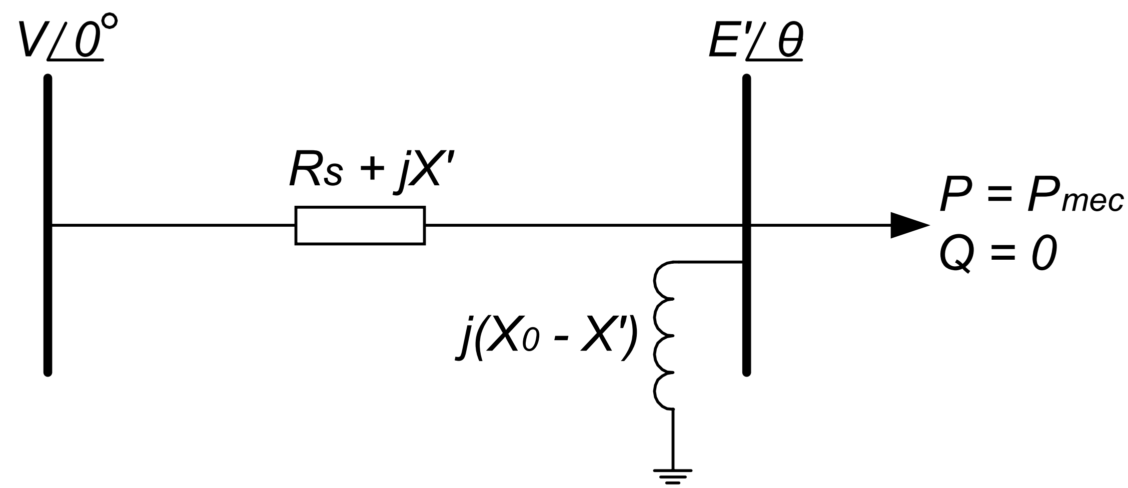
- Part I
  - Motor Modeling in Power Flow Studies
  - Maximum Loadability of the Rio Area
- Part II
  - Determining the System Loads that most Impact the Damping of Inter-area Modes
  - Estimating the Damping of the Brazilian North-South Mode as Affected by Frequency-Sensitive Loads
- Conclusions

Part I: Maximum Loadability Studies

- Static load characteristics may be expressed as algebraic functions of bus voltage and frequency
- The depressed voltage conditions in the Rio Area that occurred during hot summer days had:
  - Active loadings below the expected critical values
  - Reactive loadings higher than expected
  - Air-conditioning load was high
- Representing loads by constant-P and constant-I models would not capture these phenomena
  - Incentive for better modeling of induction motor loads in power flow studies

Motor Modeling in Power Flow Studies

- Two-bus steady-state model for induction motors



- The mechanical torque is assumed independent of rotor speed
- Every motor augments the electrical network by one bus having an additional shunt reactor and connected, on its turn, to the motor terminal bus by an additional impedance

Motor Modeling in Power Flow Studies

- Implementation of aggregate induction motor models into a continuation power flow program
- Motor models of several types and with typical parameters were hard-coded into the program
- User must only specify the motor type and the motor content in each load bus
- Validation tests on practical systems
  - Maximum loadability studies of the Rio Area

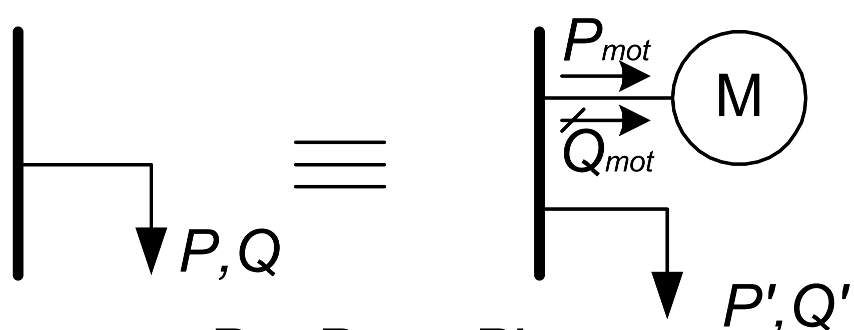
Motor Modeling in Power Flow Studies

- Bus Data indicate which motor type will be used and the percentage of load to be modeled as motors

Motor Type	Motor Characteristics
1	Small Industrial I
2	Large Industrial
3	Mean values for 11 kVA motors
4	Small Industrial II
5	Commercial + Feeder
6	Aggregate residential
7	Single Phase

Motor Modeling in Power Flow Studies

- Motor MVA base used to indicate the part of the load bus to be modeled as induction motor
- Power flow program computes, for every motor:
  - Active and reactive power consumptions
  - Internal voltage *E'*, angle θ, and rotor slip *s*
- The part of the original load that is not modeled as motor is denoted as *P'* and *Q'*



$$P = P_{mot} + P'$$
$$Q = Q_{mot} + Q'$$

Motor Modeling in Power Flow Studies

- Methodology for continuation power flow studies
  - A larger motor load is simulated by increasing the MVA base of the aggregate motor
  - A larger aggregate load means that a higher number of motors is connected to the system

