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

Distributed reactive power feedback control for voltage regulation and loss minimization, *IEEE Transactions on Automatic Control*,

A distributed control strategy for optimal reactive power flow with power constraints, *IEEE Conference on Decision and Control (CDC13)*,

A distributed control strategy for optimal reactive power flow with power and voltage constraints, *IEEE SmartGridComm 2013 Symposium*,

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Research topics and publications

- **Active power control**: generation cost minimization

A distributed control algorithm for the minimization of the power generation cost in smart micro-grid, *IEEE Conference on Decision and Control (CDC14)*,

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


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

  Optimal distributed control of reactive power via the alternating direction method of multipliers

- convexification techniques

  Distributed Algorithms for Optimal Power Flow Problem

  Distributed Algorithms for Optimal Power Flow Problem

  Distributed optimal power flow for smart microgrids
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

Electrical Grid

Distributed Controller
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 $\nu$ voltage and injected current.
$p_\nu, q_\nu \in \mathbb{R}$ are the powers injected ($> 0$) or absorbed ($< 0$) by $\nu$
impedances with homogeneous 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

\[
\begin{cases}
i = Yu \\
u_1 = U_N \\
v_i^* v_i = p_v + i q_v \quad \forall \neq 1
\end{cases}
\]

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

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

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

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

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

$q_G$

Electrical Grid

Distributed Controller
Optimal Reactive Power Flow Problem

We formulate the ORPF Problem as

$$\min_{q_G}, \quad \bar{u}^T Y u$$

$$s.t. \quad q^m_h \leq q_h \leq q^M_h, \quad h \in G$$

$$U_{min} \leq |u_h| \leq U_{max}, \quad h \in G$$

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

We formulate the ORPF Problem as

$$\min_{q_G}, \quad \bar{u}^T Yu$$

$$s.t. \quad q_h \leq q_h^M, \quad h \in G$$

$$|u_h| \geq U_m, \quad h \in G$$

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.
Dual Ascent like Algorithm

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

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

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

q_G

Electrical Grid

u_G

Distributed Controller
Lagrange multipliers update → trivially distributed

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

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

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

leads to Minimizer closed form

\[
q_G(t+1) = -M^{-1}Nq_L + \lambda(t)\sin \theta - M^{-1}\mu(t)
\]

Minimizer approximation

\[
q_h(t+1) \approx q_h(t) + \sum_{k \in \mathcal{N}_h} M_{hk}^{-1}(|u_h||u_k|\sin(\angle u_k - \angle u_h - \theta) - \mu_k(t)) + \sin \theta \lambda_h(t)
\]
At every iteration, node $h$ gathers from its neighbors voltage phasorial measurements and Lagrange multipliers $\lambda, \mu$ and then takes part in computation and actuation of the minimizer

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

2. Lagrange multipliers updates

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

Convergence Condition

If

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

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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