Modeling, Control and Identification of a Smart Grid

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INTRODUCTION

New energetic scenario

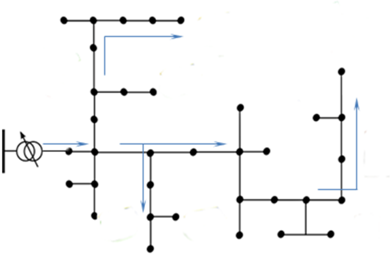
The power distribution scenario is deeply changing

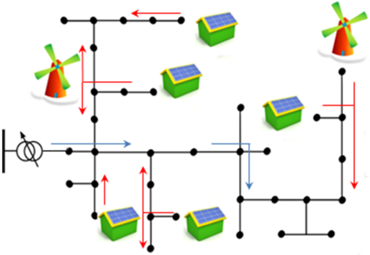
- Distributed Renewable Energy Resources (DRES) development
- great potential performance improvement.
- strategic research field (20 20 20 objectives)

We need new control and scheduling techniques in order to:

- fully exploit DRES
- avoid instabilities
- maintain grid infrastructure

Distribution network evolution





Traditional distribution network

- passive loads
- mono-directional power flows
- slow and manual control action (electro-mechanic devices)
- no measurements

Future distribution network

- DRES dispersed in the grid
- bi-directional power flows
- fast and automatic control action (inverters)
- real-time measurements

RESEARCH TOPICS AND PUBLICATIONS

Research topics and publications

- Reactive power control for voltage support and losses minimization

[2] S. Bolognani, R. Carli, G. Cavraro, S. Zampieri, (2015)
Distributed reactive power feedback control for voltage regulation and loss minimization, *IEEE Transactions on Automatic Control*,

[3] S. Bolognani, R. Carli, G. Cavraro, S. Zampieri, (2013)
A distributed control strategy for optimal reactive power flow with power constraints, *IEEE Conference on Decision and Control (CDC13)*,

[4] S. Bolognani, R. Carli, G. Cavraro, S. Zampieri, (2013)
A distributed control strategy for optimal reactive power flow with power and voltage constraints, *IEEE SmartGridComm 2013 Symposium*,

Research topics and publications

- Active power control: generation cost minimization

[5] G. Cavraro, R. Carli, S. Zampieri, (2014)
A distributed control algorithm for the minimization of the power generation cost in smart micro-grid, *IEEE Conference on Decision and Control (CDC14)*,

[6] G. Cavraro, L. Badia, (2013)
A Game Theory Framework for Active Power Management with Voltage Boundary in Smart Grids, *European Control Conference (ECC13)*,

Research topics and publications

- Real time switches status identification for topology detection

[7] G. Cavraro, R. Arghandeh, G. Barchi, A. Von Meier, (2015)
Distribution network topology detection with time-series measurements, *IEEE PES conference on Innovative Smart Grid Technologies (ISGT 2015)*,

[8] G. Cavraro, R. Arghandeh, K. Poolla, A. Von Meier (2015)
Data-Driven Approach for Distribution Network Topology Detection, *IEEE PES General meeting 2015*,

[9] R. Arghandeh, M. Gahr, A. Von Meier, G. Cavraro, M. Ruh, G. Andersson (2015)
Topology Detection in Microgrids with Micro-Synchrophasors, *IEEE PES General meeting 2015*,

REACTIVE POWER CONTROL FOR VOLTAGE REGULATION AND LOSSES MINIMIZATION (OPTIMAL REACTIVE POWER FLOW PROBLEM)

Solution approaches for the optimal reactive power flow problem

- ADMM approach

[10] P. Sulc, S. Backhaus, and M. Chertkov, (2013)
Optimal distributed control of reactive power via the alternating direction method of multipliers

- convexification tecniques

[11] L. Gan, Na Li, U. Topcu, and S. Low, (2013)
Distributed Algorithms for Optimal Power Flow Problem

[12] A. Lam, B. Zhang, and D. N. Tse, (2012)
Distributed Algorithms for Optimal Power Flow Problem

[13] E. Dall'Anese, H. Zhu, and G. B. Giannakis, (2013)
Distributed optimal power flow for smart microgrids

Solution approaches for the optimal reactive power flow problem

Solutions proposed in the literature:

- they require that all the buses of the grid are monitored;
- they require that all the grid parameters (topology, line impedances etc.) are perfectly known;
- the convergence to a optimal or feasible solution is not always guaranteed (restrictive conditions, i.e. radial networks);
- They are "communication based", open loop algorithm.