Maximum Loadability of Rio Area

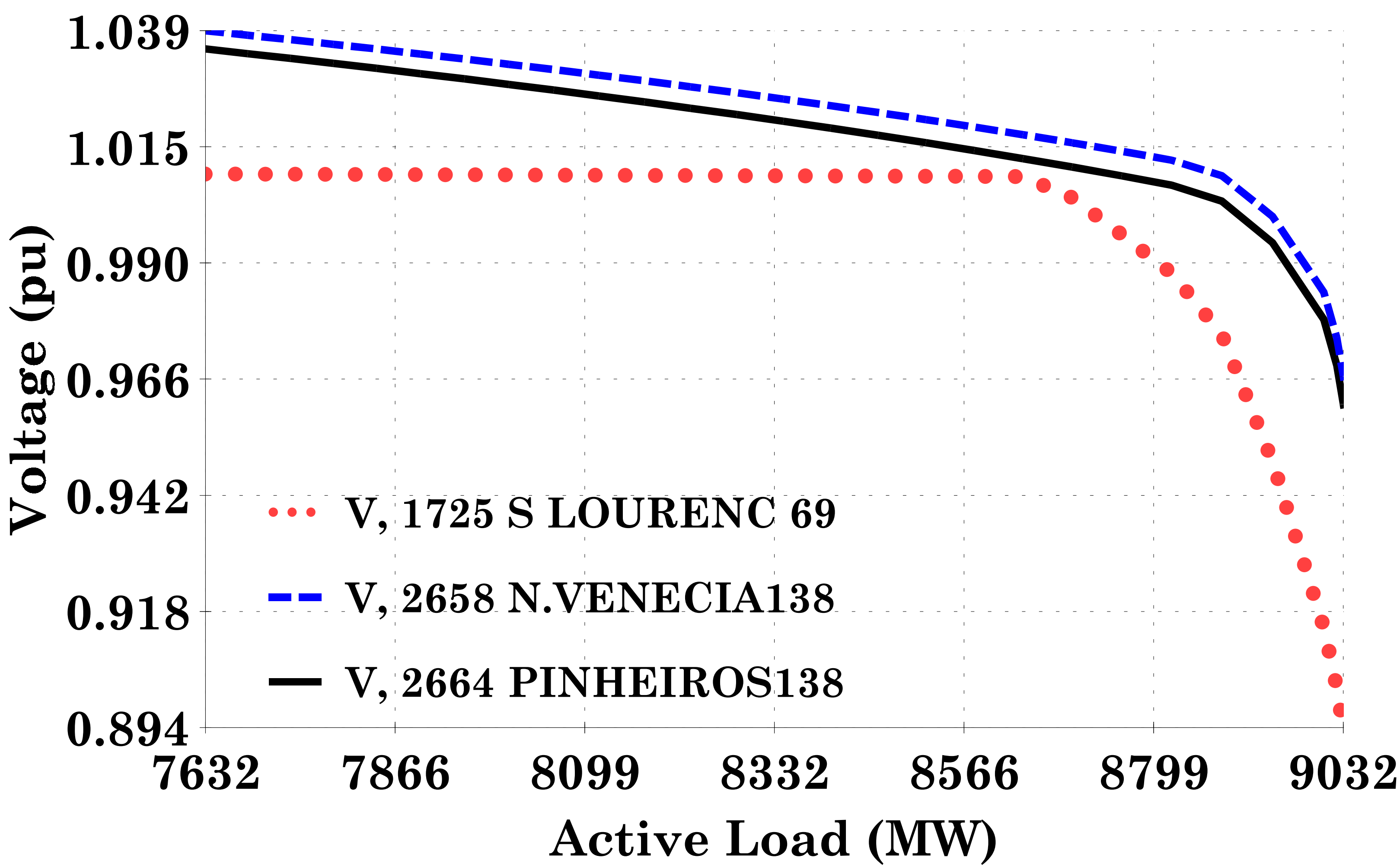
- Rio Area – 3 utilities: LIGHT, CERJ and ESCELSA
  - 288 buses
  - 200 load buses (7632 MW)
  - 149 load buses have induction motors (5733 MW)
    - ⇨ Industrial: 2227 MW / Commercial: 3506 MW
  - Operating point refers to a heavy load condition for the Rio Area on a hot summer day

Maximum Loadability of Rio Area

- Other assumptions made in the continuation power flow analysis:
  - Industrial motor load remains constant
  - Only commercial motor load is increased
  - Commercial and industrial load is initially modeled as constant P and Q, with fixed power factor
  - The PV curves
    - ⇨ Most critical buses belong to ESCELSA (a more distant distribution utility)

Maximum Loadability of Rio Area

- Constant P and Q load model



Maximum Loadability of Rio Area

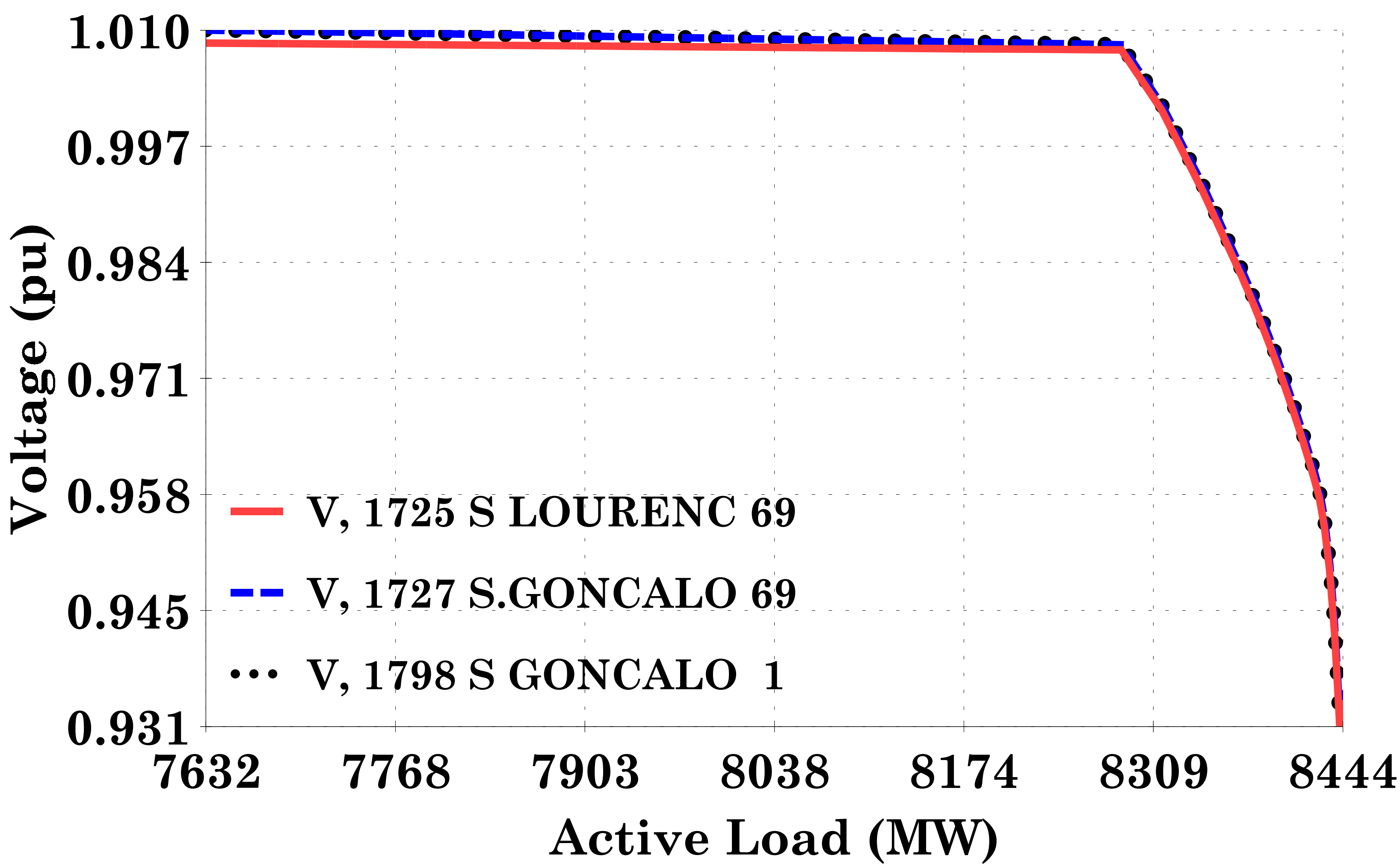
- In each program run, all the commercial motor loads were assumed to be of one type. Either:
  - Commercial + Feeder (Type 5)

    or

  - Small Industrial (Type 4)
- The industrial motor load was modeled as Large Industrial (Type 2), and remained fixed at the base case value

