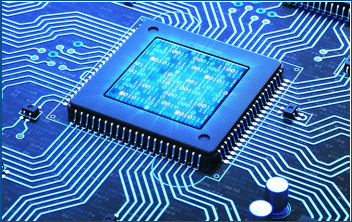
Norwegian University of Science and Technology

INTEGRATION OF ELECTRIC VEHICLES INTO POWER DISTRIBUTION SYSTEMS

Using High-Performance Multi-Period AC Optimal Power Flow Solver

Salman Zaferanlouei
28-10/2020



Outline

Background - EV- before

Figure: [economictimes.indiatimes.com]

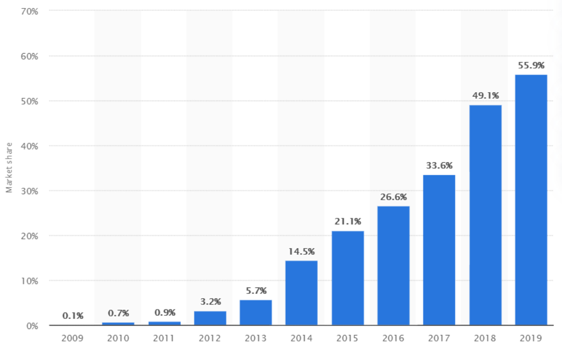
Background - EV- Now 379-mile range 610 km

Figure: [www.carmagazine.co.uk]

Background - Statistics

Market Share

Market share of electric cars (BEV and PHEV) in Norway from 2009 to 2019



Background - Statistics

Penetration

Around 9% EV penetration in Norwegian transport sector. The Norwegian Parliament has decided on a national goal that all new cars sold by 2025 should be zero-emission (electric or hydrogen)[a].

[a] https://elbil.no/

Background - Is there any challenge?

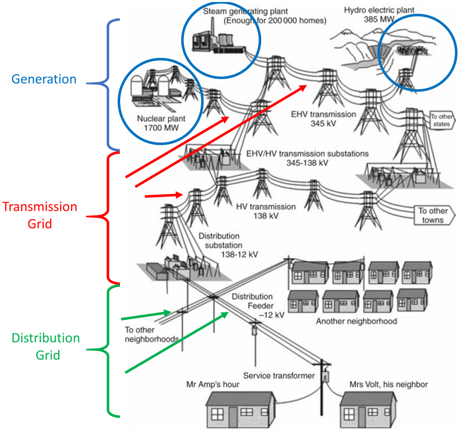


Figure: Source[1]

[1] https://www.sciencedirect.com/science/article/pii/B9781845697846500019

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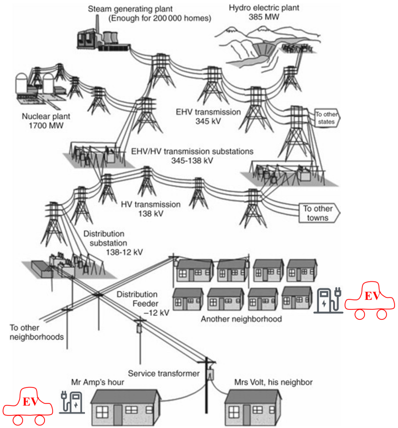

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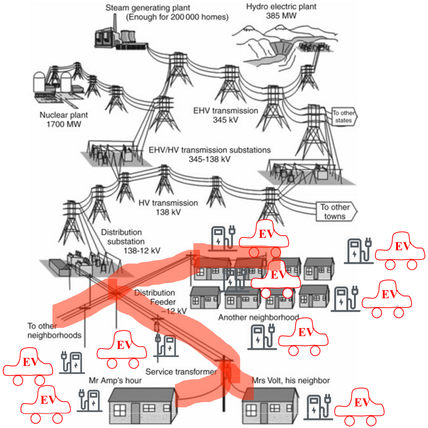

Background - Challenge

Distribution Grid will be under heavy stress in a near future!

