FREQUENCY STABILITY USING INVERTER POWER CONTROL IN LOW-INERTIA POWER SYSTEMS

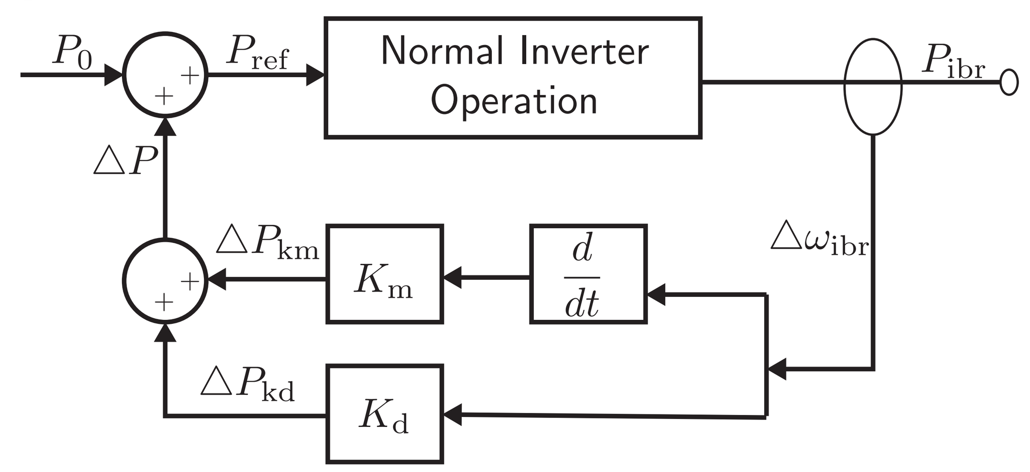
Atinuke Ademola-Idowu and Baosen Zhang
Electrical and Computer Engineering Department, University of Washington

Introduction

- The increased penetration of inverter-based resources (IBRs) in the electric grid has led to the displacement of conventional synchronous generators and subsequently a decline in the available rotational inertia which provides immediate frequency response to power imbalance in the grid.
- We propose a new control strategy termed Inverter Power Control (IPC), based on model predictive control, to determine the optimal active power set-point for the inverters in the event of a disturbance in the grid and show by comparison to an optimally-tuned VSM, the superior performance of the IPC.

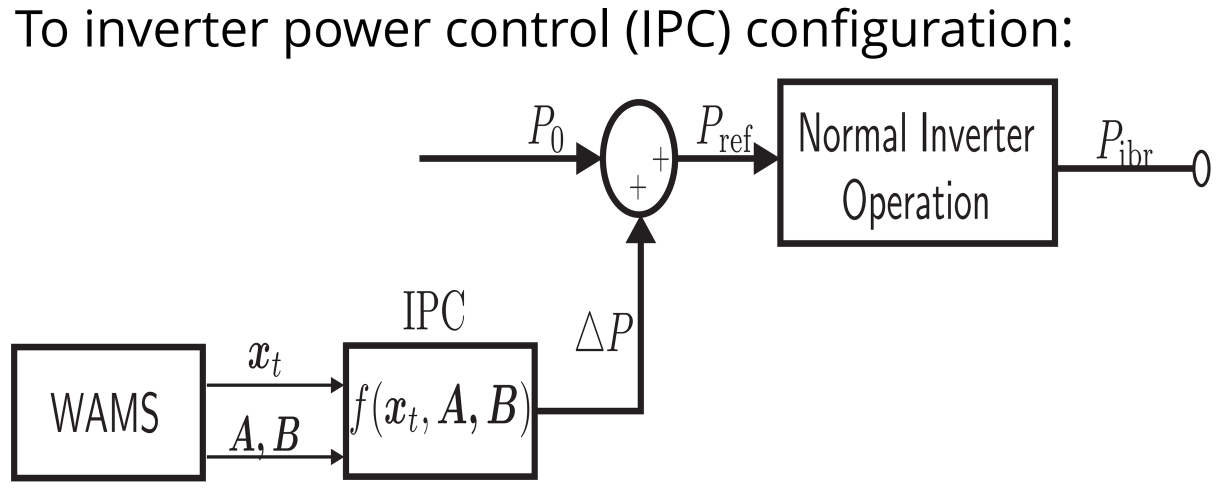
Inverter Power Control (IPC)

