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A Novel Two-Stage Tractable Approach to Multi-Period Optimal Power Flow in Smart Grids

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ATTEST

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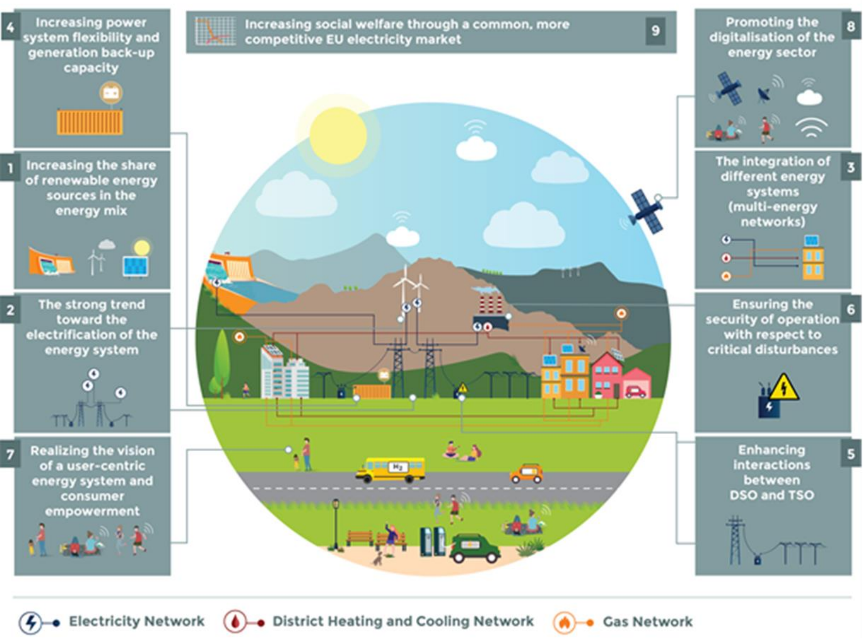


Outline

- Motivation
- Key Contributions
- Flexibility Procurement through AC Multi-Period Optimal Power Flow
- Proposed Tractable two Stage Solution Algorithm
- Case Studies
- Conclusions

Motivation

- Flexibility procurement by DSOs in future smart grids from distributed energy resources (DER) → Key requirement for reliable network operation and hosting more DER
- Procurement of flexibility in day-ahead → AC **multi-period** optimal power flow (OPF)
- Some flexibility options (storage, flexible loads, OLTCs) → binary variables
- Flexibility procurement framework based on OPF falls under mixed-integer **non-linear** programming class → Intractable → Cannot be used for practical applications
- A novel scalable framework through OPF for procuring flexibility in day-ahead operation planning of active distribution grids is proposed

Key Contributions

Scalable flexibility procurement framework relies on:

- Novel tractable mixed integer linear programming (MILP) model
  - Linear approximations of AC power flow and branch current expressions proposed in our paper [1]
- Novel two-stage solution algorithm for solving deterministic **multi-period** OPF flexibility procurement model
  - First stage solves the MILP model & fixes the binary variables
  - Second stage further optimizes the continuous variables through sequential linear programming

[1] Usman, M., & Capitanescu, F. (2021, September). A New Second-Order Linear Approximation to AC OPF Managing Flexibility Provision in Smart Grids. In *2021 International Conference on Smart Energy Systems and Technologies (SEST)* (pp. 1-6). IEEE.

Tractable Flexibility Procurement MILP Model: linear approximated expressions

- Linear active/reactive power flows and linear longitudinal branch current expressions:

$$P_{ij,t} = \alpha^{p}_{i,t} V^2_{i,t} + \alpha^{p}_{j,t} V^2_{j,t} + \beta^{p}_{ij,t}\theta_{ij,t} + \gamma^{p}_{i,t}$$
$$Q_{ij,t} = \alpha^{q}_{i,t} V^2_{i,t} + \alpha^{q}_{j,t} V^2_{j,t} + \beta^{q}_{ij,t}\theta_{ij,t} + \gamma^{q}_{i,t}$$
$$I^2_{ij,t} = (g^2_{ij} + b^2_{ij})(\alpha^{I}_{i,t} V^2_{i,t} + \alpha^{I}_{j,t} V^2_{j,t} + \beta^{I}_{ij,t}\theta_{ij,t} + \gamma^{I}_{i,t})$$

- Proposed expressions are linear in terms of $\boldsymbol{V^2}$ and θ variables
- (α, β and γ) coefficients depend upon initial point-of-linearization

