SMART GRID ANALYTICS: SELECTED APPLICATIONS

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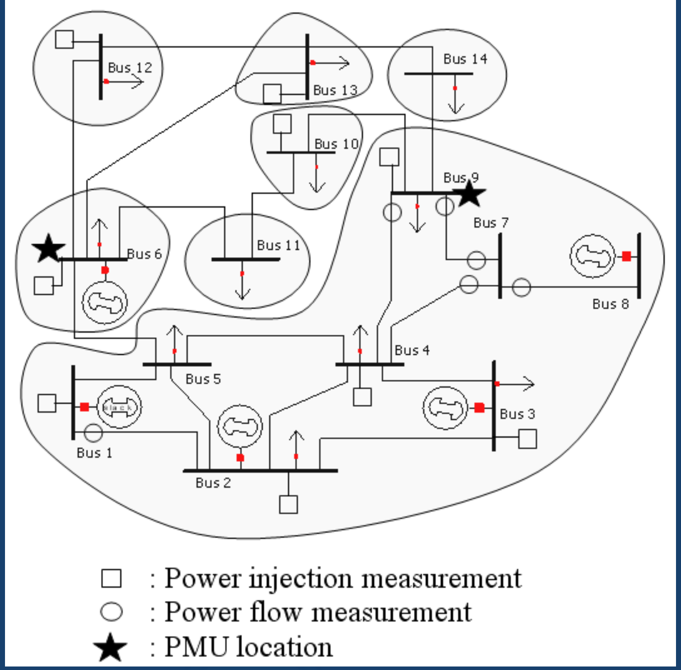
Some important smart grid analytics

- Real-time visualization of power systems
- **Improved state estimation**
- **Online estimation of load models**
- **Online monitoring of power system stability**
- Analysis of the causes of a total or partial blackout
- Real-time congestion management
- Design of an adaptive protection system
- Detection of faults on transmission/distribution lines

Improved state estimation

Ensuring system observability (pre-requisite for state estimation):

- Optimal placement for PMU-only measurement system
- Increasing measurement redundancy and avoiding critical measurements
- Coordinating measurements in a multi-area system
- Making an unobservable system observable (while replacing old conventional measurements)
- To enhance the performance of the existing SCADA-based state estimator



Improved state estimation…contd.

Integration of PMUs into the state estimator (SE):

- The design and deployment of the hybrid SE is still in the experimental stage
- Following are some of the benefits that can be derived as a result of including PMU measurements in the SE:
  - Improved accuracy of the SE
  - Better observability
  - Enhanced convergence characteristics
  - Better handling of bad data

Hybrid state estimator

Two possible approaches to the inclusion of PMU measurements in the SE:

- Post-processing:
  - More practical at the moment, since PMUs are being installed only in incremental fashion.
  - Power companies are usually reluctant to go for expensive modification of their existing state estimation software.
- Pre-processing:
  - As the number of PMUs increases in power systems, it will be wise to adopt the SE which can handle both conventional and PMU measurements at the same time.
  - Existing SEs at the control centres need to be replaced with this type of hybrid SE (HSE).

Post-processing HSE

With limited number of PMUs, an obvious choice is to mix the PMU measurements with the outputs of the existing SE, and improve the estimate of the states.

Let $\mathbf{z}_{PMU}$ be the vector containing the measurements obtained from the PMUs.

$$\mathbf{z}_{PMU} = \left[\tilde{V}_i, \tilde{V}_j, \dots, \tilde{I}_{pq}, \tilde{I}_{rs}, \dots\right]^T$$

where $\tilde{V}_i = V_i \angle \theta_i$ is the voltage phasor at bus *i* (where a PMU is placed); and $\tilde{I}_{pq} = I_{pq} \angle \theta_{pq}$ is the current phasor between buses *p* and *q*, as measured by the PMU placed at bus *p*.

Post-processing HSE…contd.

The output, $\mathbf{x}_{conv}$ of the conventional power system SE is the minimal set of states, typically, the voltage magnitudes and phase angles at all buses in the system, as shown below for an *N*-bus system.

$$\mathbf{x} = [\theta_1, \theta_2, \dots, \theta_N, V_1, V_2, \dots, V_N]^T$$

The new measurement vector for the HSE is,

$$\mathbf{z}_{new} = [\mathbf{x}_{conv}^T \;\; \mathbf{z}_{conv}^T]^T$$

The state estimation is carried out on the new measurement vector $\mathbf{z}_{new}$ to determine the new state vector $\mathbf{x}_{new}$ for the system.

Pre-processing HSE

- As the number of installed PMUs will increase in power systems, a state estimator capable of handling both conventional and synchronized measurements will become the obvious choice.
- This will eliminate the additional computational burden and reduction in estimation accuracy due to multiple processing in the post-processing type estimator.
- In the pre-processing type HSE, the conventional and PMU measurements will be processed together to obtain the final estimates of the states.
- This will require modification or replacement of the existing state estimation software in the EMS

Pre-processing HSE…contd.

- Inclusion of voltage phasor measurements by the PMUs in the existing SE is straightforward.
- There are three possible ways in which the current measurements by the PMUs can be directly incorporated in an SE:
  1. Current phasor magnitude and phase angle (tend to pose numerical ill-conditioning problem)
  2. Real and imaginary part of the complex current measurement (found most suitable, in terms of accuracy and convergence characteristics)
  3. Pseudo-voltage measurement with the help of current phasor measurement and known line parameters (almost comparable with the 2nd method above, slightly less accurate).