Going from virtual synchronous machine (VSM) configuration:



$$\triangle P = \triangle P_{\text{km}} + \triangle P_{\text{kd}} = K_{\text{m}} \frac{d\triangle\omega_{\text{ibr}}}{dt} + K_{\text{d}} \triangle\omega_{\text{ibr}}$$

To inverter power control (IPC) configuration:



$$\triangle P = f(\mathbf{x}, \mathbf{A}, \mathbf{B})$$

IPC System Model

Define: $u_k \triangleq \triangle\delta_{k\in\mathcal{I}} \quad \forall\, i \neq j,\ i \neq k,\ i,j \in \mathcal{G}$ and $k \in \mathcal{I}$

Linearized power flow in matrix form:

$$\triangle P_e = \underbrace{\begin{bmatrix} b_{ii} & -b_{ij} \\ -b_{ji} & b_{jj} \end{bmatrix}}_{B_{ee}} \begin{bmatrix} \triangle\delta_i \\ \triangle\delta_j \end{bmatrix} + \underbrace{\begin{bmatrix} -b_{ik} \\ -b_{jk} \end{bmatrix}}_{B_{eI}} u_k$$

Modified swing equation in matrix form:

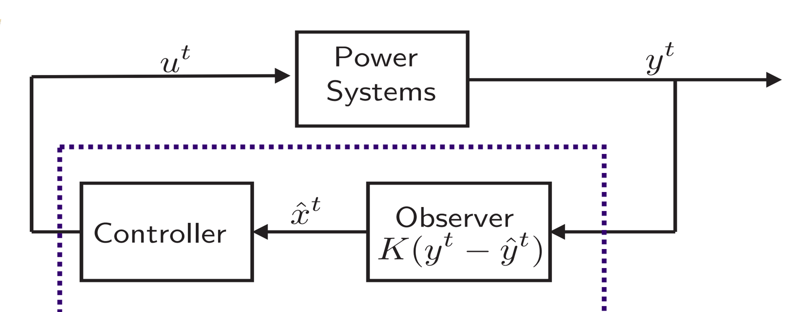
$$\underbrace{\begin{bmatrix} \triangle\omega^{t+1} \\ \triangle\delta^{t+1} \end{bmatrix}}_{x^{t+1}} = \underbrace{\begin{bmatrix} -M^{-1}D & -M^{-1}B_{ee} \\ I_n & 0_n \end{bmatrix}}_{A} \underbrace{\begin{bmatrix} \triangle\omega^t \\ \triangle\delta^t \end{bmatrix}}_{x^t} + \underbrace{\begin{bmatrix} -M^{-1}B_{eI} \\ 0_n \end{bmatrix}}_{B_u} u^t + \underbrace{\begin{bmatrix} M^{-1} \\ 0_n \end{bmatrix}}_{B_d} \underbrace{\triangle P^t}_{d^t}$$

Objective: Minimize <u>frequency</u> and <u>rate of change of frequency</u>

Frequency: $y^t = \underbrace{[I_n \quad 0_n]}_{C} x^t = \triangle\omega^t$

Rate of change of frequency: $\triangle y^t = \frac{1}{h}\left[y^t - y^{t-1}\right] = \frac{1}{h}\left[\triangle\omega^t - \triangle\omega^{t-1}\right]$

Disturbance Estimation



State and Disturbance Estimation:

$$\underbrace{\begin{bmatrix} \hat{x}^{t|t} \\ \hat{h}^{t|t} \end{bmatrix}}_{\hat{z}^{t|t}} = \underbrace{\begin{bmatrix} \hat{x}^{t|t-1} \\ \hat{h}^{t|t-1} \end{bmatrix}}_{\hat{z}^{t|t-1}} + \begin{bmatrix} K_x \\ K_h \end{bmatrix} \left(y_t - [C \quad C_h] \begin{bmatrix} \hat{x}^{t|t-1} \\ \hat{h}^{t|t-1} \end{bmatrix} \right)$$