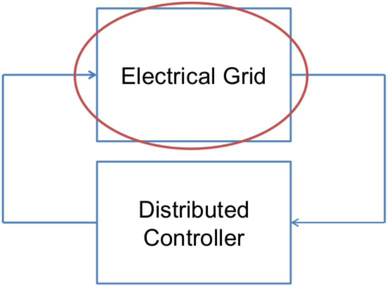
Solution approaches for the optimal reactive power flow problem

Our novel solution approach:

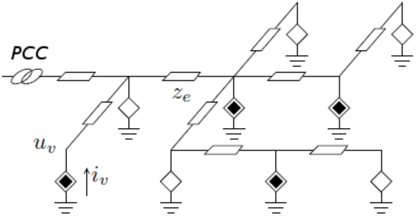
- it is a feedback control algorithm;
- it works also if few buses are monitored;
- it needs just partial knowledge of the grid parameters;
- it exploits local voltage measurements and communication to infer global information.

Grid model

ELECTRICAL GRID MODELING



Grid model



- The PCC as an ideal voltage generator, that imposes U_N;
- generators and loads as constant power devices (PQ Node)
- voltages and currents in a phasorial notation (steady state), $u_v, i_v \in \mathbb{C}$ are the node v voltage and injected current.
- $p_v, q_v \in \mathbb{R}$ are the powers injected (> 0) or absorbed (< 0) by v
- impedances with homogeneus R/X ratio

Grid equation

We introduce the following block partition of the vectors, e.g. for the reactive powers

$$q = \begin{bmatrix} q_1 \\ q_G \\ q_L \end{bmatrix}$$

- G is the Micro-Generators set (set of controlled and monitored nodes)
- L is the Loads set (set of uncontrolled and unmonitored nodes)

The grid state is described by the static system of equations

$$\begin{cases} i = Yu \\ u_1 = U_N \\ u_v i_v^* = p_v + i q_v \qquad v \neq 1 \end{cases}$$

where Y is the bus admittance matrix of the grid. There is a non-linear relation among voltages, currents and powers.

Grid equation approximation

There exists a unique symmetric, positive semidefinite matrix $X \in \mathbb{C}^{n\times n}$ such that, by adopting the same block partitioning as before, it can be written

$$u = \begin{bmatrix} u_1 \\ u_G \\ u_L \end{bmatrix} \longrightarrow X = e^{i\theta} \begin{bmatrix} 0 & 0 & 0 \\ 0 & M & N \\ 0 & N^T & Q \end{bmatrix},$$

The matrix X depends only on the topology of the grid and on the power lines impedance

Grid equation approximation

Proposition

Consider the set of nonlinear equations. Node voltages can be approximated with

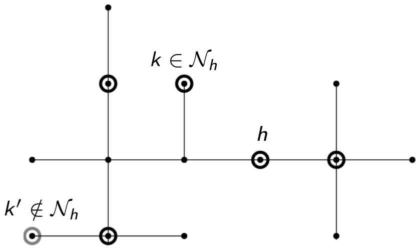
$$\begin{bmatrix} u_0 \\ u_G \\ u_L \end{bmatrix} \simeq \left(U_N \mathbf{1} + \frac{e^{i\theta}}{U_N} \begin{bmatrix} 0 & 0 & 0 \\ 0 & M & N \\ 0 & N^T & Q \end{bmatrix} \begin{bmatrix} * \\ p_G - iq_G \\ p_L - iq_L \end{bmatrix} \right)$$

[1] S. Bolognani and S. Zampieri, (2013)
A distributed control strategy for reactive power compensation in smart microgrids

Agents' Assumption

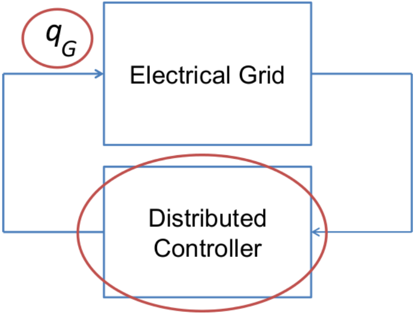
We assume the Microgenerators (Agents) have