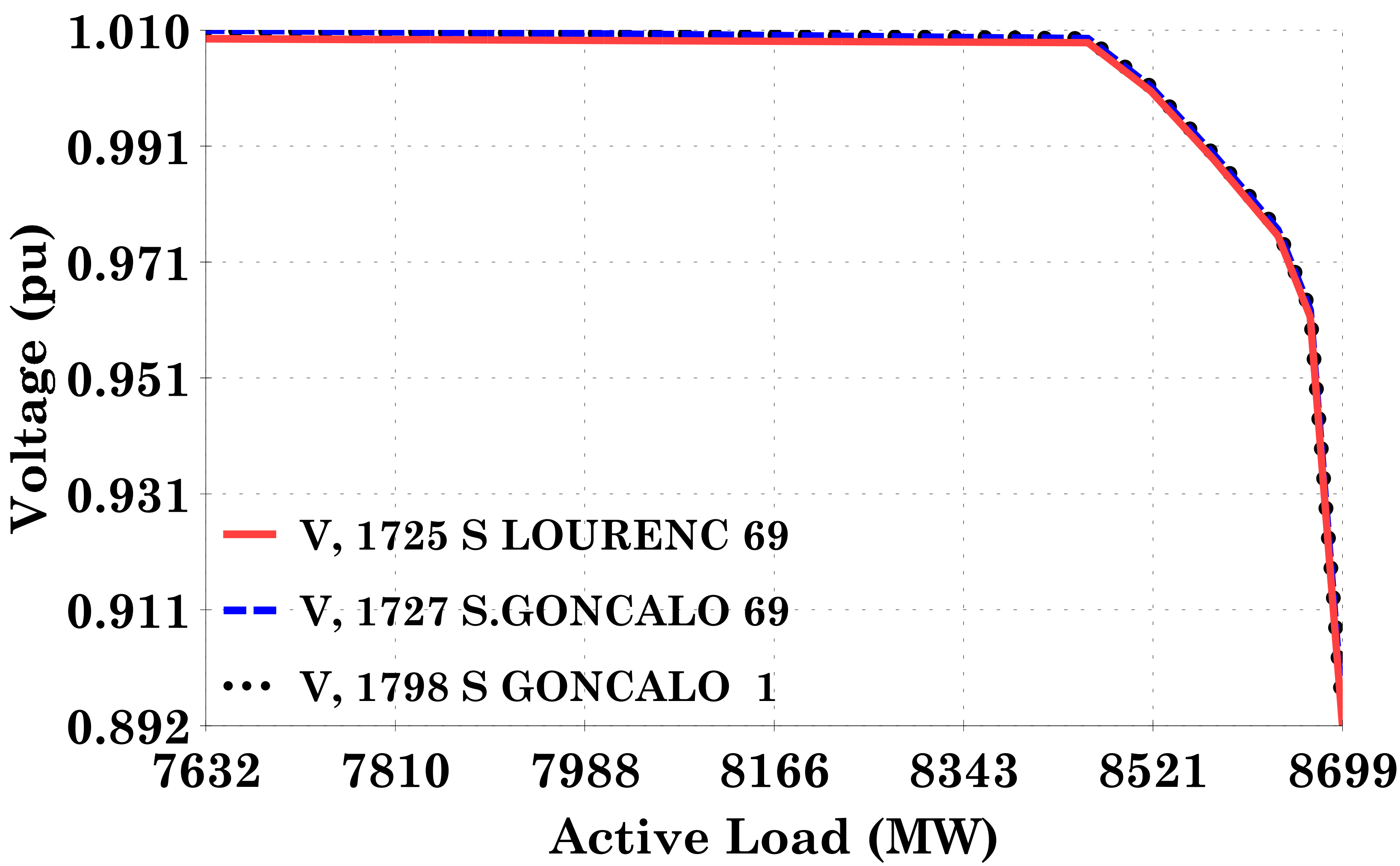
Maximum Loadability of Rio Area

- Commercial induction motors as Comm.+Feeder



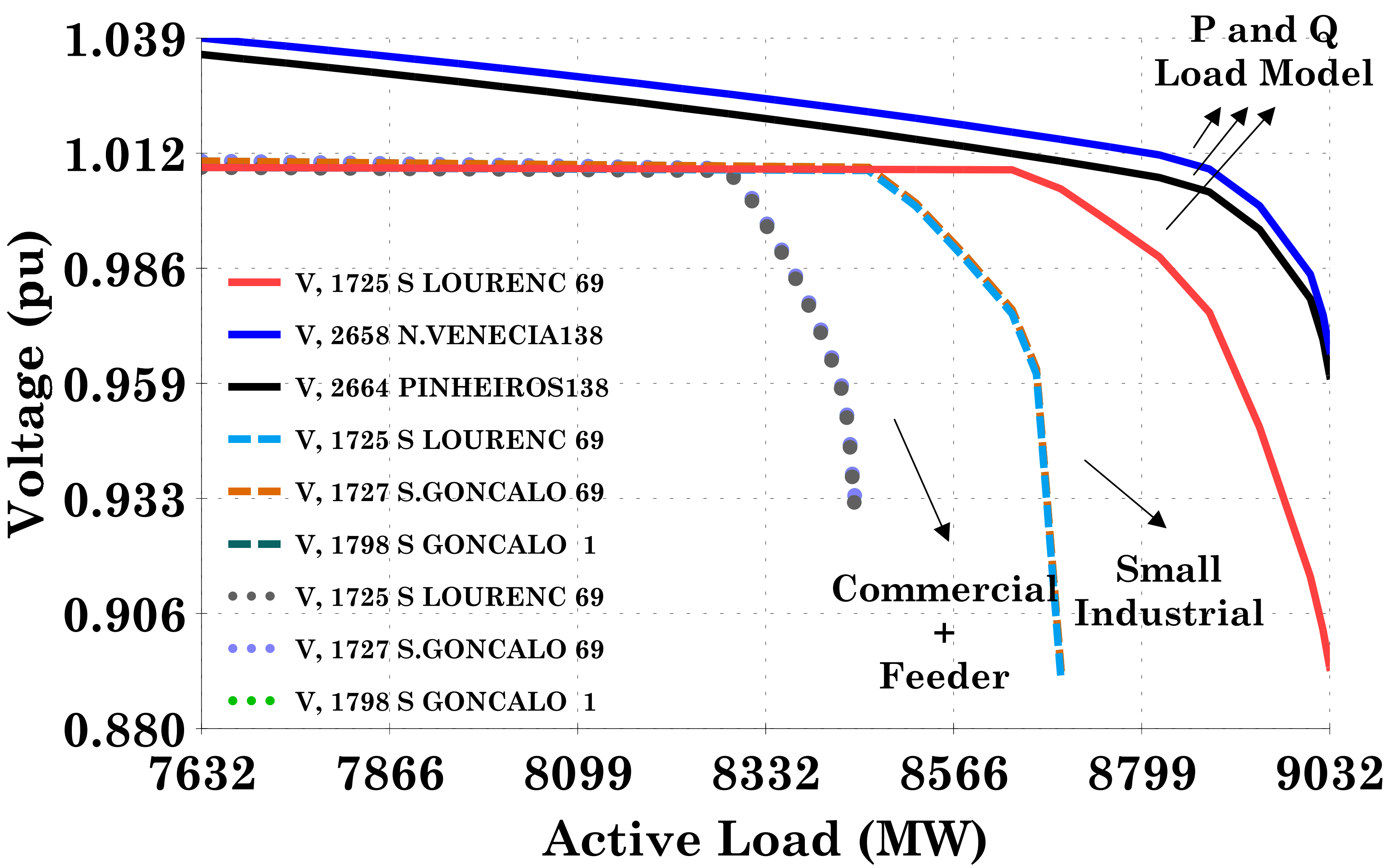
Maximum Loadability of Rio Area

- Commercial induction motors as Small Industrial



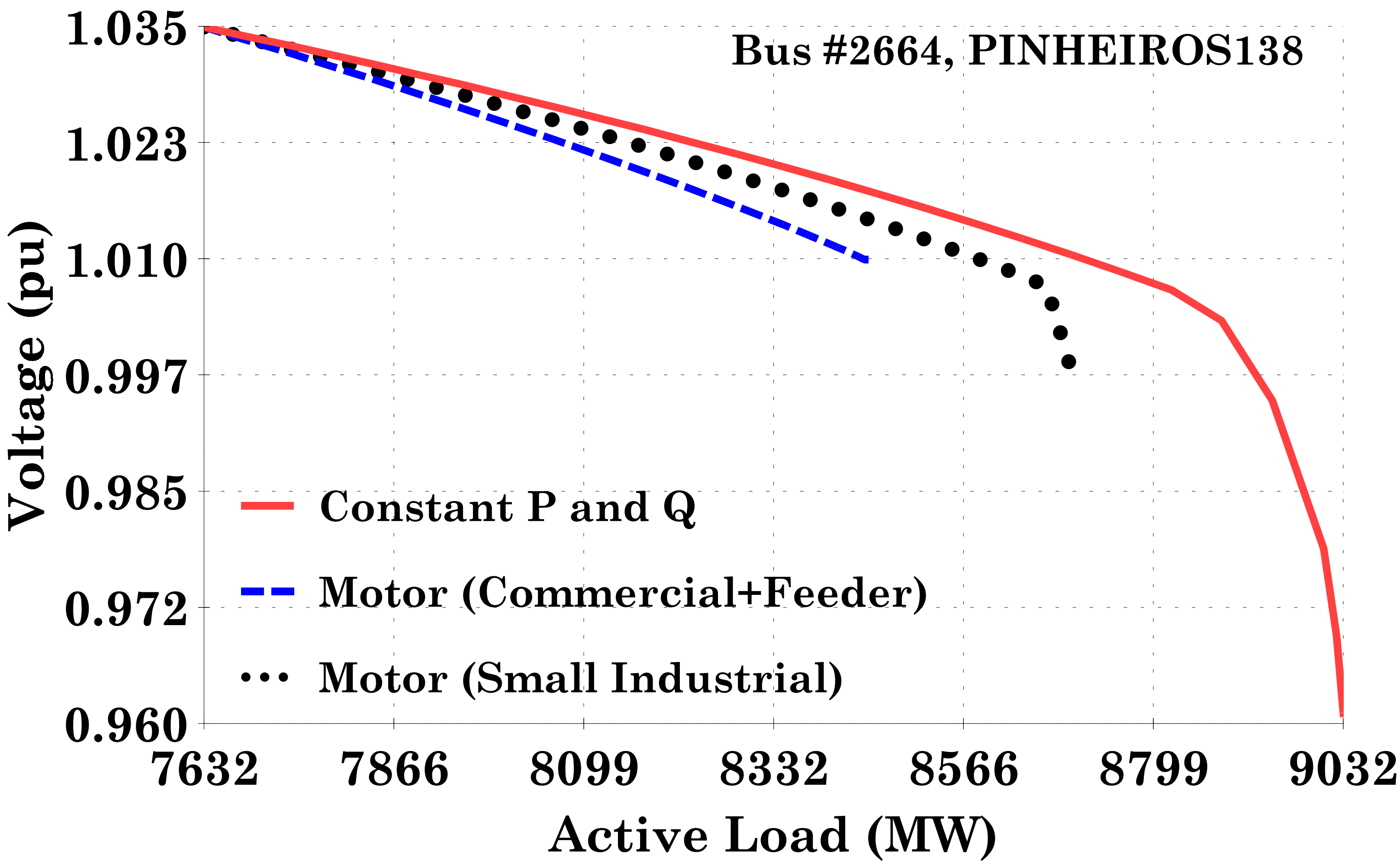
Maximum Loadability of Rio Area

- Maximum loadabilities for 3 different load models