Scenario	Number of EV per household	Charging Power (kW)	Simultaneous charge	Additional power per house in max load (kW)
1	0.5	5.1	30%	1
2	0.75	6.0	50%	2
3	1	7.1	70%	5

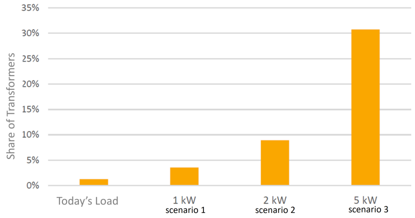

Figure: The Norwegian Water Resources and Energy Directorate (NVE) Report [Skotland, C. et al, "Hva betyr elbiler for strømnettet." (2016)]

Background - Dumb (Uncoordinated) VS Smart (Coordinated) Charging

I. Dumb Charging

- **I.a** Anytime connects, it gets charged
- **I.b** No control on maximum power capacity usage

II. Smart Charging

- **II.a** From user perspective:
  - ➢ Sensitive to price?

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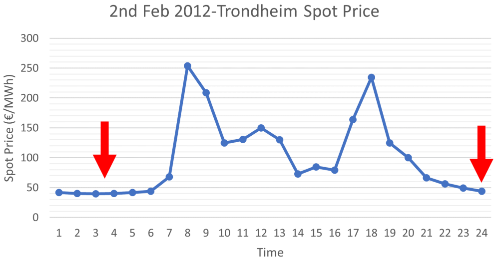

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> Cost of Investments?
> Cost of Operations?
> Socio-Economic Cost?

Background - Motivation

1. Sustainability: Need tools for analysing operating conditions resulting from renewables, EV, storage and flexible demand.
2. Economics: Norway electric industry revenues of 61.6 billion NOK in 2018[1]. 1% savings worth 615 million NOK (estimated using [??] and [2])
3. Reliability: Annual cost of power interruptions to Norway economy is 1600 MNOK/year (estimated using [3] and [4])

[1] https://www.nve.no/energy-market-and-regulation/retail-market/electricity-disclosure-2018/

[2] https://www.nordpoolgroup.com/Market-data1/Dayahead/Volumes/NO/Hourly/?view=table

[3] http://publikasjoner.nve.no/rapport/2018/rapport2018_74.pdf

[4] Samdal, K., Kjolle, G. H., Singh, B., & Kvitastein, O. (2006, June). Interruption costs and consumer valuation of reliability of service in a liberalised power market. In 2006 International Conference on Probabilistic Methods Applied to Power Systems (pp. 1-7). IEEE.

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Background - Research Questions

RQ 1. With only “passive charging”, the deployment of EVs will be limited by grid constraints. Can “smart-charging” overcome this problem?

RQ 2. How many additional EVs can be served by fast-charging points with a “smart-charging” regime compared to “passive charging”?

- **C 1.** Without any reinforcements of the grid.
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RQ 3. How much grid reinforcements is needed with smart vs passive-charging to fulfill increasing targets for an EV fleet as a replacement for gasoline and diesel cars?

RQ 4. Could integration of PV mitigate the impact of increasing EV penetration on the distribution grid?

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Task 1. Develop a smart-charging algorithm/scheme with the objective to compare and analyse how many additional EVs can be served by a smart-charging method.

Task 2. Develop a simulator for the combined power-and-transport system.

Task 3. Simulate the combined system with an increasing number of charging points (and cars), and measure the “saturation point” with respect to the requirements in ??.

Task 4. Develop a power flow solver that takes into account the operational grid constraints, grid losses and also local generations.

Task 5. Investigate the impact of growing penetration of EVs and PVs together in the distribution grid.

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Publications - Relevant to Thesis

Under Review

I. S. Zaferanlouei, H. Farahmand, V. Vadlamudi, and M. Korpås, “BATTPOWER Toolbox: Memory Efficient and High-Performance MultiPeriod AC Optimal Power Flow Solver—Part I: Mathematical Concepts,” submitted for review, IEEE transaction on Power Systems, 2020.

II. S. Zaferanlouei, H. Farahmand, V. Vadlamudi, and M. Korpås, “BATTPOWER Toolbox: Memory Efficient and High-Performance MultiPeriod AC Optimal Power Flow Solver—Part II: Case Study,” submitted for review, IEEE transaction on Power Systems, 2020.

III. S. Zaferanlouei, V. Lakshmanan, S. Bjarghov, H. Farahmand and M. Korpås, “BATTPOWER Application: Large Scale Integration of EVs in a Local Distribution Grid—Norwegian Case Study,” submitted for review, Electric Power Systems Research, 2020.