- sensing capabilities (voltage PMU)
- computational capabilities
- communication capabilities
- partial knowledge of the topology



Controller Design

CONTROLLER DESIGN



Optimal Reactive Power Flow Problem

We formulate the ORPF Problem as

$$\begin{array}{rll} \min_{q_G,} & \bar{u}^T Y u & \\ s.t. & q_h^m \leq q_h \leq q_h^M, & h \in \mathrm{G} \\ & U_{min} \leq |u_h| \leq U_{max}, & h \in \mathrm{G} \end{array}$$

where

- the objective function models the active power distribution line losses;
- the control variables are the q_G's;
- the first constraint represent the microgenerators limited generation capability;
- the second constraint forced the grid in a feasible operative condition.

Optimal Reactive Power Flow Problem

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where

- the objective function models the active power distribution line losses;
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Dual Ascent like Algorithm

We have been inspired by the classical dual-ascent algorithm. The Lagrangian of the problem

$$\mathcal{L}(q_G, \lambda, \mu) = \bar{u}^T Y u + \lambda^T (U_m^2 - |u_G|^2) + \mu^T (q_G - q_G^M)$$

We solve iteratively the OPRF problem proposing a dual-ascent algorithm

1. Lagrange multipliers update

$$\lambda(t+1) = \max\left\{\lambda(t) + \gamma(U_m^2 - |u_G(t)|^2), 0\right\}$$
$$\mu(t+1) = \max\left\{\mu(t) + \gamma(q_G(t) - q^M), 0\right\}$$

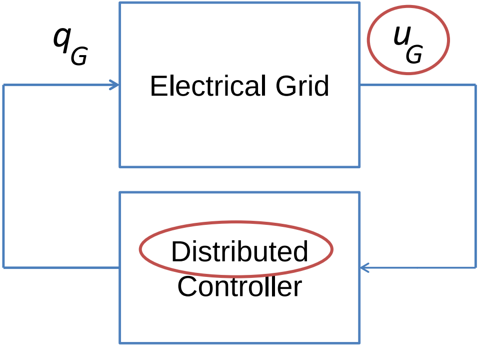
2. computation and actuation of the minimizer

$$q_G(t+1) = \arg\min_{q_G} \mathcal{L}(q_G(t), \lambda(t), \mu(t)),$$

The grid reacts to the reactive power actuation by moving on another state

Controller Distributed Implementation

CONTROLLER DISTRIBUTED IMPLEMENTATION



Controller Distributed Implementation

1. Lagrange multipliers update → trivially distributed

$$\lambda(t+1) = \max\left\{\lambda(t) + \gamma(U_m^2 - |u_G(t)|^2), 0\right\}$$
$$\mu(t+1) = \max\left\{\mu(t) + \gamma(q_G(t) - q^M), 0\right\}$$

2. computation of the minimizer

$$q_G(t+1) = \arg\min_{q_G} \mathcal{L}(q_G(t), \lambda(t), \mu(t)),$$

Controller Distributed Implementation

The minimizer condition

$$\frac{\partial \mathcal{L}(q_G(t+1), \lambda(t), \mu(t))}{\partial q_G} = 0$$

leads to Minimizer closed form

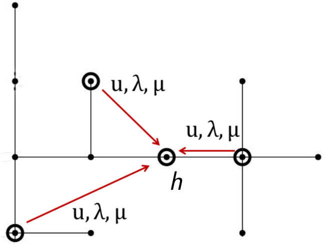
$$q_G(t+1) = -M^{-1} N q_L + \lambda(t) \sin\theta - M^{-1} \mu(t)$$

Minimizer approximation

$$q_h(t+1) \simeq q_h(t) + \sum_{k \in \mathcal{N}_h} M_{hk}^{-1} (|u_h||u_k| \sin(\angle u_k - \angle u_h - \theta) - \mu_k(t)) + \sin\theta \lambda_h(t)$$

Controller Distributed Implementation

At every iteration, node *h* gathers from its neighbors voltage phasorial measurements and Lagrange multipliers λ, μ and then takes part