Challenges in HSE

- Refresh rate and accuracy of the conventional and PMU measurements are widely different. Combining these two measurements in practice is not an easy task.
- The accuracy of the PMU measurements are usually much higher compared to the conventional measurements. This causes large difference in the magnitude of the weights in a WLS state estimator, and hence convergence problems may arise.
- Some of the steps taken to improve the numerical property of the estimator are constrained formulation of the SE problem, optimal ordering of the rows of the gain-matrix, robust numerical techniques, etc.
- Further research is needed to arrive at a complete solution to this problem

Dynamic estimator of state

- Static state estimator (SSE), for which WLS is the most popular algorithm, estimates the state based on a snapshot of the available measurements.
- Dynamic estimator of state (DES) utilizes past behavior of the states along with the incoming new measurements to estimate the new state.
- One attractive feature of the DES is its ability to predict the states at future instants. This helps in taking preventive and corrective control actions in the system.
- Different variations of Kalman filters are used to implement DES algorithms

Dynamic estimator of state…contd.

- There are mainly two challenges to the implementation of DES at the control centers:
  - modelling the system dynamics
  - computational complexity
- Utilizing the high refresh rate and high accuracy of the PMUs, the system dynamics described by the so-called state transition process can be better captured.
- Computational complexity of the DES is easily handled by the state-of-the-art computing facilities.

Above two factors, in addition to potential usage in improving the SE convergence, bad data processing, and topology processing, have renewed the interest in DES

Few comments on DES

- The performance of DES can be further improved by using some smoothing technique (e.g. Rauch-Tung-Striebel smoother), where the estimated states at an earlier instant is re-estimated after the arrival of new measurements.
- Variations of Kalman filters: unscented Kalman filter (UKF) (does not need linearization of the system), cubature Kalman filter (CKF) (better accuracy and computational efficiency).
- An efficiently designed DES can be executed within few milliseconds even for a large power system. This may enable estimation of system states at each arrival of complete PMU measurement set at the control centre.
- DES has been used to estimate dynamic states (rotor angle, speed, etc.) also for power systems.

Distribution system state estimator (DSSE)

- Deployment of SE at the distribution level needed for:
  - handling massive penetration DGs
  - managing demand response
  - manage EVs and storage
- Challenges in DSSE:
  - Unbalanced system – requiring 3-phase formulation
  - High R/X ratio
  - Large number of nodes
  - Incomplete observability – possibility of utilizing smart meter data along with SCADA measurements

PMU applications in stability monitoring

Voltage stability (VS) assessment using PMU measurements

- Local measurement-based
  - Uses local measurements of a PMU installed at a bus
  - Synchronized measurements are not needed
  - Algorithm may be implemented locally
- Wide-area measurement-based
  - WAMS-based assessment of VS
  - Better system-wide picture of VS
  - Can be implemented in the control centre

VS monitoring with local measurements

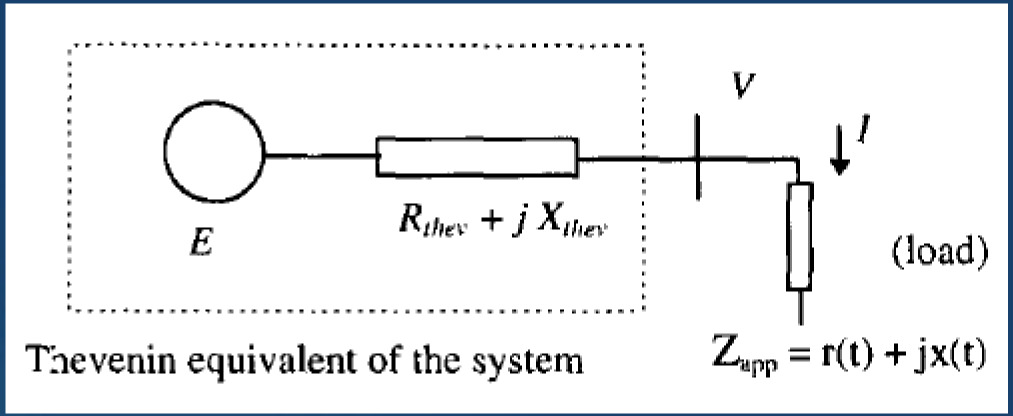
Basic concept:

