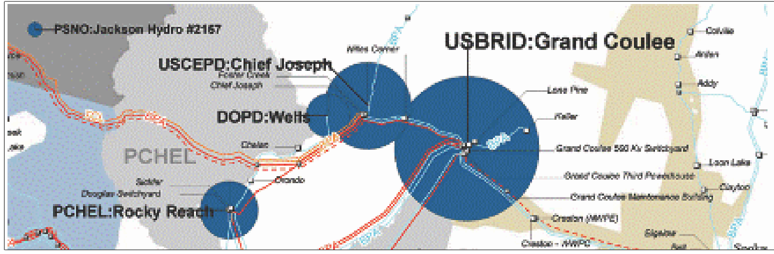


# AN ENERGY FUNCTION APPROACH FOR THE MONITORING OF POWER SYSTEMS DYNAMICS USING SYNCHRONISED PHASOR DATA

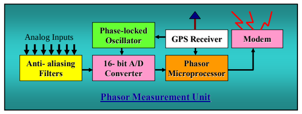
Aranya Chakrabortty, Joe H. Chow, Murat Arcak, Bharat Bhargava, Armando Salazar

## PHASOR MEASUREMENT UNITS

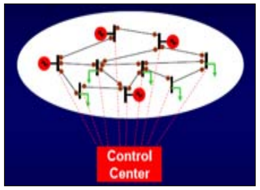
### REAL TIME DATA ACQUISITION & CONTROL

- Synchronized Phasor Measurement Units (PMUs) are digital data recording devices that measure positive sequence current and voltage phasors in a substation and time-stamp these measurements with GPS derived reference.

- The measurements from different substations are accumulated at a common point (like an Energy Management System center) via Internet for analysis and taking subsequent remedial actions.



Phasor Measurement Unit



- The primary advantages of PMUs over conventional state estimators are :

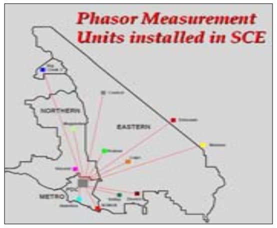
1. Fast sampling
2. Non-iterative state estimation
3. Incomplete observability no longer an issue
4. Analyzable disruptions of external power systems (no dependence on reduced models)

- Challenges – Cost and Communication constraints, data concentration, selection of PMU locations etc.

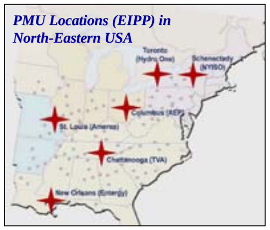
## EASTERN INTERCONNECTION PHASOR PROJECT (EIPP)

### PMU DATA ANALYSIS FOR ASSESSING DYNAMIC SECURITY OF LARGE POWER SYSTEMS

Since the Northeast Blackout on August 14, 2003, the EIPP has been formed to initiate the installation of a network of PMUs in the Eastern Interconnected Power System, similar to that already existing in the west coast. The primary objective is to formulate useful analysis tools or metrics out of the measured phasor data and utilize them for the assessment of overall system performance in order to take appropriate control actions.



*Phasor Measurement Units installed in SCE*



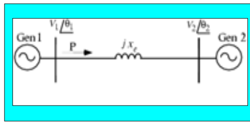
*PMU Locations (EIPP) in North-Eastern USA*

In the present research work we apply an energy function analysis using phasor data to monitor damping stability of large interconnected power systems following a disturbance in the transfer path. We use power angle curves to identify dominant transfer paths and approximate them as two machine- single line systems. We separate the angular swing between the two ends into fast and quasi-steady state components by filtering, and then demonstrate the construction of kinetic energy and potential energy functions for the perturbed power system using these filtered quantities.

## ENERGY FUNCTION CONSTRUCTION

### PRE AND POST- DISTURBANCE DYNAMIC ENERGY MONITORING OF LARGE POWER SYSTEMS

We consider two types of power transfer path for our analysis – the first is a two-machine system interconnected by a reactance (where the generator Gen 1 is supplying power to the generator Gen 2) while the second path is characterized by an additional intermediate voltage support by a Static Var Compensator (SVC).



$$\dot{\delta} = \Omega\omega$$
$$2H\dot{\omega} = P_m - \frac{E_1E_2\sin(\delta)}{x_e'} - D\omega$$

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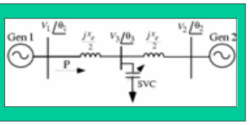


- **Assumptions :** Since each generator represents an aggregate of many coherent machines, we can assume the bus voltages, bus angles and frequencies to be almost the same as the generator internal voltages, rotor angles and machine frequencies respectively. Also, the transformer reactances and open circuit transient generator reactances are assumed to be negligibly small so that $x_e \approx x_e'$.