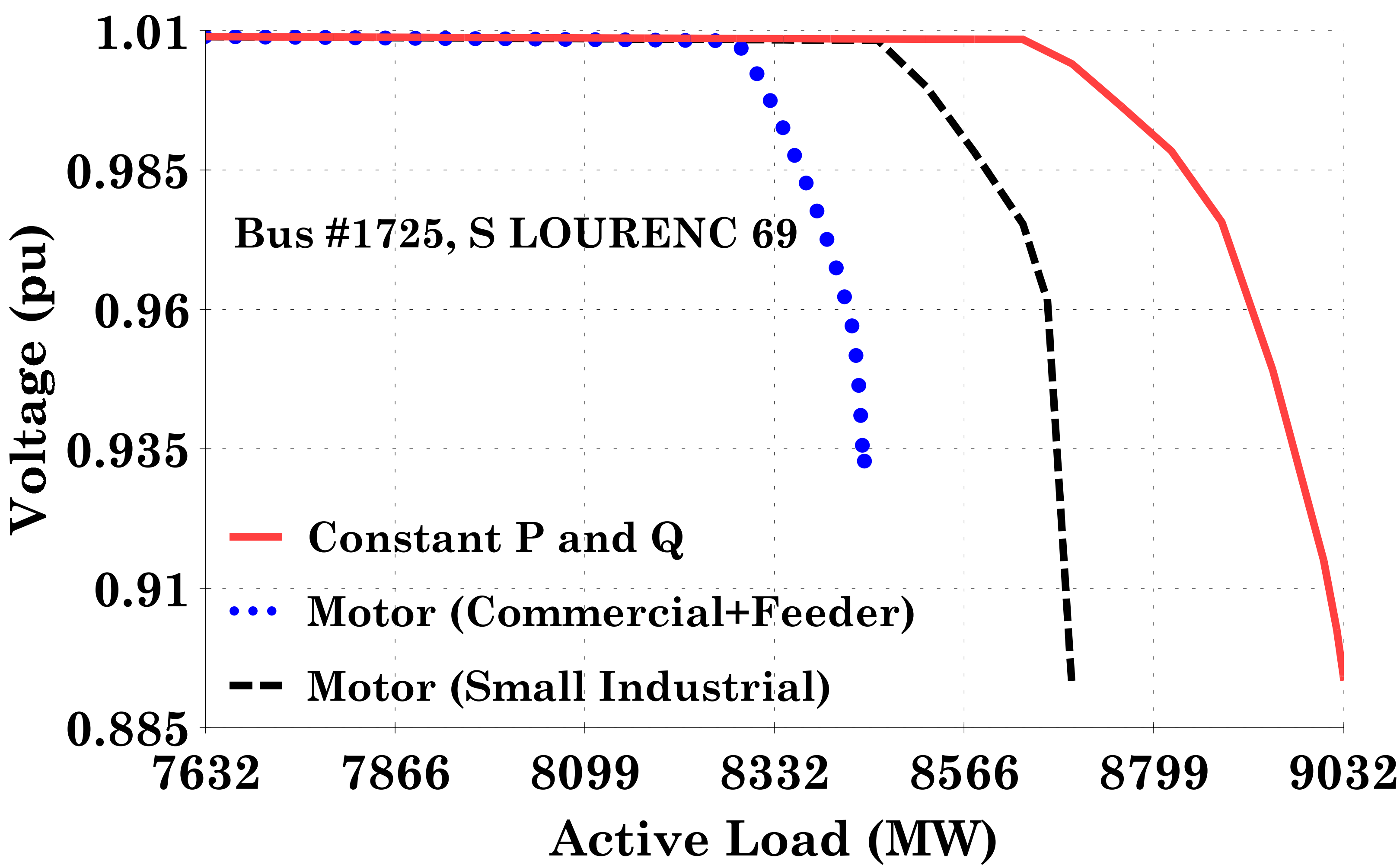
Maximum Loadability of Rio Area

- PV curves of Pinheiros-138 kV for 3 load models



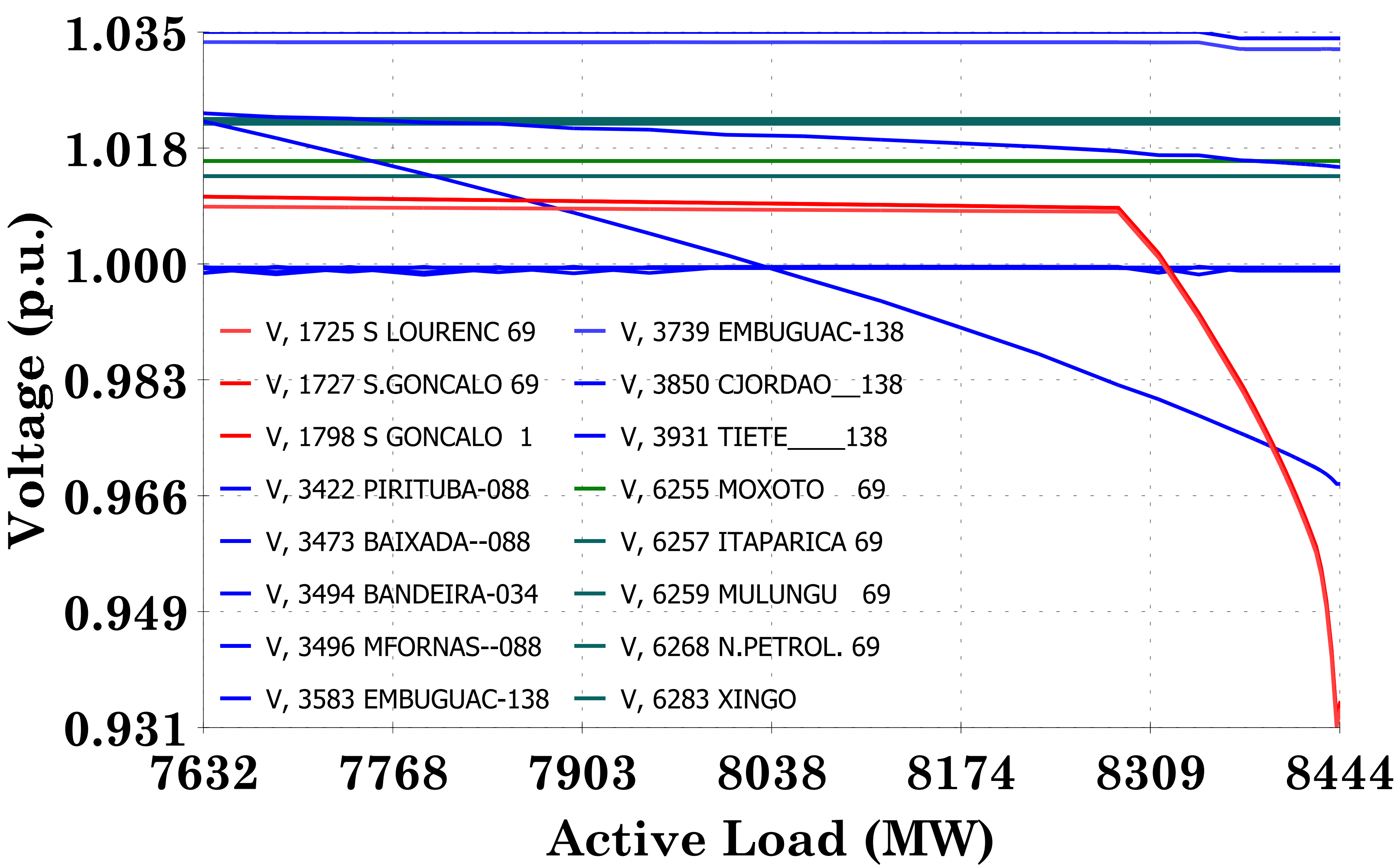
Maximum Loadability of Rio Area

- PV curves of S. Lourenco - 69 kV for 3 load models



Maximum Loadability of Rio Area

- Bus voltages in various parts of the system