Publised

IV. S. Zaferanlouei, M. Korpås, J. Aghaei, H. Farahmand and N. Hashemipour, “Computational Efficiency Assessment of Multi-Period AC Optimal Power Flow including Energy Storage Systems,” in 2018 International Conference on Smart Energy Systems and Technologies (SEST), Sep. 2018, pp. 1– 6. DOI: 10.1109/SEST.2018.8495683.

V. S. Zaferanlouei, M. Korpås, H. Farahmand and V. V. Vadlamudi, “Integration of PEV and PV in Norway Using Multi-Period ACOPF—Case study,” in 2017 IEEE Manchester PowerTech, ISSN: null, Jun. 2017, pp. 1–6. DOI: 10.1109/PTC.2017.7981042.

VI. S. Zaferanlouei, I. Ranaweera, M. Korpås and H. Farahmand, “Optimal Scheduling of Plug-in Electric Vehicles in Distribution Systems Including PV, Wind and Hydropower Generation, eng. Energynautics GMBH, 2016,” ISBN: 978-3-9816549-3-6.

VII. S. Flinstad Harbo, S. Zaferanlouei and M. Korpås, “Agent Based Modelling and Simulation of Plug-In Electric Vehicles Adoption in Norway,” in 2018 Power Systems Computation Conference (PSCC), Jun. 2018, pp. 1– 7. DOI: 10.23919/PSCC.2018.8442514.

VIII. M. Lillebo, S. Zaferanlouei, A. Zecchino and H. Farahmand, “Impact of large-scale EV integration and fast chargers in a Norwegian LV grid,” The Journal of Engineering, vol. 2019, no. 18, pp. 5104–5108, 2019, ISSN: 2051-3305. DOI: 10.1049/joe.2018.9318.

IX. S. Bjarghov, M. Korpås and S. Zaferanlouei, “Value comparison of EV and house batteries at end-user level under different grid tariffs,” in 2018 IEEE International Energy Conference (ENERGYCON), Jun. 2018, pp. 1–6. DOI: 10.1109/ENERGYCON.2018.8398742.

Publications - Other Publications

under review

I. G. Sæther, P. Crespo del Granadob, S. Zaferanlouei, “Peer-to-Peer electricity trading in an Industrial site:Value of buildings flexibility on peak load reduction,” Submitted on Energy and Buildings, Elsevier 2020.

Published

II. F. Berglund, S. Zaferanlouei, M. Korpås and K. Uhlen, (2019). “Optimal Operation of Battery Storage for a Subscribed Capacity-Based Power Tariff Prosumer—A Norwegian Case Study,” Energies, 12(23), 4450.

Power Flow - Power Flow Equations

Source of Non-linearity

Nonlinear relationship between the voltage phasors and the power injections

Node i

$S_i = P_i + jQ_i$
$= V_i.\bar{I}_i$

Power Line with conductance G and susceptance B

$Y = G + jB \ and \ G = \frac{R}{R^2 + X^2}, B = \frac{-X}{R^2 + X^2}$

Where R and X are resistance and reactance respectively

Node j

$S_j = P_j + jQ_j$
$= V_j.\bar{I}_j$

$$
\begin{aligned}
P_i + jQ_i &= V_i.\bar{I}_i \\
&= V_i.(\bar{Y}_i.\bar{V}) \\
&= V_i.(G_i - jB_i)\bar{V} \\
|V_i|^2 &= V_i.\bar{V}_i
\end{aligned}
$$

"Power Flow Equations"
"Load Flow Equations"

Y admittance matrix

G and B conductance and susceptance matrices

$Y = G + jB$

> Coupled quadratics in complex voltage phasors

Power Flow - Power Flow Equations in Different Coordinates

The bus injection model

Power Line with conductance G and susceptance B

Node i

$S_i = P_i + jQ_i = V_i . \bar{I}_i$

Node j

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Polar Voltage Coordinates	$V_i = \|V_i\|\angle\theta_i \quad \theta_1 = 0$

$$P_i = |V_i| \sum_{j=1}^{N} |V_j| (\boldsymbol{G}_{ij} cos(\theta i - \theta j) + \boldsymbol{B}_{ij} sin(\theta i - \theta j))$$

$$Q_i = |V_i| \sum_{j=1}^{N} |V_j| (\boldsymbol{G}_{ij} sin(\theta i - \theta j) - \boldsymbol{B}_{ij} cos(\theta i - \theta j))$$