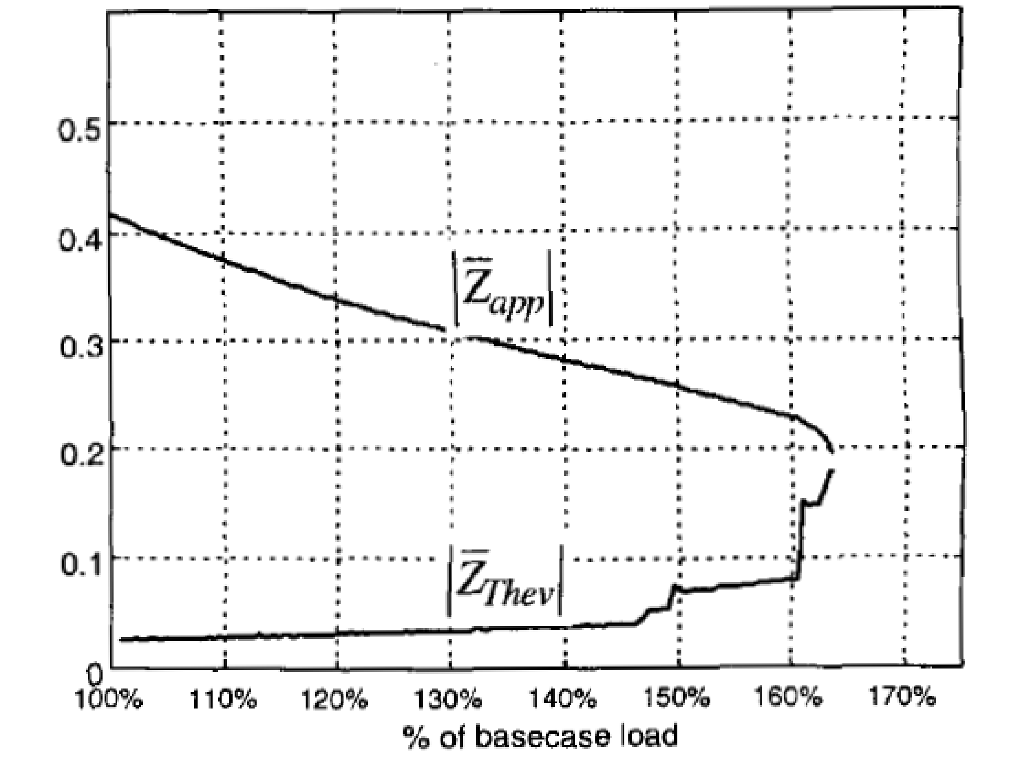
- Based on local measurements of voltage and current phasors, transmission capacity of the network is determined.
- The closer the load demand is to the estimated capacity, the more imminent is the voltage instability.
- For radial type of system, the method is equivalent to finding the closeness of the load impedance to the conjugate of the source impedance, using Thevenin equivalents, and the principle of maximum power transfer.

K. Vu et.al., "Use of Local Measurements to Estimate Voltage-Stability Margin", IEEE trans. Power syst., Vol. 14., No. 3, Aug. 1999.

VS with local measurements…contd.

Tracing the Thevenin equivalent impedance:

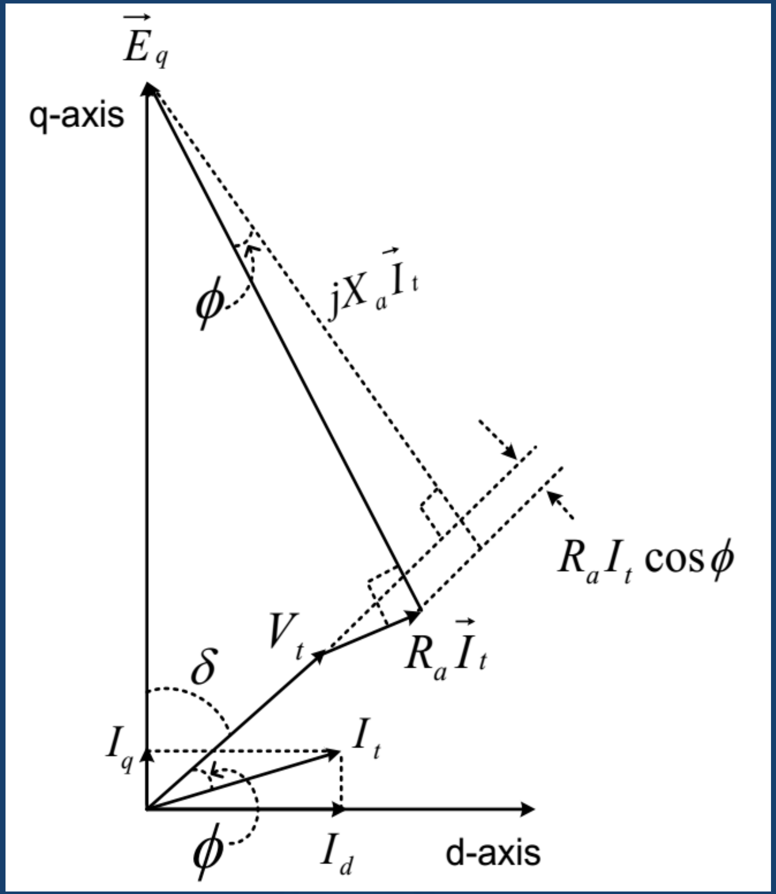




Measurements from 2 or more instants are needed to solve for the Thevenin equivalent impedance