Tractable Flexibility Procurement MILP Model

Objective: Minimize the expected deviation cost of DER output from the market schedule

$$\min \sum_{t \in T} \left\{ \sum_{i \in G} c_{i,p}^{curt} P_{i,t}^{curt} + \sum_{i \in B} c_{i,b}^{str} (P_{i,t}^{dch} - P_{i,t}^{ch}) + c_{i,l}^{fl} \sum_{i \in F} (P_{i,t}^{od} + P_{i,t}^{ud}) \right\} \Delta T + c_{ij}^{oltc} \cdot \kappa_{if,t}$$

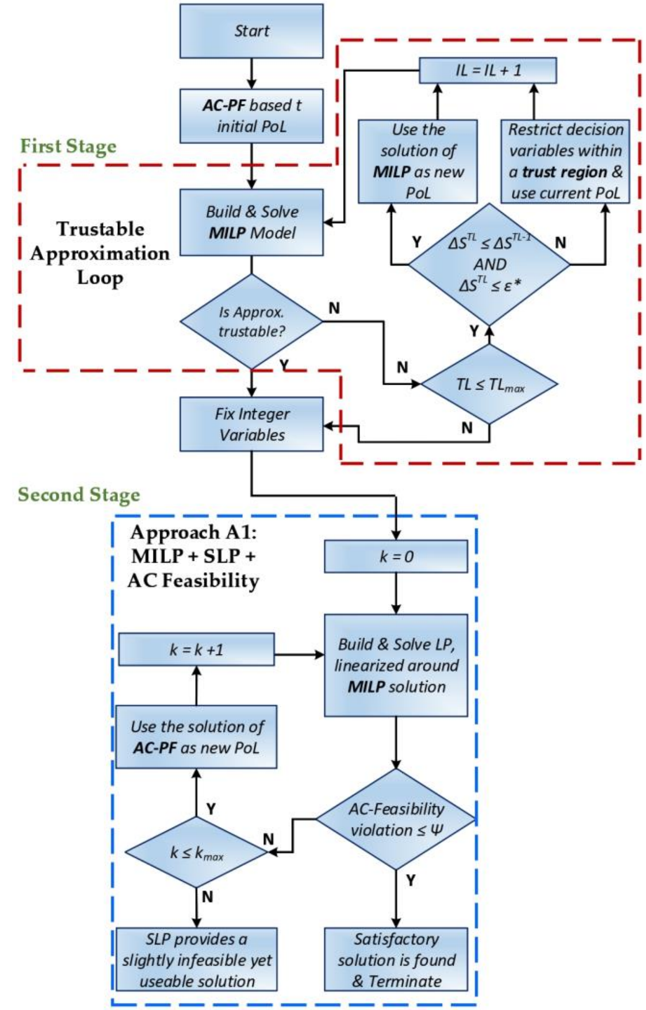
Subject to:

- Linear active and reactive power balance constraints
- Linear branch flow loading limit constraints
- Active and reactive power import from HV upstream grid
- Active power curtailment and reactive power provision from renewable energy resources
- Constraints modelling the behaviour of flexible loads/electrical energy storage/OLTC

Proposed Two Stage Solution Algorithm

Key Steps:

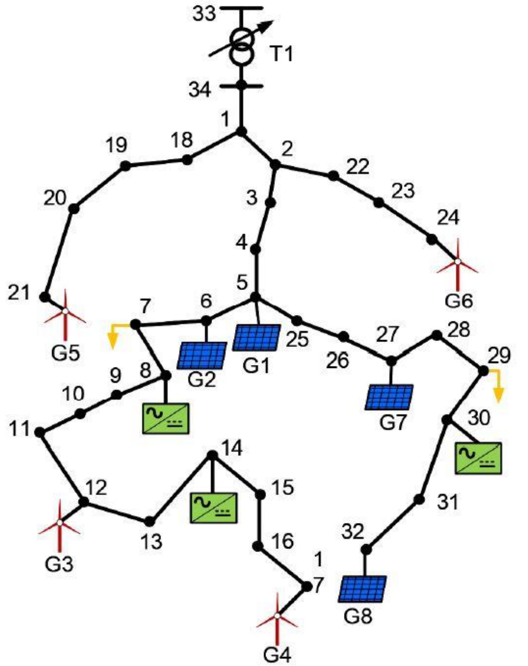
- First stage solves the MILP model around *t* points of linearization
- Integer variables are fixed once required accuracy is achieved in the first stage
- Second stage further optimizes the continuous variable
- LP model is solved in a sequential manner in the second stage
- The algorithm terminates once a feasible solution is obtained at the results of LP model