Part II: Study on the Impact of Frequency-Sensitive Loads to the Damping of Inter-Area Modes

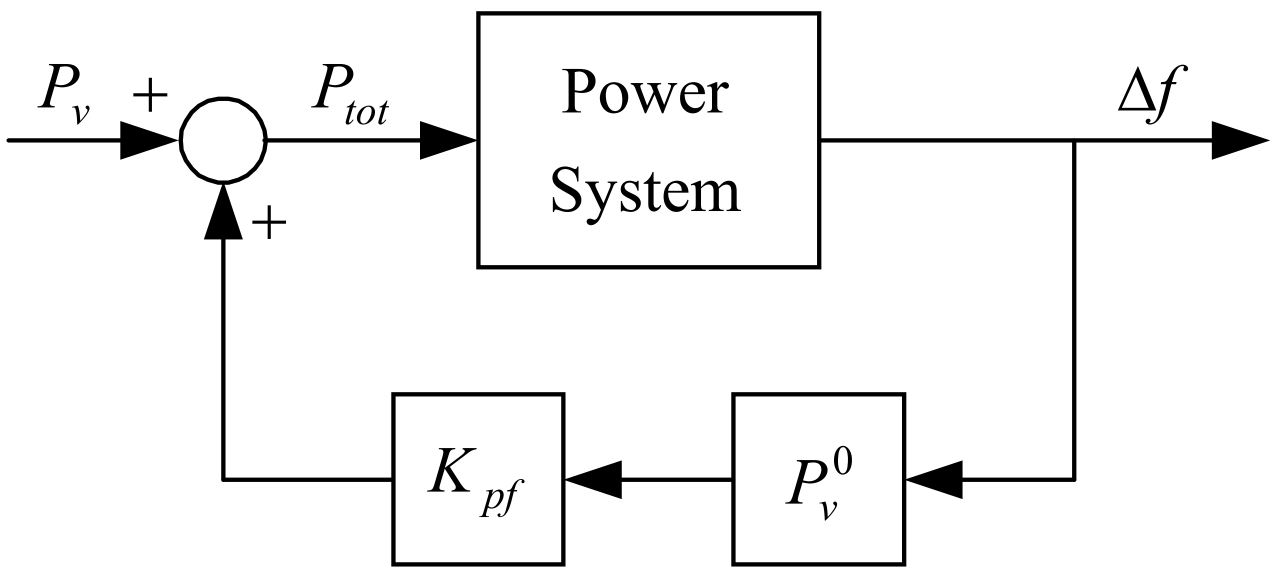
- Selective eigenvalue computation (Dominant Pole Algorithm) and modal sensitivity analysis
  - Results for the Brazilian North-South inter-area mode
  - Damping of this mode was seen to significantly vary with the modeling of frequency-sensitive loads