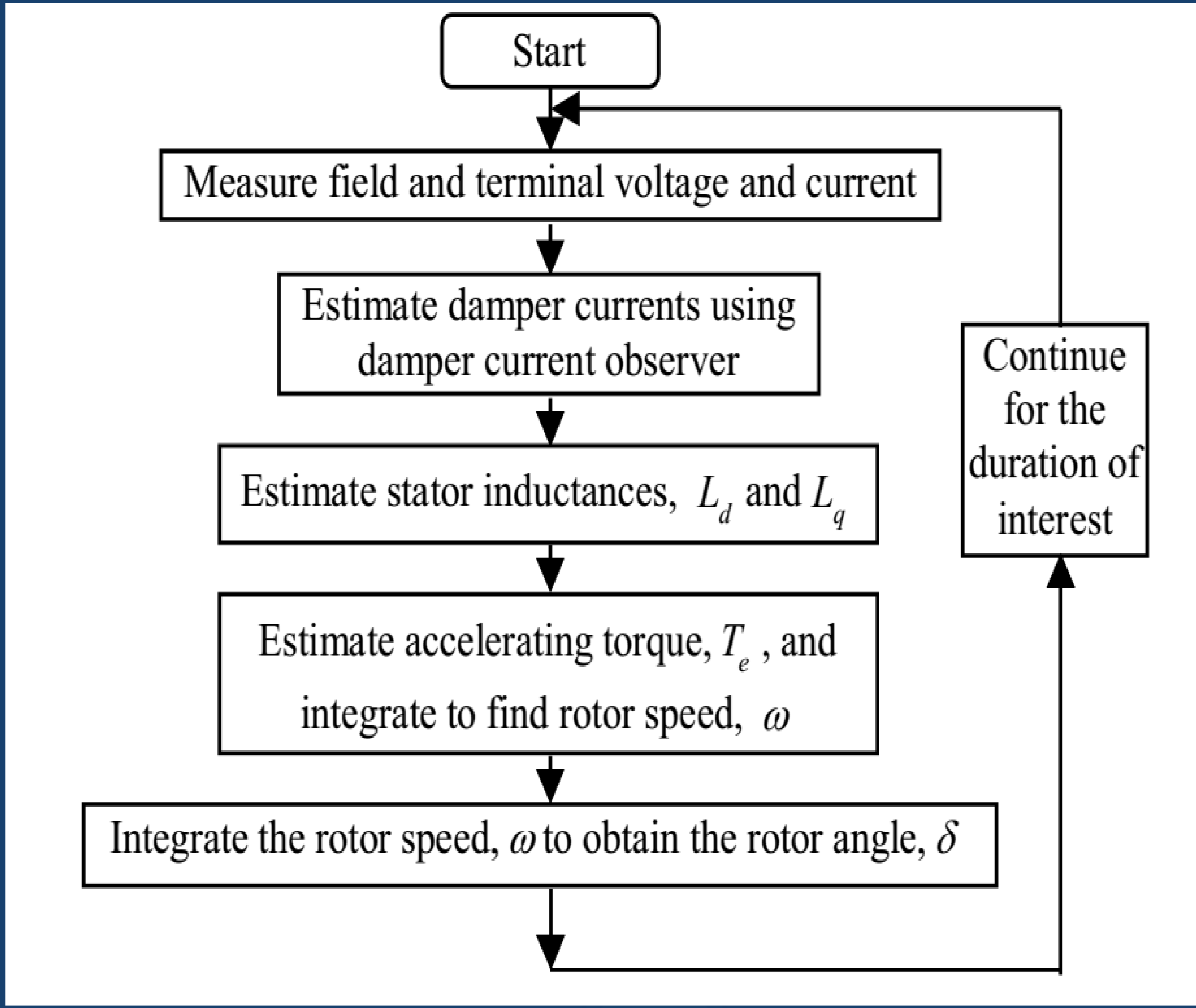
Rotor angle estimation

- For the assessment of the transient stability of a power system, knowledge of the rotor angle of the generators is essential.
- In the steady state, the rotor angle of a synchronous generator can be directly obtained using its terminal voltage and current measurements.
- During transient conditions, some of the reactances of the machine change their effective values.
- Under these conditions, estimation of the rotor angle based on the terminal measurements is not straight-forward.



Rotor angle estimation…contd.

- Based on the measurements from a PMU, an observer for the damper winding currents is developed
- Using the observed damper currents, known or estimated parameters, and available measurements, machine reactances are found out
- Using these reactances and detailed machine model, rotor angle of the generator is then estimated

