Automating AC Power Flow Simulations

The European Electricity Grid

Shravan Chipli

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Motivation

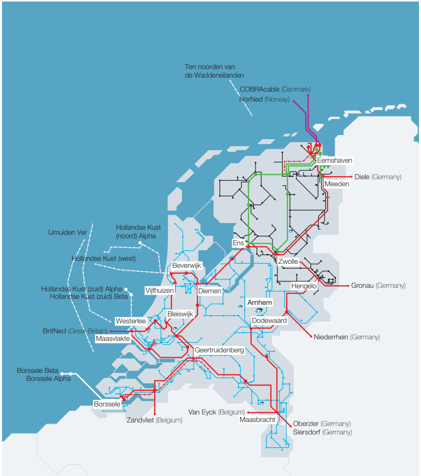
Motivation

1. Automating AC power flow simulations

   Reactive power compensation assessment

2. AC vs DC comparison

   Capacity planning



Contents

The power flow problem

Power flow problem

Given:

- **Power** injections

Determine:

- **Voltage** at every bus
- **Current** in every line

Power flow problem

Given:

- Power injections

Determine:

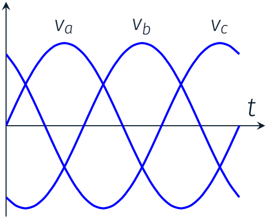
- Voltage at every bus
- Current in every line

Essentials:

- *AC circuit fundamentals*
- *Network topology*

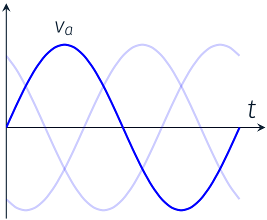
AC circuits

- Three phase **AC**
- Steady state: **50 Hz**



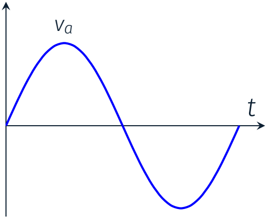
AC circuits

- Three phase **AC**
- Steady state: **50 Hz**

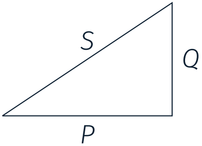


AC circuits

- *Single* phase
- Steady state: **50 Hz**



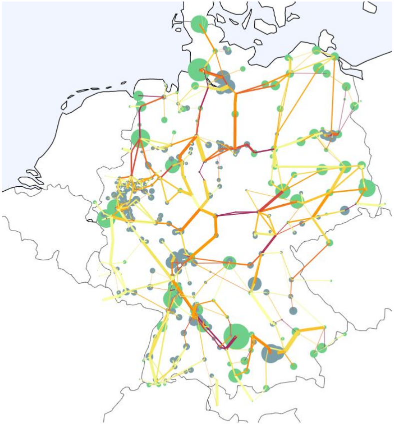
- Complex power **S**



Network topology

Nodes and edges

Buses and **lines**



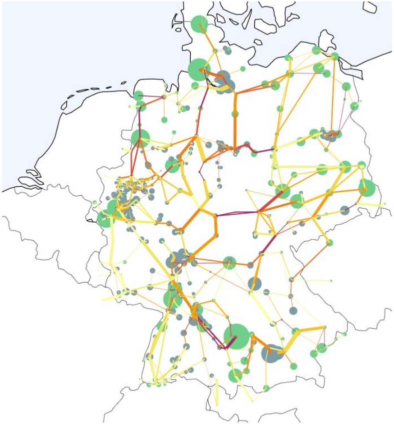
Network topology

Nodes and edges

Buses and **lines**

Buses: P, Q, V, δ

Lines: $\mathbf{Y}$



Network topology

Table 1: Bus types and variables

Bus type	Number of buses	Known	Unknown
Slack bus	1	δ, $\lvert V \rvert$	P, Q
PV bus	N_g	P, $\lvert V \rvert$	δ, Q
PQ bus	$N - N_g - 1$	P, Q	δ, $\lvert V \rvert$