Rectangular Voltage Coordinates	$V_i = V_{di} + jV_{qi} \quad V_{q1} = 0$

$$P_i = V_{di}(\boldsymbol{G}_{ij} V_{dj} - \boldsymbol{B}_{ij} V_{qj}) + V_{qi}(\boldsymbol{B}_{ij} V_{dj} + \boldsymbol{G}_{ij} V_{qj})$$

$$Q_i = -V_{di}(\boldsymbol{B}_{ij} V_{dj} + \boldsymbol{G}_{ij} V_{qj}) + V_{qi}(\boldsymbol{G}_{ij} V_{dj} - \boldsymbol{B}_{ij} V_{qj})$$

$V_{di} = Re(V_i) \quad V_{qi} = Im(V_i) \qquad N = \text{number of Nodes}$

Power Flow

PF equations are a set of nonlinear algebraic equations which can be solved with Newton-Raphson, Gauss–Seidel, Fast-decoupled-load-flow method and etc.

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Power Flow - Single period ACOPF - problem formulation

Single Period AC Optimal Power Flow (ACOPF)

We are controlling some variables in OPF to minimise system costs with respect to constraints.

Objective Function	$\min_{\mathrm{x}} f(\mathrm{x})$	
Equality Constraints (Balance) Power Flow	$\text{s.t.}\ \ \mathrm{g}(\mathrm{x}) = \begin{bmatrix} \widetilde{\mathrm{g}}(\mathrm{x}) \\ \overline{\mathrm{g}}(\mathrm{x}) \end{bmatrix} = 0$	$\in \mathbb{R}^{n_{gx} \times 1}$
Inequality constraints (line and transformer) Operational Constraints	$\mathrm{h}(\mathrm{x}) = \begin{bmatrix} \widetilde{\mathrm{h}}(\mathrm{x}) \\ \overline{\mathrm{h}}(\mathrm{x}) \end{bmatrix} \leq 0$	$\in \mathbb{R}^{n_{hx} \times 1}$
Vector of Variables	$\mathrm{x} = \begin{bmatrix} \boldsymbol{\Theta} & \boldsymbol{\mathcal{V}} & \boldsymbol{\mathcal{P}}^{\mathrm{g}} & \boldsymbol{\mathcal{Q}}^{\mathrm{g}} \end{bmatrix}^{\top}$	$\in \mathbb{R}^{n_x \times 1}$

Limitation of Power Flow

- PF is only a set of static equations which provides status of a system for time: $t = t_s$
- It does not include generation constraints and operational constraints

Limitation of Single Period AC Optimal Power Flow

- OPF is an optimisation problem which optimises status of a system for a SINGLE time: $t = t_s$.
- Although it includes the operational constraints for single time, it will not include operation of DERs and generators over a time horizon.
- It is not capable of integrating storage devices and EVs.

Our suggested approach: multi-period ACOPF

Solves the OPF problem over several time-steps at once useful formulation for systems with Energy Storage and Shiftable Loads (e.g. Evs)

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> Integrating dependent time power system's components such as stationary ESS, EV, generators ramp rate, and so on.

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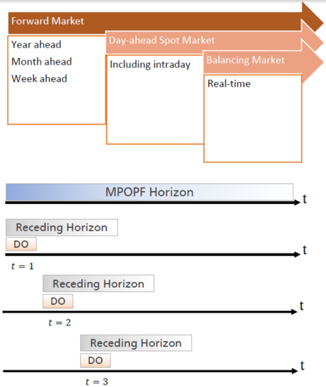

Advantages of MultiPeriod ACOPF

> Integrating dependent time power system's components such as stationary ESS, EV, generators ramp rate, and so on.
> between 2% to 5% less costly solutions.

Disadvantage of MultiPeriod ACOPF

The problem grows very large as the number of time-steps is increased, which may lead to an intractable solution.