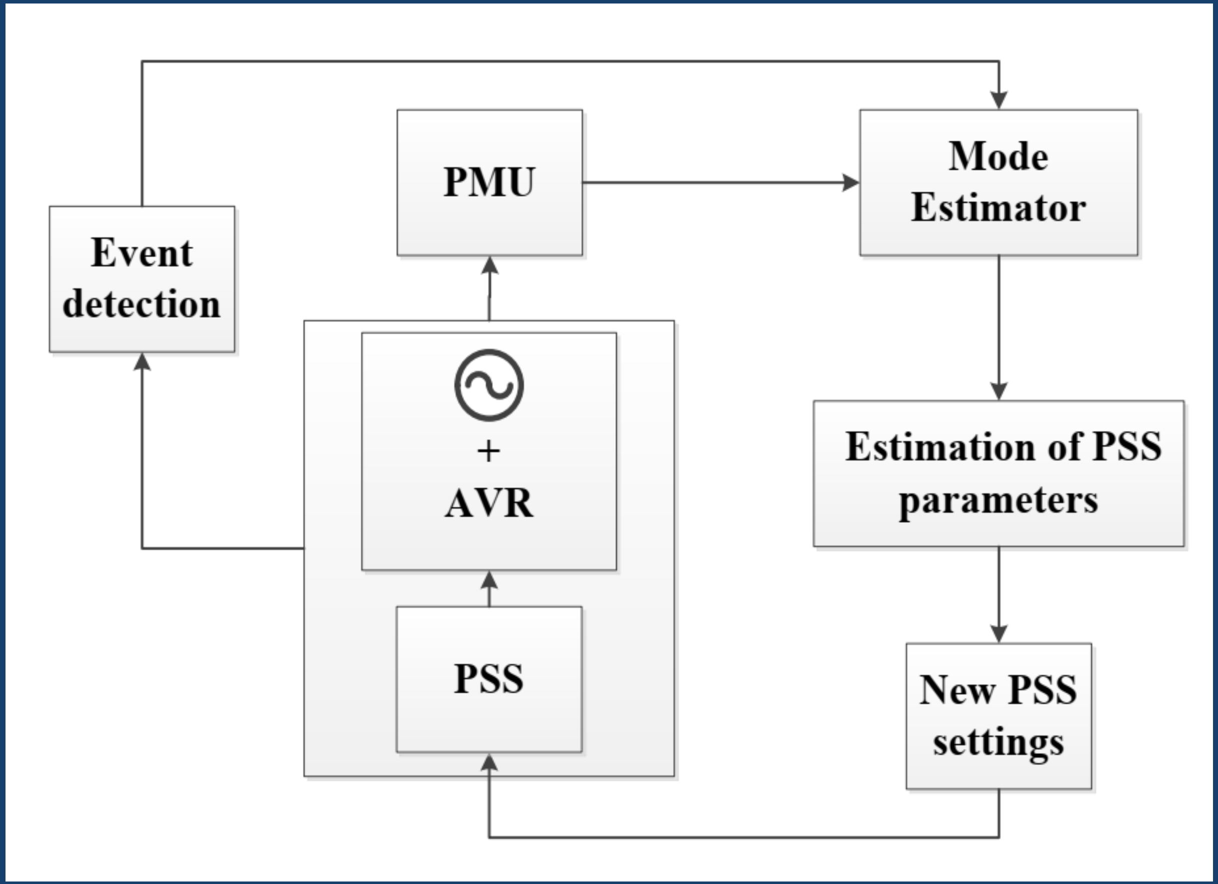


Small-signal stability assessment

- Conventional method linearizes the system and finds the Eigenvalues or modes of oscillation
- Computationally demanding task for a large system
- Needs detailed model of the system
- Model-free estimation of the modes is possible using time-window of oscillation data (e.g. real power flow through a line) captured by PMU
- Methods such as Prony, ESPRIT, matrix pencil can be used to estimate the modes based on the captured data
- This process can be implemented for real-time applications

Online mode estimation and PSS tuning

- A PMU at the terminal of the generator captures the real power output over a time-window
- An event detection algorithm triggers the mode identification process
- Estimated modes are used to tune the PSS connected to the generator



Part of the PSS tuning project with NTPC NETRA for Dadri power plant

Under-frequency load-shedding

- Imbalance between the generation and the demand is the major factor that causes frequency instability in a power system.
- This power imbalance or the so-called disturbance power can be estimated based on the rate of change of frequency information.
- One of the most effective means of restoring the frequency stability under severe power imbalance is to shed part of the loads.
- How much load should be shed thereof and where, i.e, how the total amount of load shedding is to be distributed, is an important consideration.

Load-shedding…contd.

The disturbance power, ΔP, can be estimated by using the rate of change of frequency of the generators.

$$\Delta P = \frac{2}{f_n} \sum_{i \in G_n} H_i \frac{df_i}{dt}$$

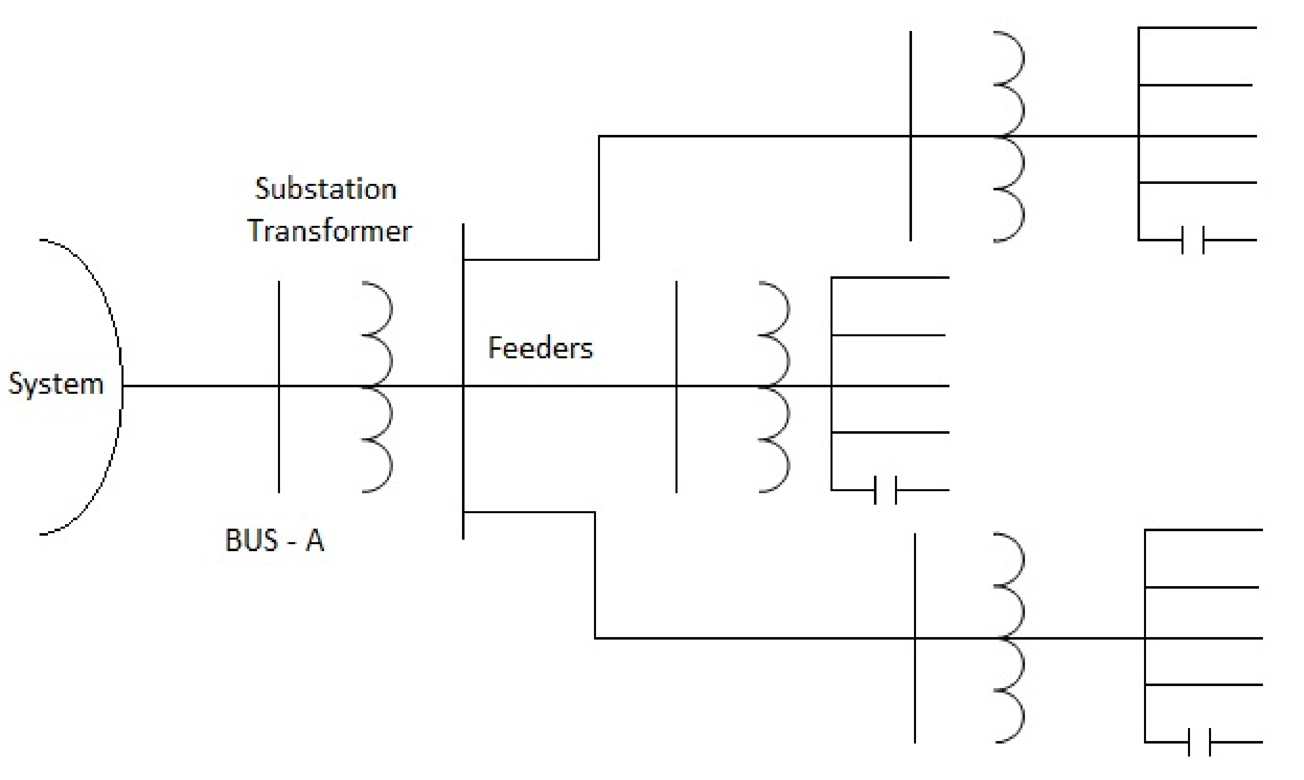
where f_n is the nominal frequency of the system, G_n is the set of generators. The rate of change of frequency, i.e., df_i/dt, is obtained from PMUs installed at the generator buses

