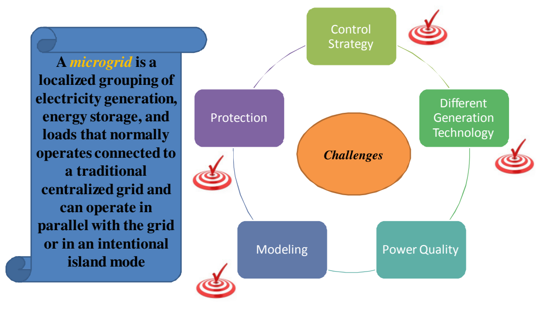
Novel Load Frequency Control in a Multi-agent based Microgrid Power System in Presence of Cyber Intrusions

Hessam Keshtkar

Advisor : Dr. Jignesh Solanki

Lane Department of Computer Science and Electrical Engineering

Microgrid Definition and Challenges



Introduction

LFC in Microgrids

➢ *For the successful operation of microgrids under contingencies load and generation should be balanced to maintain the frequency. The goal of load frequency controller (LFC) is to maintain the frequency of the power system to its nominal value and minimize the variations in frequency of the system.*

Importance

➢ *With the introduction of distributed generation like renewable energy sources that have variable output electromechanical oscillations occur in the system which require fast-response devices and control strategies to damp these oscillations.*

Objective

➢ *The objective of this research is to maintain the frequency of microgrid distribution power system under intermittencies of renewable resources, ESSs and also under sudden load changes, wind speed variations, and cyber attacks.*

Problem Statement

➢ ***In this research*** *an isolated smart microgrid comprising both controllable and uncontrollable sources, such as solar, wind as Renewable Energy Sources (RES), diesel generator, fuel cell as Distributed Generation (DG) units, aqua-electrolyser, hydrogen storage, and Superconducting Magnetic Energy Storage (SMES) as storage unit in a multi-agent based infrastructure is modeled.*

➢ *This microgrid network is subjected to a large load with rapid changes, which results in* ***system frequency to be severely deteriorated*** *and become oscillatory. Additionally, the stability issues grow with wide penetration of wind into microgrid.*

➢ *After discussing the* ***modeling of the multi-agent based power system*** *and different generating units, different kinds of* ***frequency control approaches****, including Adaptive Dynamic Programming (ADP) which is based on the neural networks and belongs to the family of Adaptive Critic Design (ACD), have been used and the results have been compared to each other.*

➢ *The Particle Swarm Optimization (PSO), and Differential Evolution (DE)* ***optimization techniques*** *have been applied to come up with the best control parameters such that the frequency oscillation due to a disturbance in the microgrid is minimized.*

➢ *The proposed control approaches are tested in presence of* ***different frequency changes*** *in the system including cyber attack effects. Implementation of new* ***attack detection and learning method*** *is also examined in the simulations.*

➢ *The results show* ***improvement in frequency response*** *of the microgrid system using the proposed* ***control method and defense strategy*** *against cyber attacks.*

Problem Formulation

Grid Design

$$\Delta f = \frac{f_{sys}}{2Hs}[\Delta P_G - \Delta P_e]$$

where

$$P_G = P_W + P_s + P_{dg} + P_{fc} - P_{ae}$$

$$\Delta P_e = \Delta P_L + D\Delta f$$

$$G_{sys}(s) = \frac{\Delta f}{(\Delta P_G - \Delta P_L)} = \frac{1}{\left[D + \left(\frac{2H}{f_{sys}}\right)s\right]} = \frac{K_{ps}}{1 + sT_{ps}}$$

State feedback LQR control design

$$\begin{cases} \dot{X} = AX + BU + \Gamma P_d \\ Y = CX \end{cases}$$

$$\begin{cases} X = \left[\Delta f \ \Delta P_{dgg} \ \Delta P_{dgt} \ \Delta P_{fc} \ \Delta P_{ae} \int \Delta f dt\right]^T \\ U = \left[\Delta U_{dg} \ \Delta U_{fc} \ \Delta U_{ae}\right]^T \end{cases}$$

$$J_{LQR} = \frac{1}{2}\int_0^\infty (\dot{X}^T Q \dot{X} + \dot{U}^T R \dot{U})$$

where

$$U = -KX, \ K = -R^{-1}B^T P$$

- where X, U, Pd and Y are the state, control, disturbance and output vectors respectively
- To remove the disturbance vector we redefine the state variable set and control variable set as $\tilde{X} = \dot{X}, \tilde{U} = \dot{U}$.
- For finding P, Algebraic Riccuti Equation should be solved:

$$A^T P + PA - PBR^{-1}B^T P + Q = 0$$

Problem Formulation

ADP Design

- A Recurrent Neural Network (RNN) Dual Heuristic dynamic Programming (DHP) critic network is trained online to approximate λ (k+1), the partial derivative of J (k+1) with respect to y (k+1), by minimizing the following error:

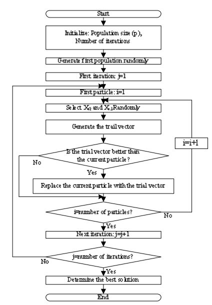
$$E_c(k) = \|e_c(k)\|^2$$

$$e_c(k) = \hat{\lambda}(k) - \left\{\frac{\partial U(k)}{\partial y(k)} + \left[\frac{\partial u(k)}{\partial y(k)}\right]' \frac{\partial U(k)}{\partial u(k)} + \gamma\left[\frac{\partial \hat{y}(k+1)}{\partial y(k)} + \frac{\partial \hat{y}(k+1)}{\partial u(k)}\frac{\partial u(k)}{\partial y(k)}\right]' \hat{\lambda}(k+1)\right\}$$

- Assuming a linear output activation function for the critic network, the DHP critic network output at time k is obtained by

$$\hat{\lambda}(k+1) = W_{oc}S_c(k) = W_{oc}f_c\left[W_{ic}\hat{y}(k+1) + W_{sc}S_c(k-1)\right]$$

Optimization (DE) Algorithm



Learning Algorithm

- The objective is to maximize the sum of returned rewards over time. The return reward in this paper is the inverse of ACE signal

$$R = \sum_{k=0}^{\infty} \gamma^k r_{t+k+1}$$

$$ACE = \Delta f + \beta \Delta P_c$$

- where 0<γ<1 is a discount factor, which gives the maximum importance to the recent rewards. The expected return (reward) when starting at state x_t while following policy pi(x, a) is called value function.

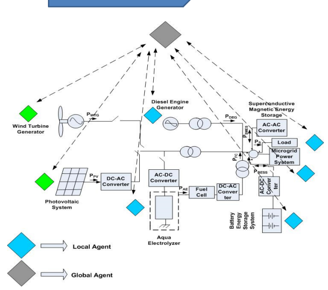
$$V^\pi(x) = E_\pi\left\{\sum_{k=0}^{\infty}\left[\gamma^k r_{t+k+1} \mid x_t = x\right]\right\}$$

- Sometimes, the value function is replaced by action value which is the expected discounted reward while starting at state x_t and taking action a_t

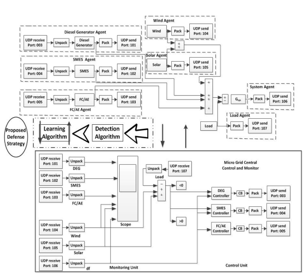
$$Q^\pi(x,a) = E_\pi\left\{\sum_{k=0}^{\infty}\left[\gamma^k r_{t+k+1} \mid x_t = x, a_t = a\right]\right\}$$

Modeling

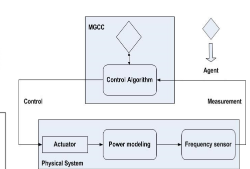
Multi agent microgrid model for LFC



Microgrid Central Control (MGCC) scheme

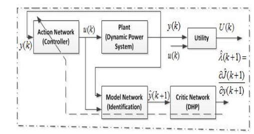


Configuration of the multi agent system

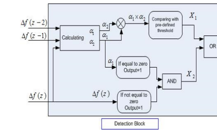


Modeling

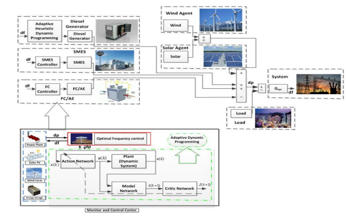
Schematic diagram of DHP neurocontrol design with RNNs



Schematic of the proposed detection strategy

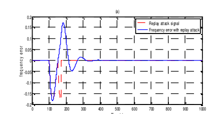


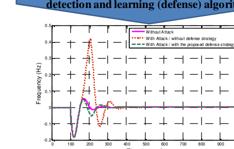
Approach Implementation

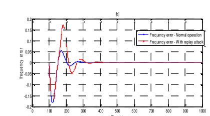


Simulation Results

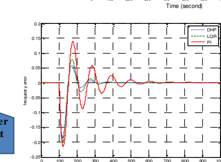
❖ **Frequency response with/without control, detection and learning (defense) algorithm**







❖ **Frequency response of the system; (a) after severe replay attack; (b) with and without severe replay attack**



❖ **Frequency response with different control methods**

Conclusions

➢ *This study has been done in order to analyze the application of optimal state feedback* ***LQR control and ADP (DHP)*** *which is proposed for a smart multi-agent based microgrid.*

➢ *The optimization algorithm which is used for designing the Q and R in LQR and also PI control parameters to minimize the frequency oscillations is* ***PSO and DE*** *which are fast enough for transient analysis.*

➢ *A comparison has been made between conventional PI controller and the proposed optimal state feedback LQR and ADP control performance in the simulation results section. The* ***effectiveness of the proposed LQR and ADP control*** *has been concluded from the observations.*

➢ *The robustness of the proposed controller has been tested against* ***different cyber attacks*** *with critical timing and severity. Simulation results show that the proposed method is fast enough and act appropriately and accordingly when facing different kinds of cyber attacks on the critical signals of the system.*

➢ *A* ***detection and learning algorithm*** *is proposed as a defense strategy against cyber attacks for improving the resiliency of the system in case of intrusions. When a cyber attack occurs on the frequency measurement signal of the multi-agent based microgrid, this detection and defense strategy along with the control approaches are used by MGCC to damp the frequency oscillations. The results show the* ***effectiveness of the proposed algorithm against cyber intrusions****.*