- **Energy Functions**

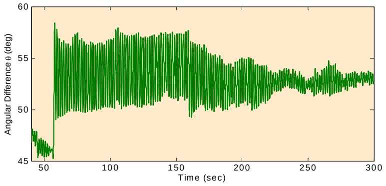
Kinetic Energy $= H\Omega\omega^2$

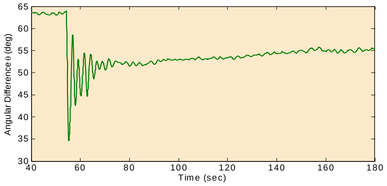
$$\text{Swing Potential Energy} = \frac{\bar{V}_1\bar{V}_2(\cos(\theta_{op}) - \cos(\theta) + \sin(\theta_{op})(\theta_{op} - \theta))}{x_e'}$$

Kinetic Energy $= H\Omega\omega^2$

$$\text{Swing Potential Energy} = \frac{4\bar{V}_1\bar{V}_2(\cos(\frac{\theta_{op}}{2}) - \cos(\frac{\theta}{2}) + \sin(\frac{\theta_{op}}{2})(\frac{\theta_{op} - \theta}{2}))}{x_e'}$$

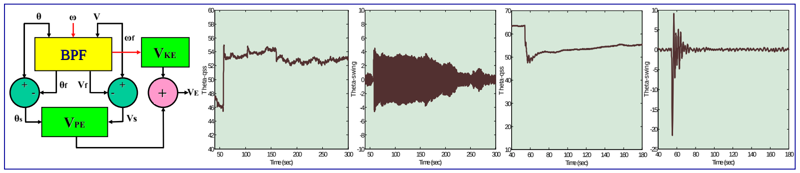
- The reference operating angle for the swing potential energy is taken as the *post disturbance equilibrium angle.*





- However, in real time operation the post-disturbance equilibrium angle is not known a priori. Therefore, we extract the quasi steady state component of the angle by filtering and approximate the post-disturbance equilibrium angle by this slow component.

- **Separation of fast and slow components of angular variation**



- **Calculation of Reactance and Machine Inertia**

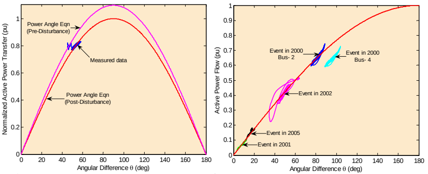
---- Since active power transfer is a sine function of the angular difference, we draw the P-delta curve from the measured data and use a least squares fit for the most accurate sine curve which passes through this drawn curve. Since the average values for the bus voltages are known, hence the reactance is computed from the amplitude of this fitted sine curve.

---- Machine inertia is estimated by linearizing the swing equation about the equilibrium angle and finding the swing frequency from the transient angular variations, using the equation

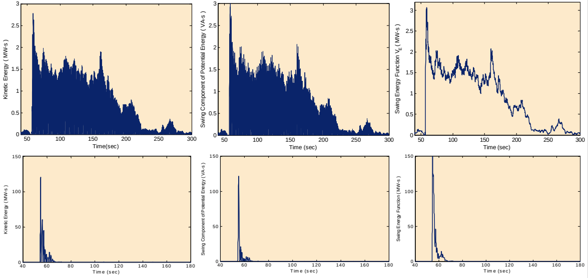
$$H = \frac{V_1V_2\cos(\theta_{eq})\Omega}{2x_e\omega_s^{\,2}}$$

---- For the both transfer paths the swing was found to be mono-modal which facilitated the calculation of the swing frequency. For first transfer path, which is a 600-mile transmission system, the calculated value H = 129 pu was found to match exactly with the machine inertia in the real system. Similarly, for the second transfer path which is a 1200-mile transmission system power to a huge load center, H was calculated to be 977 pu, which is consistent with the actual inertia.

## VERIFICATION WITH REAL DATA

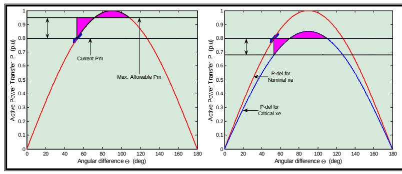


Considering several disturbance events in path 2 we see that we can fit an approximate sine curve through the P-delta plots for all the events in Bus 2 but not in Bus 4, which is a nearby bus. This gives us a way to identify dominant buses in a given area aggregate of slow coherent machines.



It is worth noting that although the kinetic energy and potential energy individually contains oscillations ( like that for a simple pendulum), the summation of the two is practically free of these oscillations, which confirms the expected out of phase behavior between the two. The overall post-disturbance energy profile is exponentially decaying indicating that the system is stable.

## CALCULATION OF ENERGY MARGINS FROM PMU DATA



By applying *Equal Area Criterion* to the measured power angle data, we can compute the critical value upto which the angle can be allowed to increase without sacrificing stability, in situations of sudden jump in power transfer following a machine run-out, or sudden increase in reactance due to loss of lines etc.

## CONCLUSIONS & FUTURE RESEARCH

- In this research we adapt an energy function analysis using synchronized phasor data to monitor the dynamic security of power transfer paths in the face of disturbances. We analyze the phasor data to identify the transfer paths and their parameters, and decompose the angular difference between the sending and receiving ends into a slow quasi steady state and a swing component. We compute the swing energy as the summation of the kinetic energy and swing component of the potential energy using the post disturbance equilibrium angle as reference and show its usefulness for monitoring the small-signal stability of the system. We use the quasi-steady-state of angular separation to predict the stability margin due to potential system contingencies such as loss of generation or lines.
- An important future research direction would be to investigate the identification of aggregate areas in a power system network using PMU data and to validate the choice of a single machine as an aggregate of several slow coherent machines in a given area.

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