Load modelling

Challenges in modelling the load

- A load bus is typically connected to a large number of different types of loads. It is practically impossible to represent all these loads individually.
- Location of the devices are not always known to the utilities.
- Lack of correct information regarding the composition of the load.
- Uncertainties regarding the characteristics of loads, especially at large deviations of voltage and frequency

Aggregate load



Source: IEEE Task Force, "Load representation for dynamic performance analysis," *IEEE Trans. on Power Systems*, Vol. 8, No. 2, May 1993, pp. 472-482.

Current practice on load modelling

- About 70 percent of utilities use constant power model for steady state analysis and ZIP model for dynamic studies.
- Only 30 percent utilities use some kind of detailed dynamic models.
- For each load class, same kind of models are being used and most of the utilities update the models once in five years.

Source: Milanovic, J.V. et.al, “International Industry Practice on Power System Load Modeling”, *IEEE Tran. on Power Systems*, vol. 28, No. 3, Aug. 2013, pp 3038-3046

Steps in the load modelling process

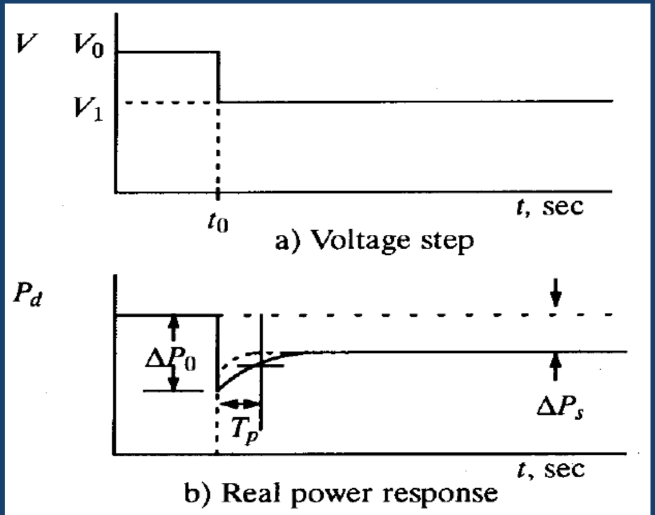
- Voltage and current measurements are obtained from measurement devices (e.g. PMU or DFR)
  - Load power is computed based on the above measurements
- Disturbance classification.
- Selection of load structure.
  - Some background knowledge is needed regarding the structure of the aggregate load
  - This structure may be dependent on time of day, month of year, season, etc.
- Parameter estimation: to estimate the most likely parameters of the assumed load structure

Commonly used load models

Nonlinear dynamic model with recovery:

$$T_p \frac{dP_d}{dt} + P_d = P_s(V) + K_p(V)\frac{dV}{dt}$$

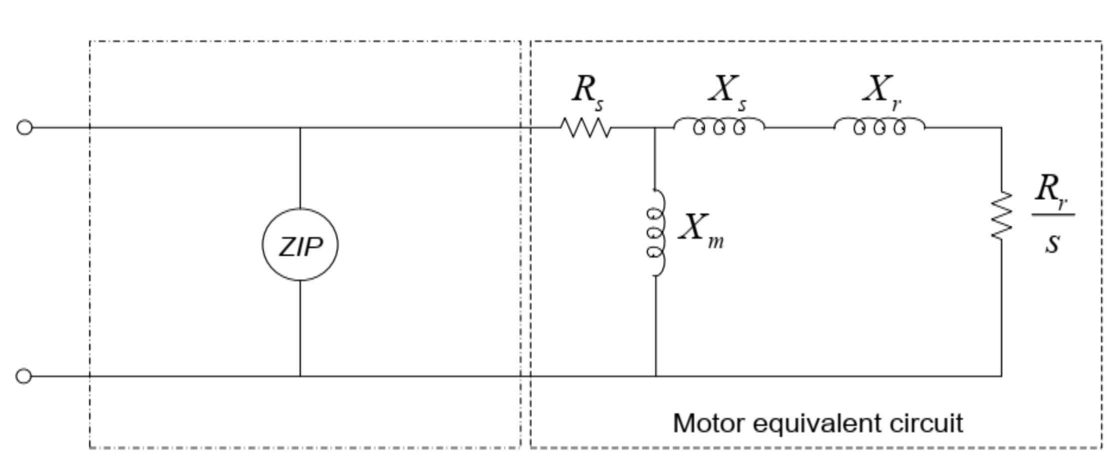
where T_p is the time constant of recovery to some specified percentage of the original load; P_d is the load demand; $P_s(V)$ and $K_p(V)$ are called static load function and dynamic load function, respectively.