IPC System Optimization

MPC Form:

$$\underset{u^t}{\text{Min.}}\ J = \frac{1}{2}\sum_{t=1}^{N-1}\left[\hat{y}^{t^T} Q_1 \hat{y}^t + \triangle\hat{y}^{t^T} Q_2 \triangle\hat{y}^t + \tilde{u}^T R\tilde{u}\right]$$
$$\text{s.t.} \quad \hat{z}^{t+1} = A\hat{z}^t + Bu^t$$
$$\hat{y}^t = C\hat{z}^t$$

Unconstrained optimization: $u^* = -H^{-1}F^T\hat{z}^0$

Constrained optimization (QP):

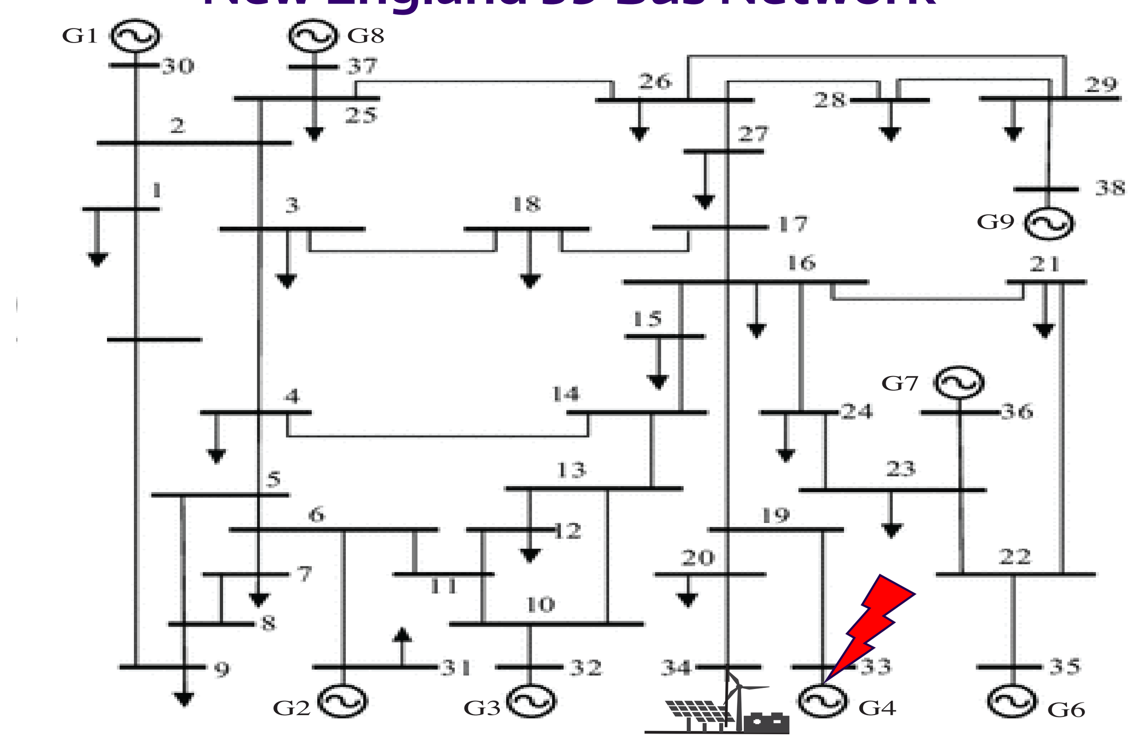
$$\underset{u}{\text{Min.}}\ J = \frac{1}{2}\hat{z}^{0^T} G\hat{z}^0 + \hat{z}^{0^T} Fu + \frac{1}{2}u^T Hu$$
$$\text{s.t.} \quad Lu \leq W + V\hat{z}^0$$

IBR power output:

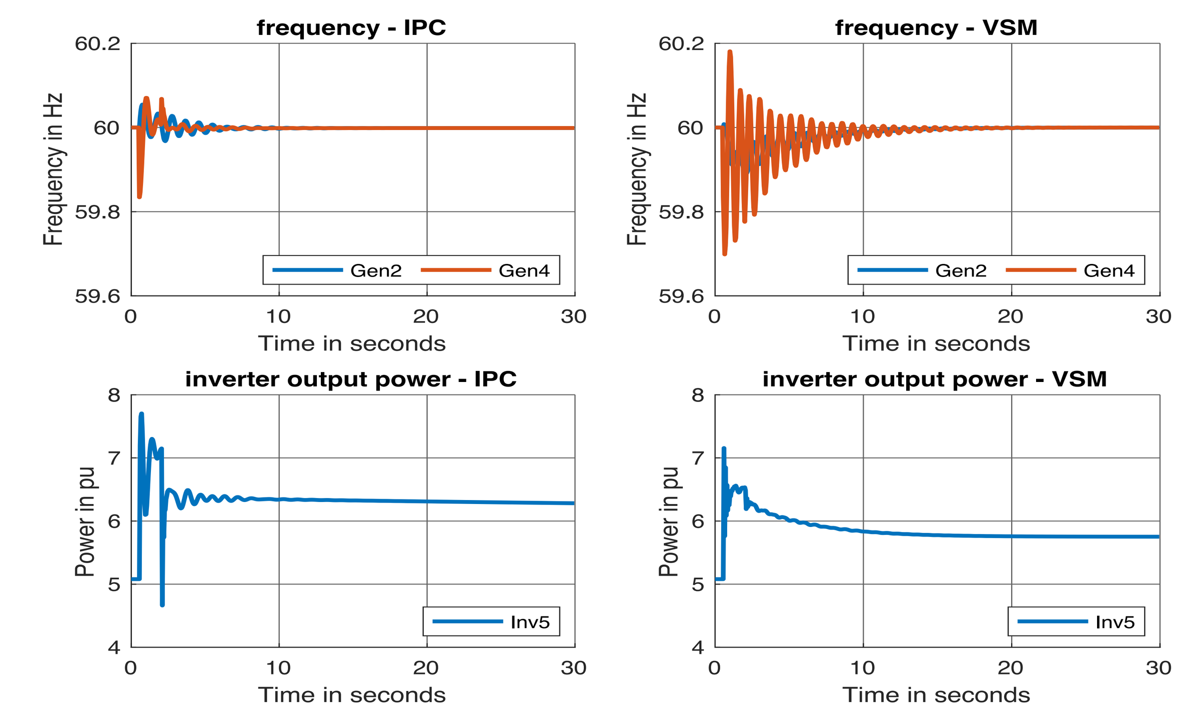
$$\triangle P^t_{ibr,k} = \sum_{k\sim i, k\in\mathcal{I}, i\in\mathcal{G}} b_{ki}(u_k(1) - \triangle\delta^t_i) + \sum_{k\sim j, j,k\in\mathcal{I}} b_{kj}(u_k(1) - u_j(1))$$