Modeling Frequency-Sensitive Loads

- Polynomial load model (MW part only) multiplied by frequency deviation at bus:

$$P_{tot} = P_v[1 + K_{pf} \cdot (f - f_0)]$$

- Block diagram below is produced from linearization of the above equation

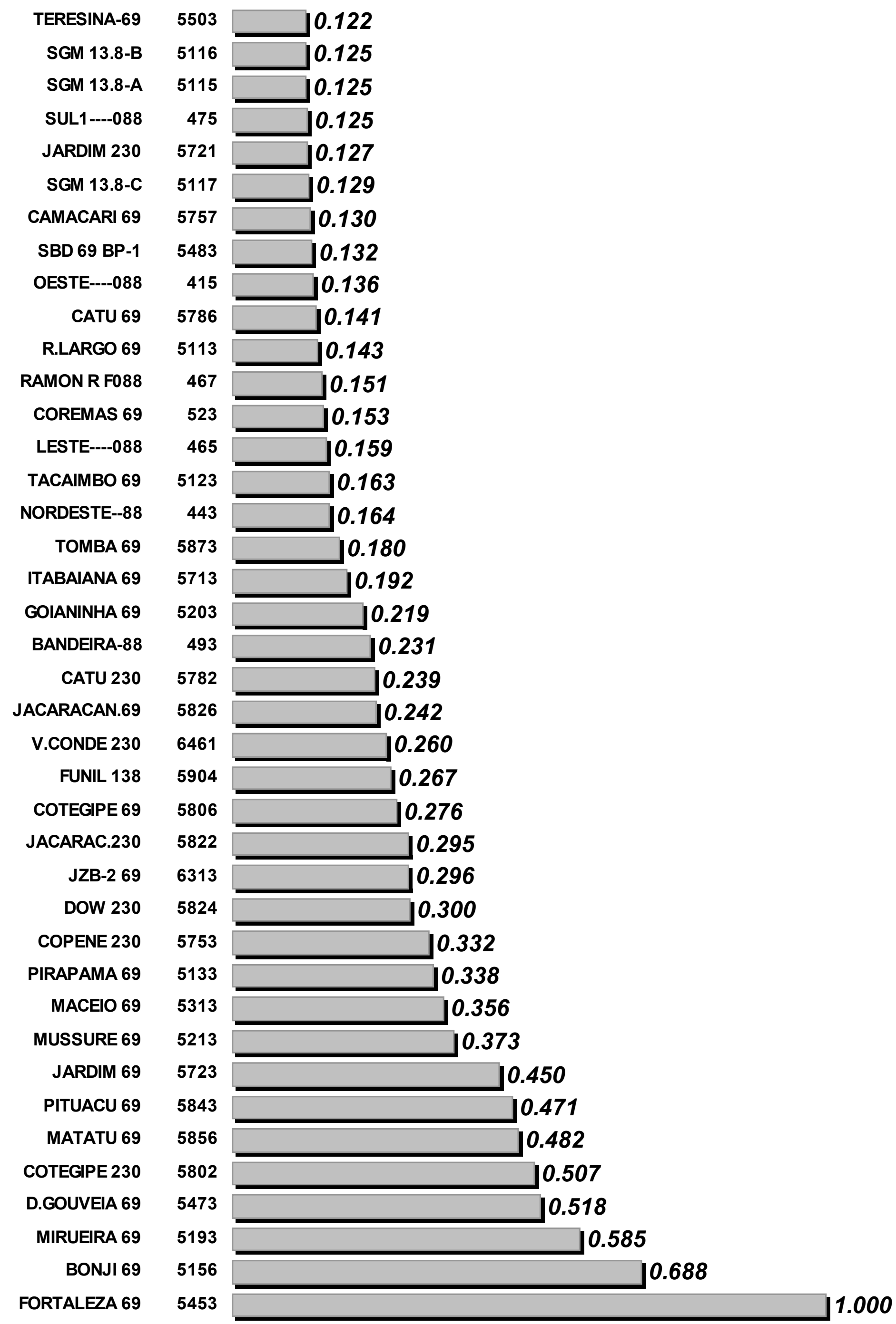


Damping of the Brazilian North-South Mode as Affected by Frequency-Sensitive Loads

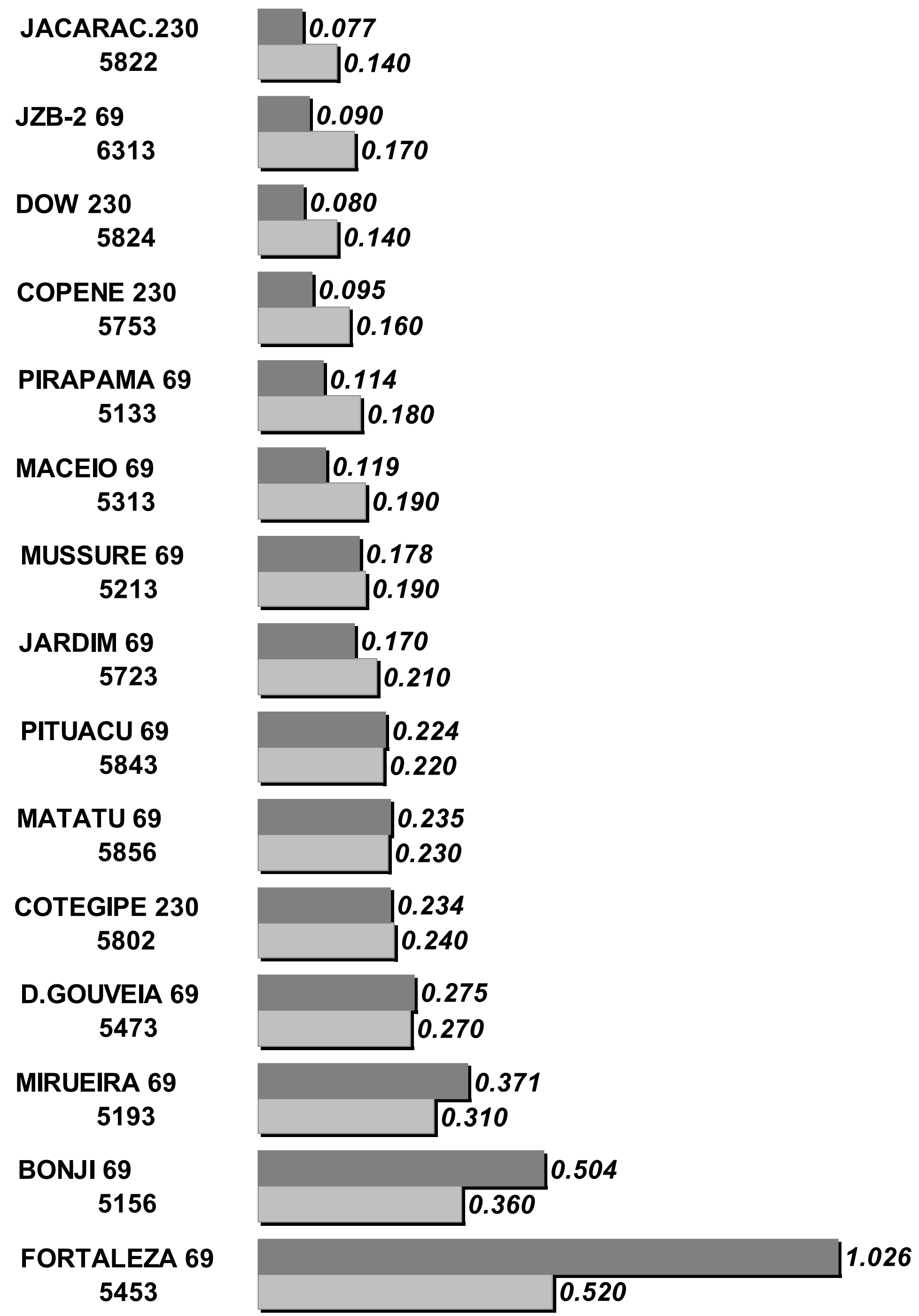
- System model contains 2,500 buses, 3,500 lines and 120 power plants, totaling 1,650 state variables
- The chosen operating point shows reduced damping for the North-South mode
- Frequency-sensitive loads whose modeling would impact most the damping of North-South mode can be identified through transfer function residues