Typical load response with voltage step change (Source: D. J. Hill, “Nonlinear dynamic load models with recovery for voltage stability studies,” IEEE Trans. Power Syst., vol. 8, no. 1, pp. 166-176, Feb. 1993).

Commonly used load models…contd.

Composite load model (induction motor + ZIP load)



The induction motor is usually represented by third order model, neglecting stator dynamics.

$$\frac{de'_d}{dt} = \frac{1}{T'_0}\left[-e'_d + (X - X')i_q\right] + (\omega_r - \omega_s)\, e'_q$$

$$\frac{de'_q}{dt} = \frac{1}{T'_0}\left[-e'_q - (X - X')i_d\right] - (\omega_r - \omega_s)\, e'_d$$

$$\frac{d\omega_r}{dt} = \left(\frac{\omega_s}{2H}\right)(T_{\text{elec}} - T_l)$$

The algebraic equations for stator currents are given by,

$$i_d = \frac{1}{R_s^2 + X'^2}\left[R_s\left(v_d - e'_d\right) + X'\left(v_q - e'_q\right)\right]$$

$$i_q = \frac{1}{R_s^2 + X'^2}\left[R_s\left(v_q - e'_q\right) - X'\left(v_d - e'_d\right)\right]$$

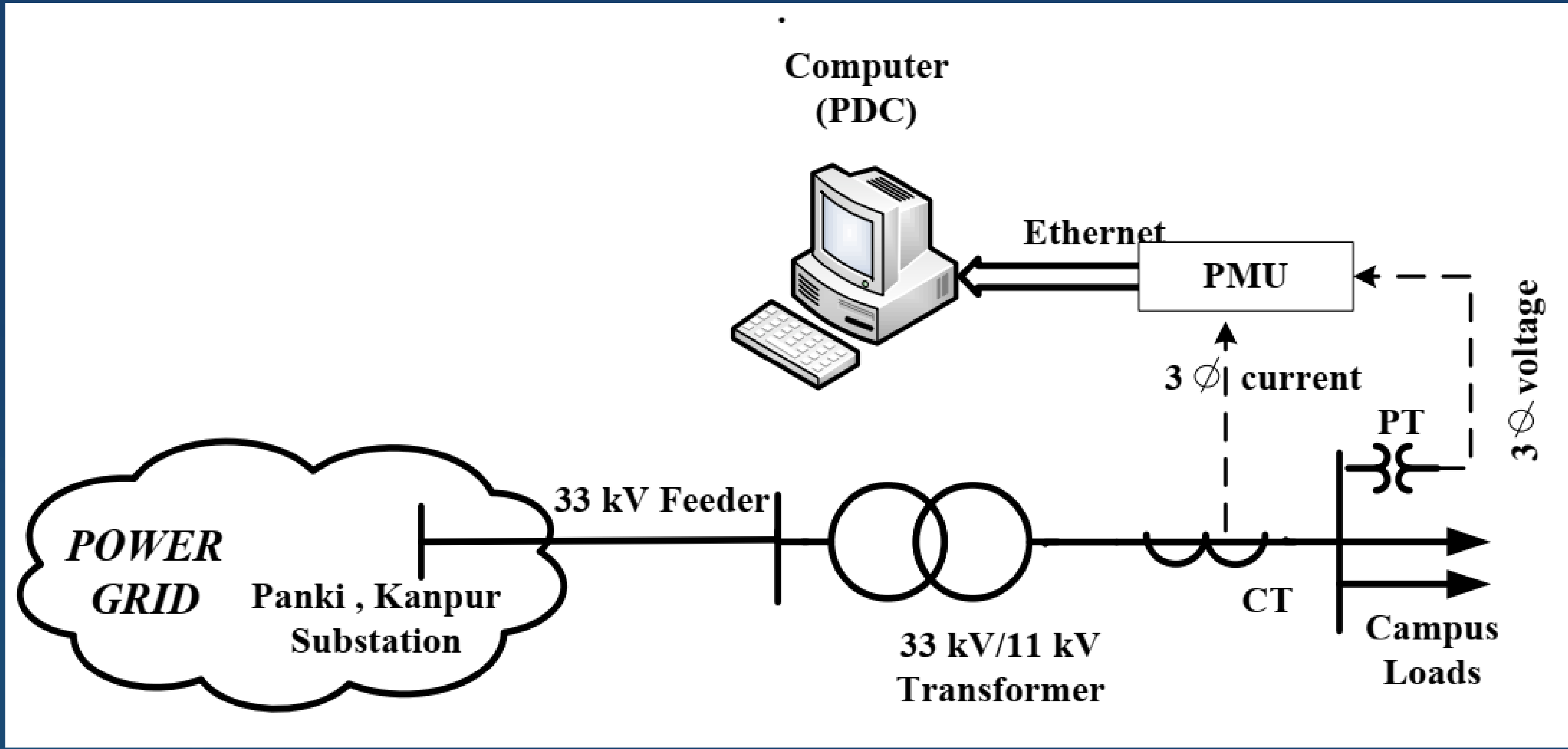
Load modelling under large and small disturbances