1. computation and actuation of the minimizer

$$q_h \leftarrow \simeq q_h + \sum_{k \in \mathcal{N}_h} M_{hk}^{-1} \left(|u_h||u_k| \sin(\angle u_k - \angle u_h - \theta) - \mu_k \right) + \sin\theta \lambda_h$$

2. Lagrange multipliers updates

$$\lambda_h \leftarrow \max \left\{ \lambda_h + \gamma(U_m^2 - |u_G|^2), 0 \right\};$$
$$\mu_h \leftarrow \max \left\{ \mu_h + \gamma(q_h - q_h^{max}), 0 \right\}.$$

Convergence Results

Convergence Condition

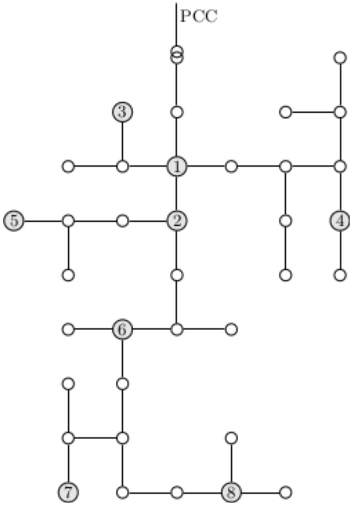
If

$$\gamma \leq \frac{U_N^2}{\rho(\Phi)}, \qquad \Phi = 2\begin{bmatrix} \sin^2\theta M & -\sin\theta I \\ -\sin\theta I & M^{-1} \end{bmatrix}$$

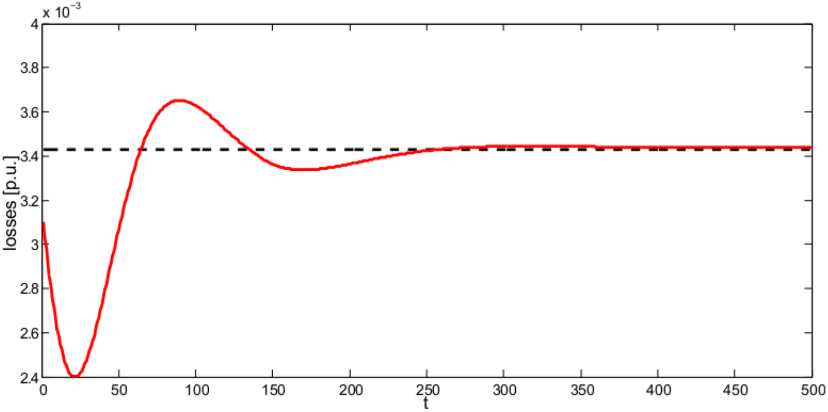
the feedback control strategy is asymptotically stable and the equilibrium is the optimum of the optimization problem.

Simulation testbed

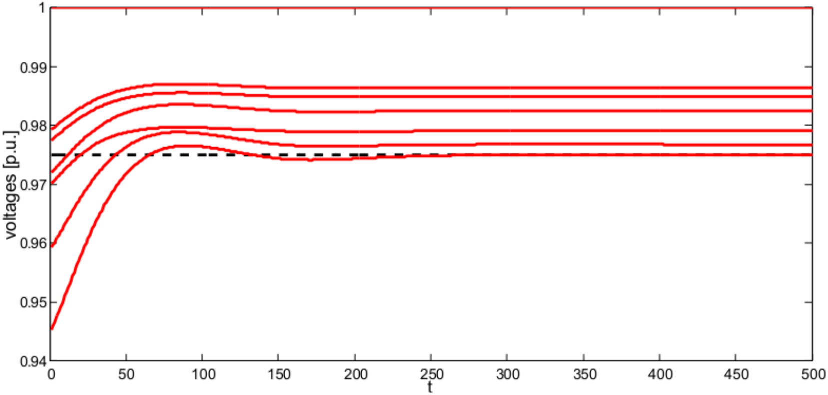
For our simulation we use a 4.8 kV testbed inspired from the standard test feeder IEEE37. Grey nodes are the agents.



Some Simulations



Some Simulations



CONCLUSIONS

Conclusions

- we studied the future distribution grid characteristics
- we studied different distribution grid models
- we studied the main optimization and control algorithm in the literature
- we developed algorithms for the optimal reactive power flow problem
- we developed algorithms for the optimal power flow problem
- we developed algorithms for the switches state monitoring

Thanks!

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