Power flow equations

$$P_i = \sum_{k=1}^{N} |V_i||V_k| \left(G_{ik} \cos \delta_{ik} + B_{ik} \sin \delta_{ik} \right)$$

$$Q_i = \sum_{k=1}^{N} |V_i||V_k| \left(G_{ik} \sin \delta_{ik} - B_{ik} \cos \delta_{ik} \right)$$

Power flow equations

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Non-linear

Power flow equations

Root finding problem

$$\Delta P_i = P_i^{sp} - \sum_{k=1}^{N} |V_i||V_k| \left(G_{ik} \cos \delta_{ik} + B_{ik} \sin \delta_{ik} \right)$$

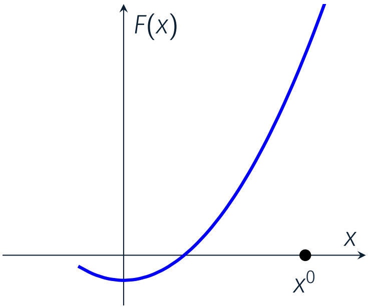
$$\Delta Q_i = Q_i^{sp} - \sum_{k=1}^{N} |V_i||V_k| \left(G_{ik} \sin \delta_{ik} - B_{ik} \cos \delta_{ik} \right)$$

Non-linear

Power flow solvers

Newton-Raphson

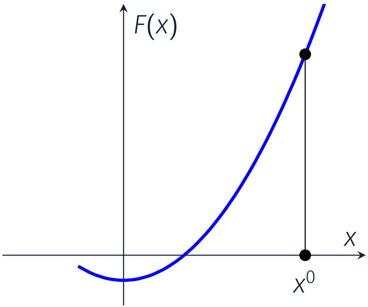
$F(x) = 0$



Newton-Raphson

$$F(x) = 0$$

$$F(x + \Delta x) = 0$$

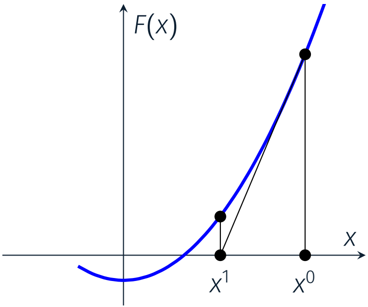


Newton-Raphson

$$F(x) = 0$$

$$F(x + \Delta x) = 0$$

$$-J(x)\Delta x = F(x)$$



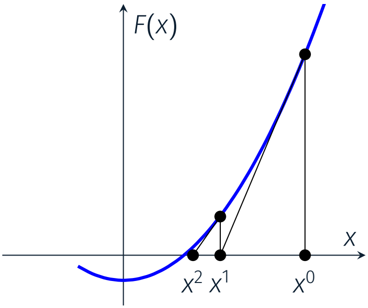
Newton-Raphson

$$F(x) = 0$$

$$F(x + \Delta x) = 0$$

$$-J(x)\Delta x = F(x)$$

$$x^{k+1} = x^k + \Delta x^k$$



Algorithm 1: Newton-Raphson Method

$k := 0$

Initialize: x^0

while *not converged* **do**

  Solve for the correction: $-J(x^k)\Delta x^k = F(x^k)$

  Update the approximation: $x^{k+1} = x^k + \Delta x^k$

  $k = k + 1$

end

Fundamental Newton power flow methods

- Power-mismatch and Current-mismatch formulations of $F(x)$
- Polar, Cartesian and Complex forms of x

Newton-Raphson

Fundamental Newton power flow methods

- Power-mismatch and Current-mismatch formulations of $F(x)$
- Polar, Cartesian and Complex forms of x

- Polar power-mismatch
- Cartesian power-mismatch
- Complex power-mismatch
- Polar current-mismatch
- Cartesian current-mismatch
- Complex current-mismatch

Newton-Raphson

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On a comparison of Newton–Raphson solvers for power flow problems

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ABSTRACT

A general framework is given for applying the Newton–Raphson method to solve power flow problems, using power and current-mismatch functions in polar, Cartesian coordinates and complex form. These two mismatch functions and three coordinates, result in six possible ways to apply the Newton–Raphson method for the solution of power flow problems. We present a theoretical framework to analyze these variants for load (PQ) buses and generator (PV) buses. Furthermore, we compare newly developed versions in this paper with existing variants of the Newton power flow method. The convergence behavior of all methods is investigated by numerical experiments on transmission and distribution networks. We conclude that variants using the polar current-mismatch and Cartesian current-mismatch functions that are developed in this paper, performed the best result for both distribution and transmission networks.