Case Studies

- Proposed tractable approach is evaluated on the two distribution grids

Test Cases	RES		EESs		FLs^{+}	Peak Load	
	No.	Cap. (MW)	No.	Cap. (MW)	No.	P (MW)	Q (MVAr)
34-bus	8	0.5/1	3	1	2	3.71	2.30
PT. 191-bus	23	2.0	10	1	20	18.75	6.16



- Both networks provide flexibility in the form of
  - Active power curtailment of renewable energy resources
  - Reactive power provision from renewable energy resources
  - Active power charging/discharging of an electrical energy storage
  - Active power over/under-demand of a flexible load
  - On-load tap changing transformer

Results for 34-bus Test System

Approach Accuracy

- Proposed approach provides optimal solution → Max Optimality gap is 0.50%
- No constraint violations (voltage, branch loading) → Feasible solution

Approach Speed

- Proposed approach (A1) solves in a fraction of a second in all flexible options
- Benchmark approach (A0) either takes more time or reaches maximum time execution limit

FOs	Optimality Gap (%)	Constraints Violations Approach A1			Computational Time (s)	
	A1	Nb.	Max (%)	$\leq 1\%$	A0	A1
FO 1	0.03	0	2.07×10^{-4}	0	0.5	0.2
FO 2	0.03	0	7.06×10^{-5}	0	3600*	0.3
FO 3	0.00	0	1.32×10^{-4}	0	0.8	0.2
FO 4	0.00	0	1.51×10^{-4}	0	21.8	0.3
FO 5	0.03	0	1.45×10^{-4}	0	5.7	0.2
FO 6	0.03	0	1.35×10^{-4}	0	2.7	0.2
FO 7	0.04	0	1.40×10^{-4}	0	4.6	0.3
FO 8	0.00	0	1.43×10^{-4}	0	4.3	0.3
FO 9	0.50	0	1.62×10^{-4}	0	7.0	0.4

A0 = MINLP; A1 = MILP + SLP + AC Feasibility
*: maximum time execution limit reached in MINLP solver

Results for 191-bus Portuguese Test System developed in ATTEST project

Approach Accuracy

- Proposed approach provides optimal solution in both base and stressed cases → Max Optimality gap is less than 0.70%
- No constraint violations (voltage, branch loading) → Feasible solution

Approach Speed

- Proposed approach (A1) outperforms the benchmark approach (A0)
- A1 solves all cases in less than 60s as compared to A0 which requires tens of minutes time

base case

FOs	Optimality gap (%)	Constraints Violations Approach A1			Computational Time (s)	
	A1	Nb.	Max (%)	$\leq 1\%$	A0	A1
FO 1	0.01	0	1.97×10^{-4}	0	6	2
FO 4	0.01	0	3.88×10^{-4}	0	3600*	9
FO 7	0.63	0	2.16×10^{-4}	0	622	3
FO 8	0.62	0	2.18×10^{-4}	0	1059	2
FO 9	0.64	0	2.16×10^{-4}	0	3600*	37

*: maximum time execution limit reached in MINLP solver

stressed case

FOs	Optimality gap (%)	Constraints Violations Approach A1			Computational Time (s)	
	A1	Nb.	Max (%)	$\leq 1\%$	A0	A1
FO 1	0.01	0	1.97×10^{-4}	0	7	2
FO 4	0.00	0	1.97×10^{-4}	0	3600*	12
FO 7	0.63	0	2.09×10^{-4}	0	794	7
FO 8	0.65	0	2.11×10^{-4}	0	2283	5
FO 9	0.65	0	2.09×10^{-4}	0	3600*	53

*: maximum time execution limit reached in MINLP solver

Conclusions

- Novel two-stage tractable flexibility procurement methodology is proposed
- Computational bottleneck of benchmark mixed-integer non-linear programming model is removed by resorting to MILP model and sequential linear programming approach
- In terms of accuracy, the proposed tractable approach is capable of providing an optimal and feasible solution
- Solution time of proposed approach remains below 1 minute
  - well compatible with the application requirements in day-ahead operation planning

- The proposed approach was already extended to stochastic AC multi-period OPF flexibility procurement problem in [2]
- The code source of [2] will be open this year on ATTEST repository: stay tunned!

[2] Usman, M., & Capitanescu, F. (in press 2022). A Novel Tractable Methodology to Stochastic Multi-Period AC OPF in Active Distribution Systems. *IEEE Transactions on Power Systems.*