Power Flow - MultiPeriod ACOPF-problem formulation

Objective Function	$\min_{\mathsf{X}} F(\mathsf{X})$
Equality Constraints (Balance) Power Flow	s.t. $G(\mathsf{X}) = \begin{bmatrix} \widetilde{G}(\mathsf{X}) & \overline{G}(\mathsf{X}) & \overline{G}^s(\mathsf{X}) \end{bmatrix}^\top = 0 \in \mathbb{R}^{N_g \times 1}$
Inequality constraints (line and transformer) Operational Constraints	$H(\mathsf{X}) = \begin{bmatrix} \widetilde{H}(\mathsf{X}) & \overline{H}(\mathsf{X}) \end{bmatrix}^\top \leq 0 \in \mathbb{R}^{N_h \times 1}$
Vectors of Constraints	$\widetilde{\mathsf{G}}(\mathsf{X}) = \begin{bmatrix} \widetilde{\mathsf{g}}(\mathsf{x}_1) & \widetilde{\mathsf{g}}(\mathsf{x}_2) & \dots & \widetilde{\mathsf{g}}(\mathsf{x}_T) \end{bmatrix}^\top$ $\overline{\mathsf{G}}(\mathsf{X}) = \begin{bmatrix} \overline{\mathsf{g}}(\mathsf{x}_1) & \overline{\mathsf{g}}(\mathsf{x}_2) & \dots & \overline{\mathsf{g}}(\mathsf{x}_T) \end{bmatrix}^\top$ $\overline{\mathsf{G}}^s(\mathsf{X}) = \begin{bmatrix} \overline{\mathsf{g}}^s(\boldsymbol{\tau}_1) & \overline{\mathsf{g}}^s(\boldsymbol{\tau}_2) & \dots & \overline{\mathsf{g}}^s(\boldsymbol{\tau}_T) \end{bmatrix}^\top$ $\widetilde{\mathsf{H}}(\mathsf{X}) = \begin{bmatrix} \widetilde{\mathsf{h}}(\mathsf{x}_1) & \widetilde{\mathsf{h}}(\mathsf{x}_2) & \dots & \widetilde{\mathsf{h}}(\mathsf{x}_T) \end{bmatrix}^\top$ $\overline{\mathsf{H}}(\mathsf{X}) = \begin{bmatrix} \overline{\mathsf{h}}(\mathsf{x}_1) & \overline{\mathsf{h}}(\mathsf{x}_2) & \dots & \overline{\mathsf{h}}(\mathsf{x}_T) \end{bmatrix}^\top$

Solution Method - Nonlinear Programming (NLP)

How do we solve Optimal Power Flow?

I. Interior Point Method
II. Gradient Decent Method
III. Heuristic Methods

Interior Point Method

The focus of this study is the interior point method solution

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Step(1): Applying Slack variables and the barrier term:

$$\min_X \left[F(X) - \gamma \sum_{i=1}^{N_h} ln(z_i) \right]$$

$$\text{s.t.} \ \ G(X) = 0$$

$$H(X) + Z = 0$$

$$Z \geq 0$$

slack variables "Z" convert inequality constraints to equality constraints.

Step (2): Calculate and form the Lagrangian of Barrier subproblem

$$\mathcal{L}^{\gamma}(X, Z, \boldsymbol{\lambda}, \boldsymbol{\mu}) = f(X) + \boldsymbol{\lambda}^{\top} G(X) + \boldsymbol{\mu}^{\top}(H(X) + Z) - \gamma \sum_{i=1}^{N_g} ln(z_i)$$

Step (3): Calculate the KKT[5] of the Lagrangian

Step (3) KKT_X	$\mathcal{L}^{\gamma}_{X}(X, Z, \boldsymbol{\lambda}, \boldsymbol{\mu}) = f_X + \boldsymbol{\lambda}^{\top} G_X + \boldsymbol{\mu}^{\top} H_X = 0$
Step (3) KKT_Z	$\mathcal{L}^{\gamma}_{Z}(X, Z, \boldsymbol{\lambda}, \boldsymbol{\mu}) = \boldsymbol{\mu}^{\top} - \gamma e^{\top} \mathrm{diag}(Z)^{-1} = 0$
Step (3) KKT_λ	$\mathcal{L}^{\gamma}_{\boldsymbol{\lambda}}(X, Z, \boldsymbol{\lambda}, \boldsymbol{\mu}) = G^{\top}(X) = 0$
Step (3) KKT_μ	$\mathcal{L}^{\gamma}_{\boldsymbol{\mu}}(X, Z, \boldsymbol{\lambda}, \boldsymbol{\mu}) = H^{\top}(X) + Z^{\top} = 0$