Results – New England 39 Bus System

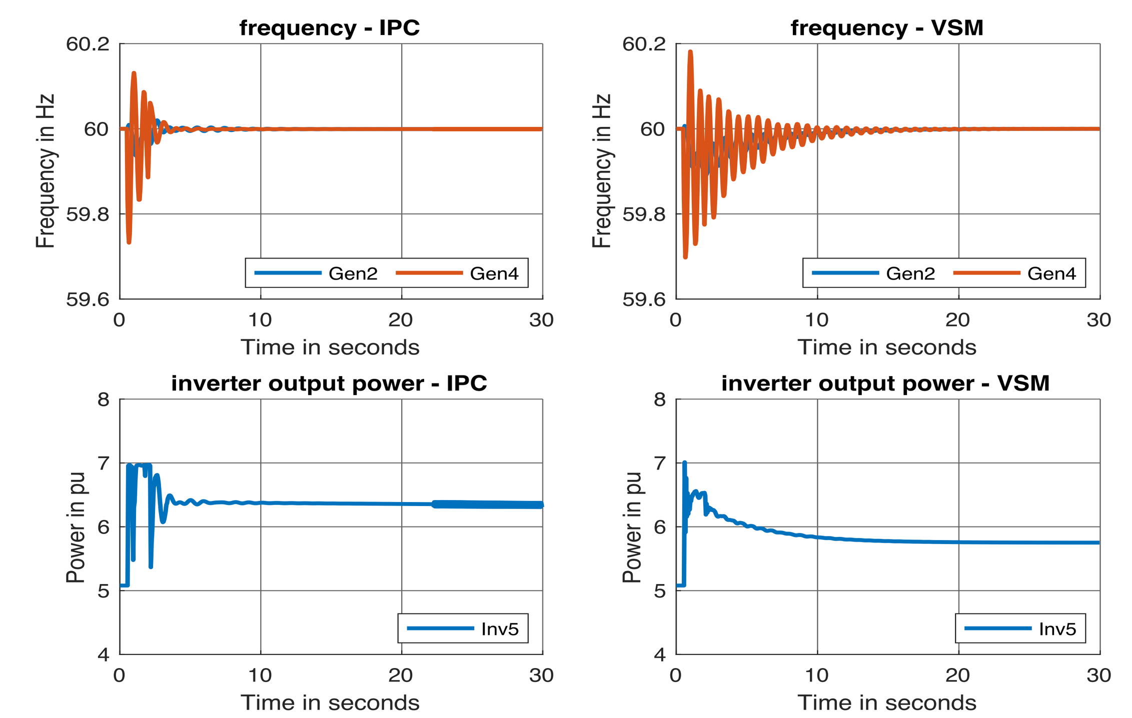
New England 39 Bus Network



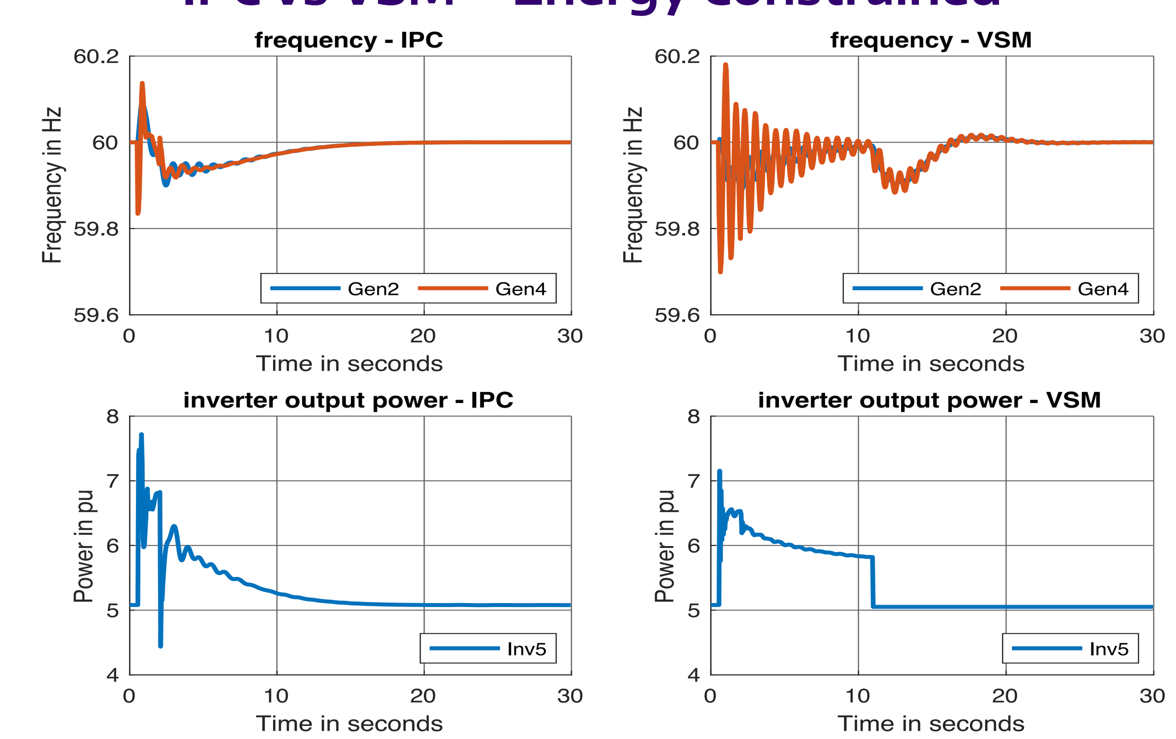
IPC vs VSM - Unconstrained



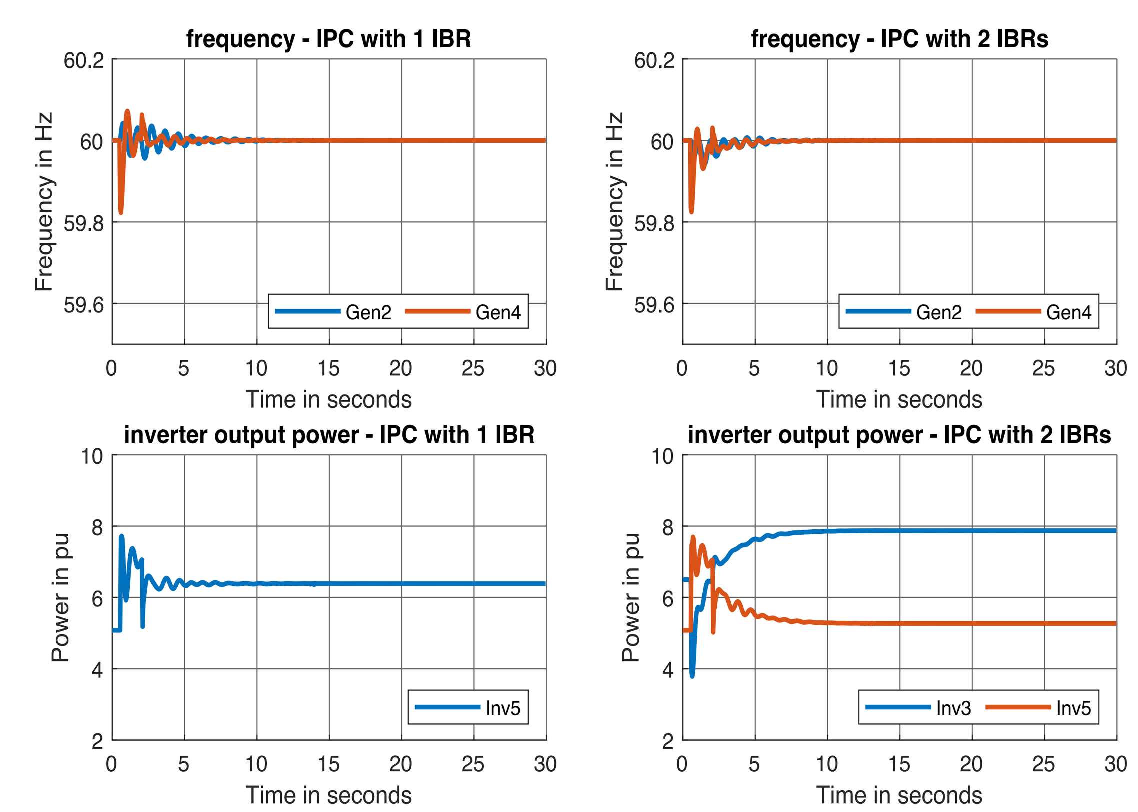
IPC vs VSM – Power Constrained



IPC vs VSM – Energy Constrained



IPC – Single (IBR 5) vs Multiple (IBR 3 & 5)



IPC – Centralized vs Partially Decentralized

IBR3 – G1, G2, G4, G6; IBR5 – G4, G7, G8, G9