$$\Delta f^{i}(\lambda)/\Delta P_{L}^{i}(\lambda)$$

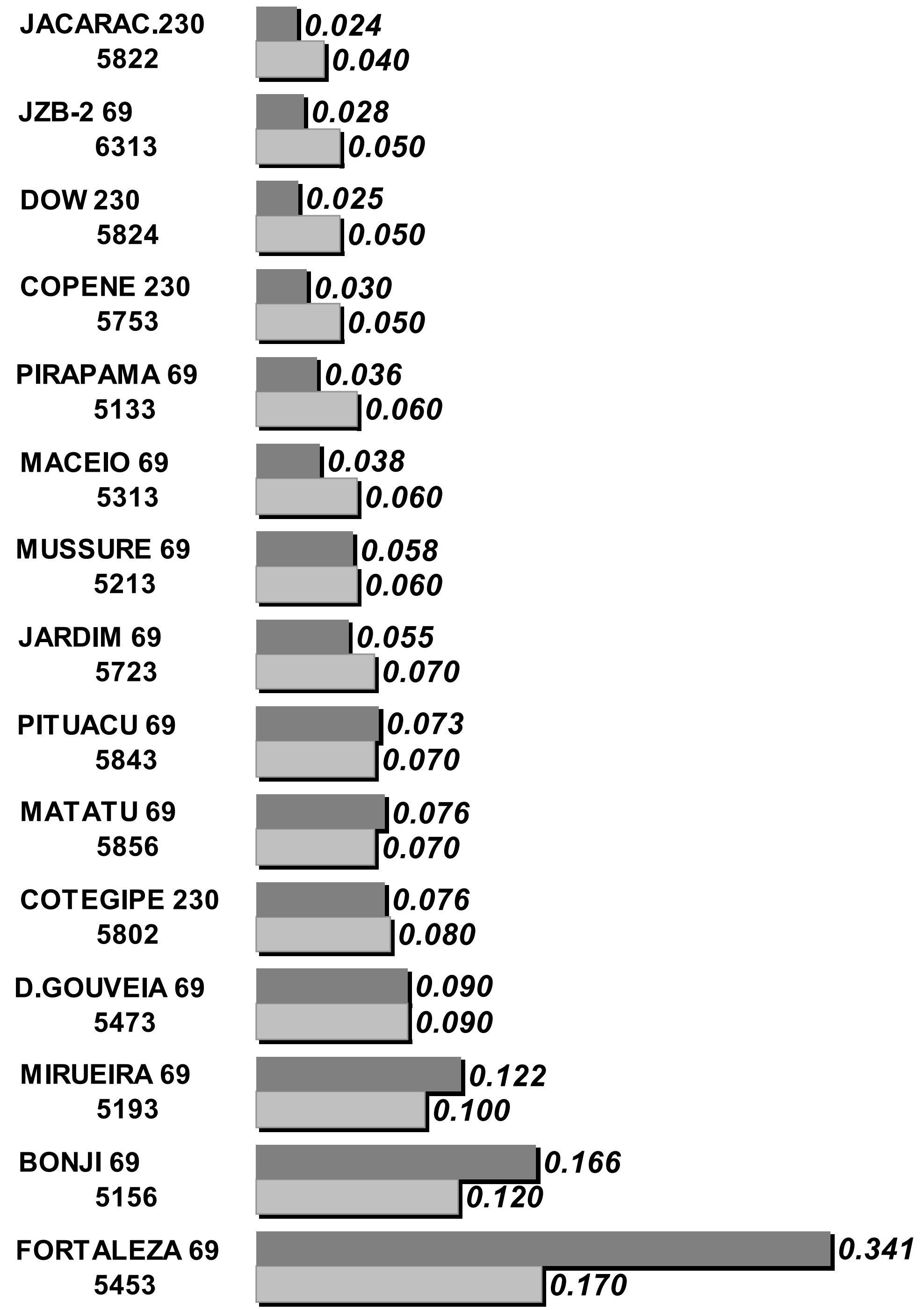
Residues of Transfer Functions $\Delta f^i / \Delta P_L^i$ associated with the North-South mode



Change in damping ratio (%) of North-South mode as affected by frequency-sensitive loads $(K_{pf} = 3)$