[5] Karush–Kuhn–Tucker conditions

Nonlinear Algebraic Equations $\quad \boldsymbol{\Omega}(X, Z, \boldsymbol{\lambda}, \boldsymbol{\mu}) = \begin{bmatrix} f_X + \boldsymbol{\lambda}^\top G_X + \boldsymbol{\mu}^\top H_X \\ \mathrm{diag}(Z)\boldsymbol{\mu}^\top - \gamma e^\top \\ G^\top(X) \\ H^\top(X) + Z^\top \end{bmatrix} = 0$

S.t. $\quad Z > 0$

$\boldsymbol{\mu} > 0$

Step (4): Apply Newton Raphson Method

$$[\boldsymbol{\Omega}_X \ \boldsymbol{\Omega}_Z \ \boldsymbol{\Omega}_\lambda \ \boldsymbol{\Omega}_\mu]^k [\Delta X \ \Delta Z \ \Delta\boldsymbol{\lambda} \ \Delta\boldsymbol{\mu}]^{\top k} = -\boldsymbol{\Omega}(X, Z, \boldsymbol{\lambda}, \boldsymbol{\mu})^k$$

Step (5):
Inverse Jacobian
of Newton Raphson

$$\begin{bmatrix} M & G_X^\top \\ G_X & 0 \end{bmatrix}^k \begin{bmatrix} \Delta X \\ \Delta \boldsymbol{\lambda} \end{bmatrix}^k = \begin{bmatrix} -N \\ -G(X) \end{bmatrix}^k$$

$M \in \mathbb{R}^{N_x \times N_x}$ and $N \in \mathbb{R}^{N_x \times 1}$ are defined as:

$$M = \mathcal{L}_{XX}^{\gamma} + H_X^\top \mathrm{diag}(Z)^{-1} \mathrm{diag}(\boldsymbol{\mu}) H_X$$
$$N = f_X^\top + G_X^\top \boldsymbol{\lambda} + H_X^\top \boldsymbol{\mu} + H_X^\top \mathrm{diag}(Z)^{-1} (\gamma e + \mathrm{diag}(\boldsymbol{\mu}) H(X))$$
$$\mathcal{L}_{XX}^{\gamma} = f_{XX} + G_{XX}(\boldsymbol{\lambda}) + H_{XX}(\boldsymbol{\mu})$$

Solution Method - Iterations

Successive iterations in Interior Point Method

i. **Function Evaluations** calculation of $G_X = \frac{\partial G}{\partial X}$, $H_X = \frac{\partial H}{\partial X}$, $F_X = \frac{\partial F}{\partial X}$, $G_{XX} = \frac{\partial}{\partial X}(G_X^\top \boldsymbol{\lambda})$, $H_{XX} = \frac{\partial}{\partial X}(H_X^\top \boldsymbol{\lambda})$, $F_{XX} = \frac{\partial}{\partial X}(F_X^\top)$ in order to form coefficient matrix and right hand side of $\begin{bmatrix} M & G_X^\top \\ G_X & 0 \end{bmatrix}^k \begin{bmatrix} \Delta X \\ \Delta \boldsymbol{\lambda} \end{bmatrix}^k = \begin{bmatrix} -N \\ -G(X) \end{bmatrix}^k$

ii. **Linear Algebraic Solver**

iii. **Miscellaneous**

iv. Bottleneck of IP:

Solution Method - Iterations

Successive iterations in Interior Point Method

i. **Function Evaluations**

ii. **Linear Algebraic Solver** Calculate the Inverse $\begin{bmatrix} M & G_X^\top \\ G_X & 0 \end{bmatrix}^k$ in

$$\begin{bmatrix} M & G_X^\top \\ G_X & 0 \end{bmatrix}^k \begin{bmatrix} \Delta X \\ \Delta \lambda \end{bmatrix}^k = \begin{bmatrix} -N \\ -G(X) \end{bmatrix}^k$$

iii. **Miscellaneous**

iv. Bottleneck of IP:

Solution Method - Iterations

Successive iterations in Interior Point Method

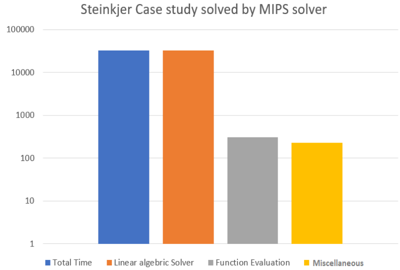
i. **Function Evaluations**
ii. **Linear Algebraic Solver**
iii. **Miscellaneous** Computational time for other components of IP such as step control and step update: $X^{k+1} = X^k + \Delta X$
iv. Bottleneck of IP:

Solution Method - Iterations

Successive iterations in Interior Point Method

i. Function Evaluations
ii. Linear Algebraic Solver
iii. Miscellaneous
iv. Bottleneck of IP:

• BUS	974
• Branch	1023
• GEN HYDRO	1
• PCC (66kV feeder)	1
• BATTERY	200
Varibles for N= 720	1837440



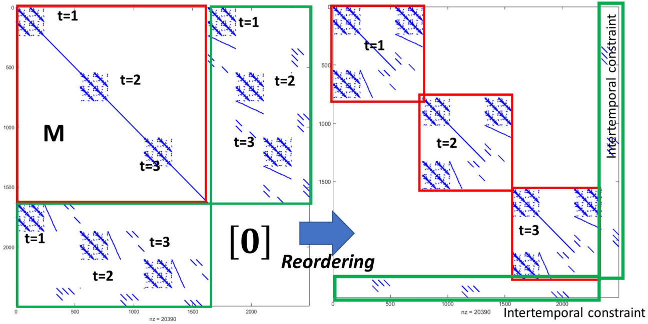


Figure: Structure of Jacobian of the Newton-Raphson's algorithm before and after reordering.

Jacobian of Newton-Raphson

$$\begin{bmatrix} M & G_X^T \\ G_X & 0 \end{bmatrix} \begin{bmatrix} \Delta X \\ \Delta \lambda \end{bmatrix} = \begin{bmatrix} -N \\ -G(X) \end{bmatrix}$$

The solution is published in Papers I and II of this thesis.

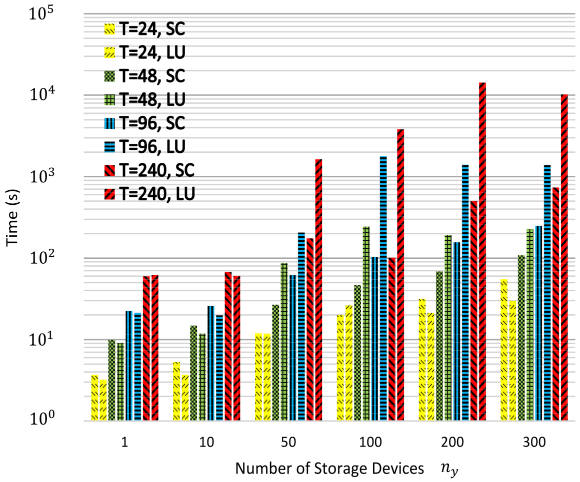


Figure: Total time ($\mathrm{TotalTime} = \mathrm{No.of\ Iter.} \times \mathrm{TimePerIter}$) for solution of the linear KKT systems, Case: IEEE 118.

Results - Analytical Derivatives

Table: Total time ($\mathrm{TotalTime} = \mathrm{No.of\ Iter.} \times \mathrm{TimePerIter}$) elapsed to calculate: 1) Analytical (hand-coded) derivatives, and 2) Numerical derivatives

				Analytical			Numerical		
Case	T	n_y	iter	$F_{\mathbf{x}}$(s)	$\mathbf{G_x}+\mathbf{H_x}$(s)	$\mathcal{L}^{\gamma}_{\mathbf{xx}}$(s)	$F_{\mathbf{x}}$(s)	$\mathbf{G_x}+\mathbf{H_x}$(s)	$\mathcal{L}^{\gamma}_{\mathbf{xx}}$(s)
Case9	2	5	13	0.03	0.13	0.14	0.43	0.98	140.07
Case9	10	5	23	0.08	0.36	0.37	11.32	30.62	22815.29
IEEE30	2	5	12	0.04	0.25	0.18	1.01	2.16	682.70
IEEE30	10	5	16	0.05	0.24	0.25	16.73	49.12	79712.78
IEEE118	2	5	22	0.04	0.19	0.20	7.41	18.07	24557.09
IEEE118	10	5	37	0.09	0.62	0.82	158.21[1]	572.09[1]	4599735[1]
PEGASE1354	2	5	23	0.05	0.61	0.78	85.54[1]	496.18[1]	7185888[1]
PEGASE1354	10	5	33	0.10	3.77	5.15	588.06[1]	3530[1]	51550941[1]

[1] Estimated total time: The time elapsed for one iteration multiplied to the iteration that would take to converge

Test Cases

Test cases of Case9, IEEE30, IEEE118, and PEGASE1354 are part of open source MATPOWER library.