Newton-Raphson

$$-J(x^k)\Delta x^k = F(x^k)$$

- Polar power-mismatch:

$$-\left[\begin{array}{c|c} J^{11} & J^{12} \\ \hline J^{21} & J^{22} \end{array}\right]\left[\begin{array}{c} \Delta\delta \\ \Delta|V| \end{array}\right] = \left[\begin{array}{c} \Delta P \\ \Delta Q \end{array}\right]$$

- Polar current-mismatch:

$$-\left[\begin{array}{c|c} J^{11} & J^{12} \\ \hline J^{21} & J^{22} \end{array}\right]\left[\begin{array}{c} \Delta\delta \\ \Delta|V| \end{array}\right] = \left[\begin{array}{c} \Delta I^r \\ \Delta I^m \end{array}\right]$$

- Cartesian current-mismatch:

$$-\left[\begin{array}{c|c} J^{11} & J^{12} \\ \hline J^{21} & J^{22} \end{array}\right]\left[\begin{array}{c} \Delta V^m \\ \Delta V^r \end{array}\right] = \left[\begin{array}{c} \Delta I^r \\ \Delta I^m \end{array}\right]$$

Fast Decoupled Load Flow (FDLF)

$$-\left[\begin{array}{c|c} J^{11} & J^{12} \\ \hline J^{21} & J^{22} \end{array}\right]\left[\begin{array}{c} \Delta\delta \\ \Delta|V| \end{array}\right] = \left[\begin{array}{c} \Delta P \\ \Delta Q \end{array}\right]$$

Assumptions:

- $\cos\delta_{ik} \approx 1; \quad \sin\delta_{ik} \approx \delta_{ik}$
- $G_{ik}\sin\delta_{ik} \ll B_{ik}$
- $Q_i \ll B_{ii}|V_i|^2$

Decoupled system:

$$-\left[\, B \,\right]\left[\, \Delta\delta \,\right] = \left[\, \Delta\widetilde{P} \,\right]$$

$$-\left[\, B \,\right]\left[\, \Delta|V| \,\right] = \left[\, \Delta\widetilde{Q} \,\right]$$

DC approximation

Assumptions:

- The reactive power balance equations are ignored
- Voltage magnitudes are set to 1 pu
- Line losses are ignored

Linearized system:

$$[B]\,[\delta] = [P]$$

Summary

1. Newton-Raphson
2. FDLF
3. DC approximation
4. Gauss-Seidel

Power Flow Convergence

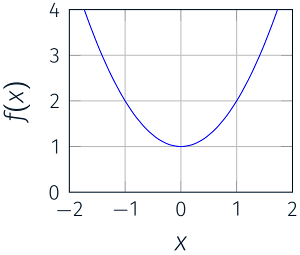
Power flow convergence

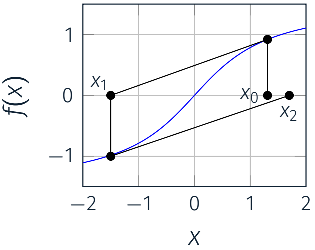
Well-posedness:

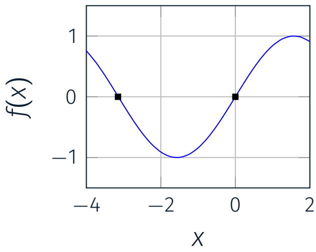
1. Existence: There exists at least one solution.
2. Uniqueness: There is at most one solution.
3. Stability: The solution depends continuously on input data.