- Measurement based load modelling is usually carried out with the data recorded following a disturbance.
- Large disturbances are less frequent in power systems.
- Load model parameters change frequently due to the changes in nature and composition of the load.
- Model parameters identified from the most recent large disturbance may change before the next large disturbance occurs.
- Modelling loads under small disturbances is therefore also equally important.

Modelling under unbalanced disturbances

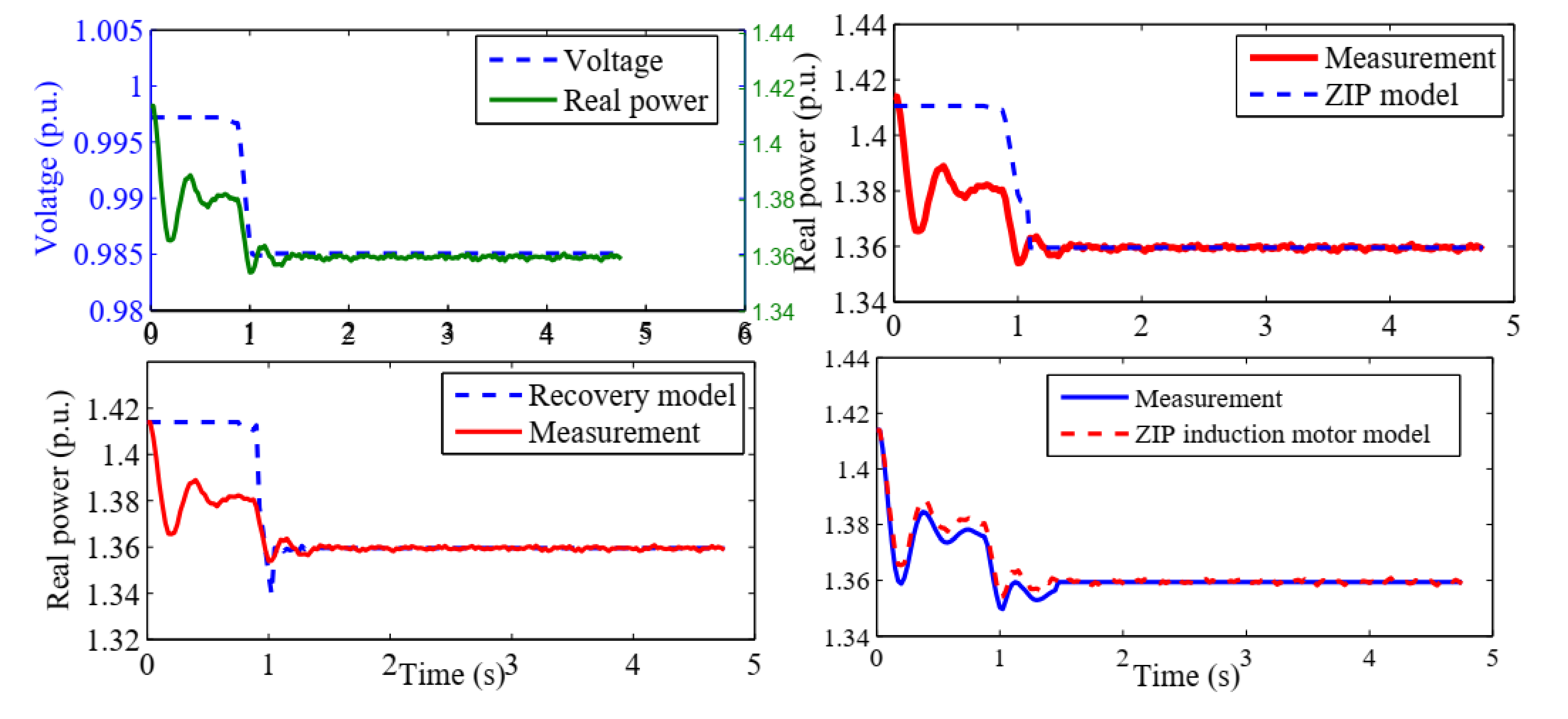
- Modelling must also be done under unbalanced disturbances.
- Fifth order induction machine is considered, incorporating the stator transients.
- The commonly used ZIP model can not be used to represent the three phase load under unbalanced disturbances.
- Existing ZIP model is modified for the unbalanced disturbances

Field experiment



IITK campus load modelling- Experimental Setup

Field experiment: results



Conclusion

- Number of PMU installations are increasing. PMU applications are going to be more common in control centres.
- WAMS is going to play a major role in monitoring, protection, and control of power systems.
- Distribution PMUs are also coming up.
- Managing the large amount of information and ensuring its security will be a big challenge.
- Cyber-security and cloud computing applications are bound to get increased importance.