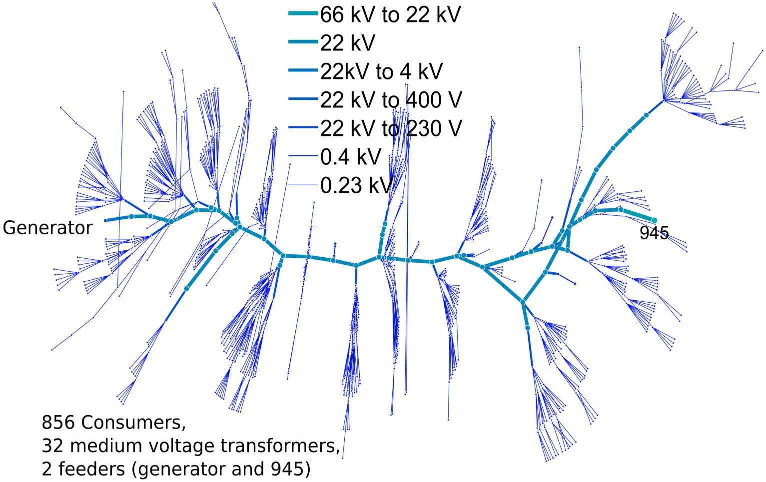


Figure: Local distribution grid located in Norway with 856 costumers

Results - Norwegian grid with 856 consumers

Table: [a) total energy production, b) active system loss, and c) system cost] in three different operational modes.

Method	Daily Energy Consumption (MWh)	LOSS (MWh)	System Cost (kNOK)	Daily Saving (NOK)–(%)	Yearly Saving (kNOK)–(%)	Max EV Hosting Capacity
Dumb Charging	118.64	9.0	76	–	–	220 EV (20%)
MPOPF without operational limits	118.74	8.6	74	1,846 – 2.4 %	674	400 EV (36%)
MPOPF with operational limits	118.74	8.6	75	1,184 – 1.6 %	432	1113 EV (100%)

Response to RQs - Brief Response to RQs

RQ 1. With only “passive charging”, the deployment of EVs will be limited by grid constraints. Can “smart-charging” overcome this problem?

Answer to RQ1. [Papers III and V]

Yes, it can. Simulation results on real data show that a centralised EV charging scheduling with consideration of operational constraints could be a solution for overloading of transformer and lines plus voltage constraints.

RQ 2. How many additional EVs can be served by fast-charging points with a “smart-charging” regime compared to “passive charging”?

- **C 1.** Without any reinforcements of the grid.
- **C 2.** Without any reduction in driving range.

RQ 3. How much grid reinforcements is needed with smart vs passive-charging to fulfill increasing targets for an EV fleet as a replacement for gasoline and diesel cars?

RQ 4. Could integration of PV mitigate the impact of increasing EV penetration

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Answer to RQ2. [Papers III and VIII]

100% EV share of EV could be charged with no issue, while maximum 20% EV share could be charged with dumb charging strategy.

RQ 3. How much grid reinforcements is needed with smart vs passive-charging to fulfill increasing targets for an EV fleet as a replacement for gasoline and diesel cars?

RQ 4. Could integration of PV mitigate the impact of increasing EV penetration on the distribution grid?

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Answer to RQ3. [Papers III, V and VII]

No grid reinforcement is needed with smart strategy. Research should be conducted to clear how much grid reinforcement is required for dumb charging strategy.

RQ 4. Could integration of PV mitigate the impact of increasing EV penetration on the distribution grid?

Response to RQs - Brief Response to RQs

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RQ 4. Could integration of PV mitigate the impact of increasing EV penetration on the distribution grid?

Answer to RQ4. [Paper V]

Yes. It can.

Conclusion - Conclusion

P 1.

In this thesis, a new toolbox is developed for large integration of EV and stationary ESS.

P 2.

A route to high performance power flow solver is taken.

P 3.

Real data w.r.t local distribution grid and EV charging are taken and tested to confirm and withhold hypothesis.

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Thank you for your attention

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