Power flow convergence

Ill-posed problems:







Power flow convergence

Optimal Multiplier Method:

$$x^{k+1} = x^k + \mu \Delta x^k$$

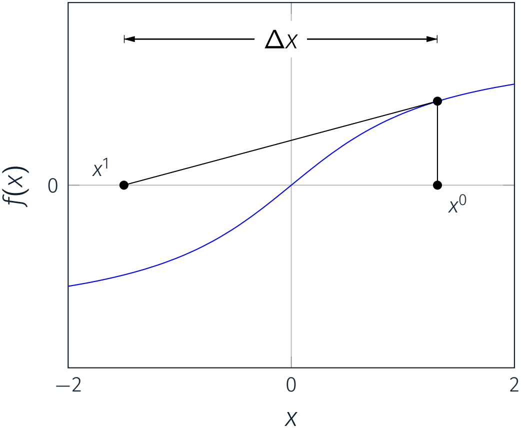
$$C(x) = \frac{1}{2} F(x)^T F(x)$$

$$\frac{dC}{d\mu} = 0$$

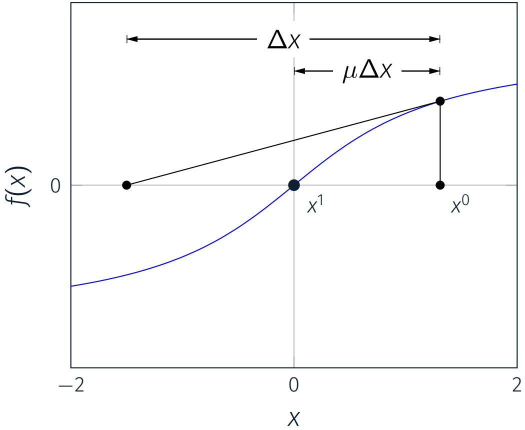
Linesearch:

$$\min_{\mu \in [0,1]} C(x^k + \mu \Delta x^k)$$

Power flow convergence



Power flow convergence



AC vs DC approach

Usefulness of DC Power Flow for Active Power Flow Analysis

Konrad Purchala, *Student Member, IEEE*, Leonardo Meeus, Daniel Van Dommelen, *Senior Member, IEEE* and Ronnie Belmans, *Fellow, IEEE*

Abstract **— In recent days almost every study concerning the analyses of power systems for market related purposes uses DC power flow. DC power flow is a simplification of a full power flow looking only at active power flows. Aspects as voltage support and reactive power management are not considered. However, such simplifications cannot always be justified and might sometimes be unrealistic. In this paper authors analyze the assumptions of DC power flow, and make an attempt at quantifying these using indexes. Among other, the paper answers the question of how low the X/R ratio of line parameters can be, and what is the maximal deviation from the perfect flat voltage which still allows DC power flow to be acceptably accurate.**

Index Terms **— power systems, power system analysis, power flow, DC power flow.**

I. Introduction

STATIC power system analysis has always been performed using full power flow. It is one of the fundamental tools for power system analysis and is used in the operational as well as planning stages. Vertically integrated companies have used it to control their systems, as very similar to fast decoupled method [3],[4]. It is a simplification of a full AC power flow and looks only at active power flows, neglecting voltage support, reactive power management and transmission losses. Thanks to its simplicity, and even more to the fact that DC power flow problem is linear, it is very often used for techno-economic studies of power systems for assessing the influence of commercial energy exchanges on active power flows in the transmission network [11],[6]. The method as such is well-known and its fundamentals have been discussed in many research papers [7],[8].