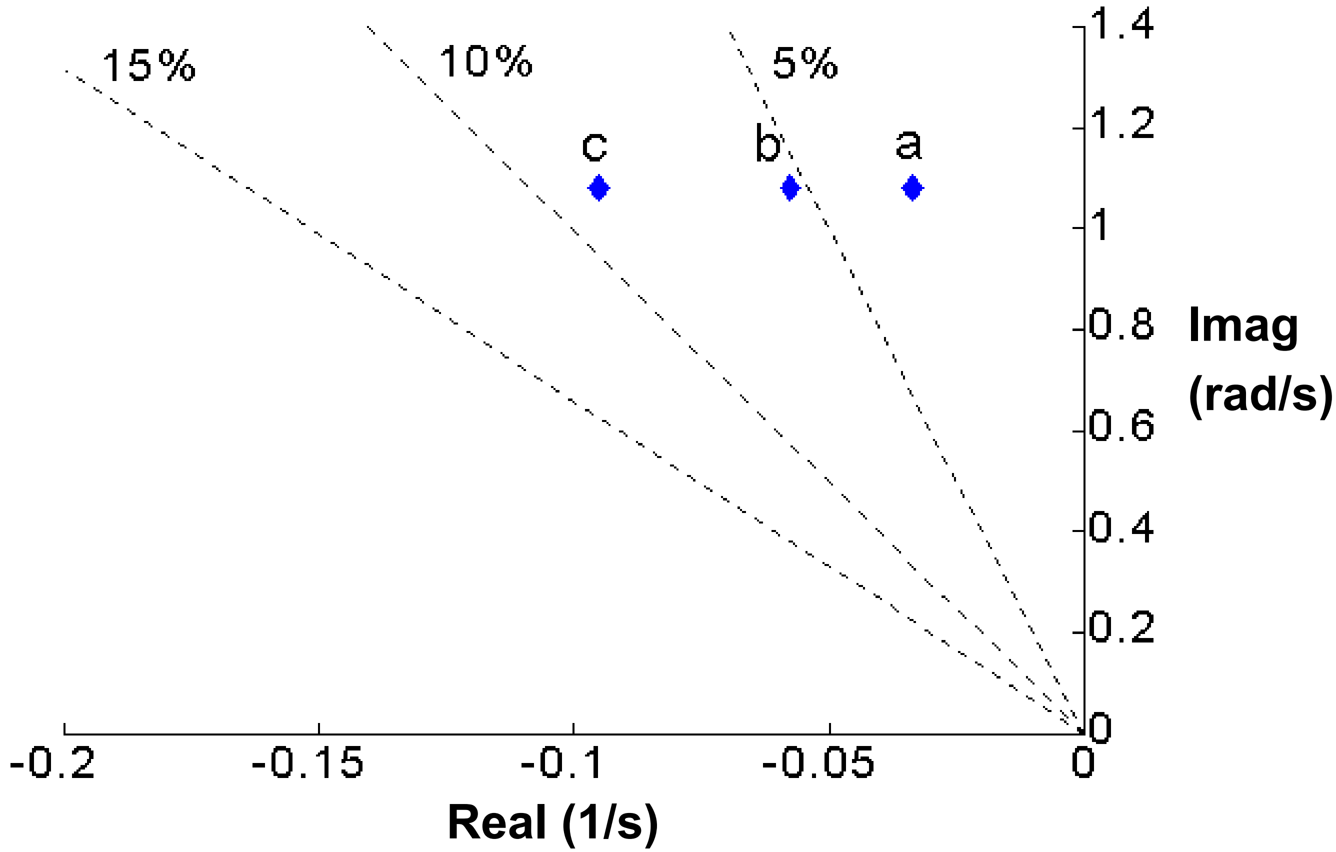


Change in damping ratio (%) of North-South mode as affected by frequency-sensitive loads $(K_{pf} = 1)$

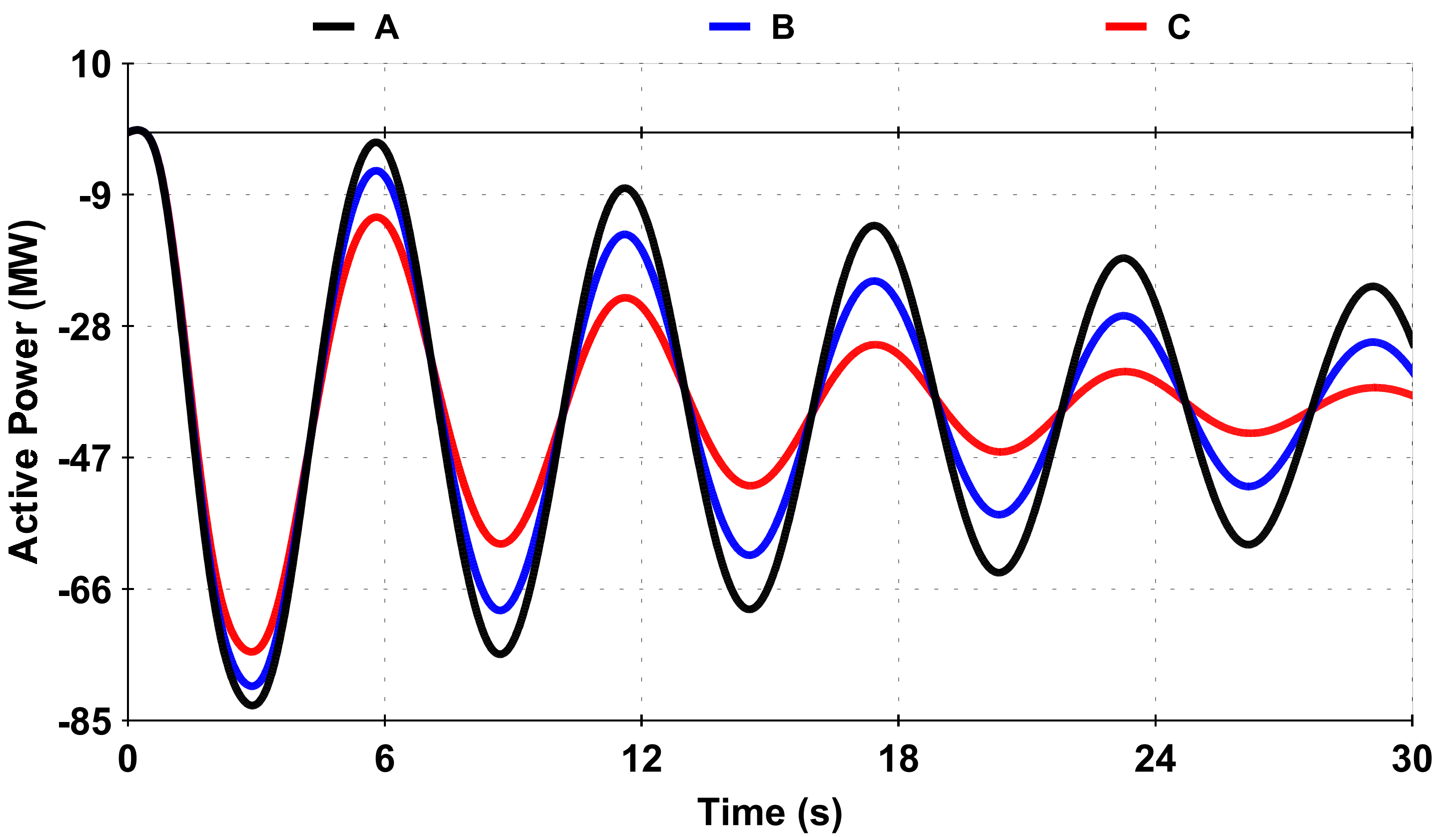


Damping of Brazilian North-South Mode as Affected by Frequency-Sensitive Loads

- Changes to the damping ratio of the North-South mode as the forty most critical loads become increasingly frequency-sensitive



Damping of Brazilian North-South Mode as Affected by Frequency-Sensitive Loads



$$A \rightarrow K_{pf}^{i} = 0, \text{ for } i = 1,\ldots,40$$

$$B \rightarrow K_{pf}^{i} = 1, \text{ for } i = 1,\ldots,40$$

$$C \rightarrow K_{pf}^{i} = 3, \text{ for } i = 1,\ldots,40$$

Conclusions

- The modeling of induction motor loads into continuation power flow programs may better assess the reductions in loadability margins and reproduce observed voltage depressed conditions
- Despite being a crude approximation, the simple frequency-sensitive model utilized allows assessing the impact of motor loads on the damping of inter-area modes
- The uncertainties associated with load composition and aggregation remain a major challenge to power system modeling