DC power flow can be applied if a number of assumptions are satisfied. However, it is not always evident how these assumptions should be understood. Take the one stating that line resistances have to be negligible. As it is obvious that the line resistances will not be infinitely small, there is somewhere a border value for X/R ratio that guarantees a given accuracy. However, where this border can be put is still an open question. Moreover, the sensitivity of the DC power flow solution to these assumptions has not been addressed. It seems that this method is often taken for granted

AC vs DC approach

Test case: Belgian HV grid - 700 buses, 900 lines, 13 GW winter peak

1. Small voltage angles: $\cos\delta_{ik} \approx 1$ and $\sin\delta_{ik} \approx \delta_{ik}$
    - $\delta < 7°$
    - In 94% of the lines: $\delta < 2°$
2. Negligible line resistance: $R \ll X$
    - $X/R > 4$
3. Flat voltage profile: All voltage magnitudes are set to 1 pu.
    - Biggest source of error
    - Standard deviation < 0.01

Software Packages

Software Packages

1. PowerFactory
   - NR power mismatch
   - NR current mismatch
   - DC approximation
2. PSSE
   - Gauss-Seidel
   - Newton-Raphson
   - Decoupled Newton-Raphson
   - DC approximation
3. pandapower
   - Newton-Raphson
   - Newton-Raphson with Iwamoto multiplier
   - Gauss-Seidel
   - FDLF
   - DC approximation

Conclusion

Conclusion

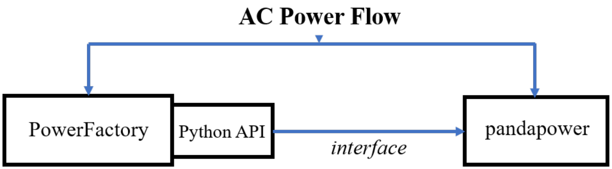
1. The power flow problem: Non-linear!
2. Power flow solver: Newton-Raphson
3. Power flow convergence: Optimal multiplier method
4. AC vs DC approach: $X/R > 4$
5. Model automation: subroutine in MATPOWER
6. Software packages: PowerFactory $\leftrightarrow$ pandapower

Research Questions

Research questions

1. Automating AC power flow simulations
   - Understanding convergence issues
   - Solving the EU grid model
   - Automating simulations: convergence and voltage regulation
2. AC vs DC approach
   - Cost analysis

Roadmap


AC Power Flow
PowerFactory
Python API
interface
pandapower

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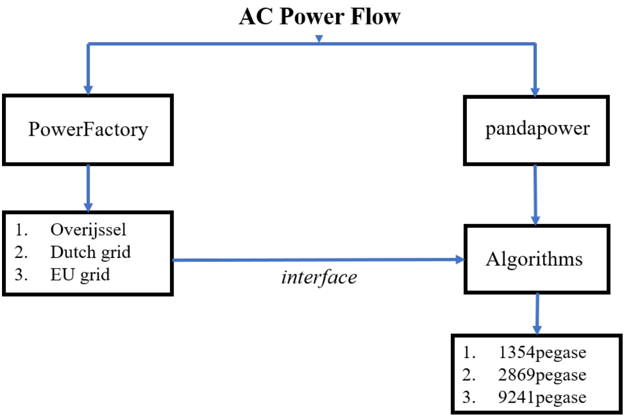
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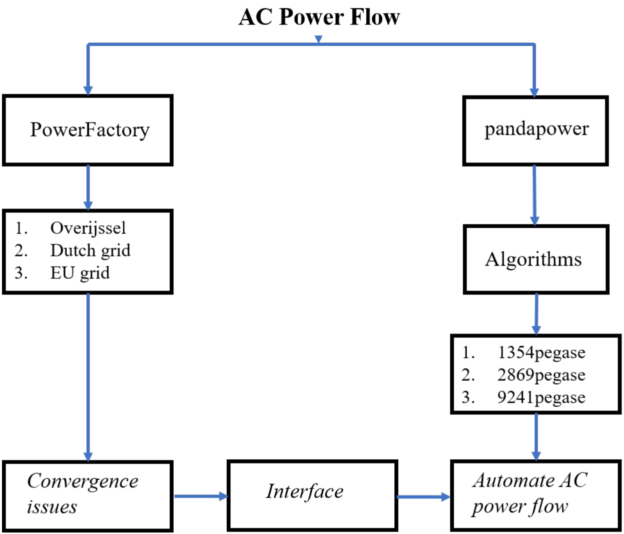

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Thank you

Questions?