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Advanced Voltage/VAr Management

Prepared by Nexant/Grid Management
H. Pinto, J. Bright, M. Prais,
B. Stott, O. Alsaç, F. Magnago

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Introduction

There is increasing demand in operational planning for Advanced Voltage/VAr Management solutions

- More automated scheduling of voltages-VArs, over a near-future timeframe that can range from an hour to a couple of days ahead.
- The need is exacerbated by higher uncertainty, e.g. penetration of renewable generation.

Such scheduling solutions are characterized by

- A multi-stage look-ahead problem, including inter-temporal constraints to ensure a smooth and actionable operational trajectory over time.
- Complex optimization, requiring sophisticated solution techniques.
- A sequence of security-constrained optimal power flow (SCOPF) calculations with full AC network models.

This presentation deals with the analytical problem formulation and solution process

The Voltage/VAr Scheduling Calculation - General

- Provide forward reactive dispatch and voltage schedules over the given timeframe (e.g. 24 hours), respecting network and operational constraints.
  - Run SCOPF for each hour in the sequence with a definable objective, ramping limits, and tunable movement-inhibiting penalties on specified controls (generator voltages, taps, shunts).
  - Coordinate each SCOPF solution over a time horizon enforcing time-coupling constraints.

Voltage/VAr Scheduling Problem (1/2)

Purpose

- Optimize hourly settings over a sequence of hours for dispatchable reactive generation voltage setpoints, transformer taps and shunts.

Objective functions

- Minimize movement of designated controls from their target values.
- Minimize losses.

Typical inter-temporal constraints on controls

- Ramping up and down
- Minimum operating time
- Number of movements in each time interval
- Number of movements over the study horizon

Voltage/VAr Scheduling Problem (2/2)

Typical network constraints (for pre- and all post-contingency scenarios)

- Bus voltage magnitudes
- Net MVAr interchanges of zones or groups of zones
- MVAr reserves of any designated generator groups
- Weighted sums of the MVAr flows in designated sets of branch groups and branches
- Differences between designated pairs of bus voltage magnitudes
- Changes in bus voltage magnitudes between the base-case and contingency cases
- Branch MVA flows

Some Critical Solution Essentials

Rigorous network optimization

- Accurate AC network models, both in the pre and post contingency states.
  - Because approximated network models for reactive-power scheduling are quite inaccurate, and can give very wrong results.
- Automatic recursive contingency analysis to capture all insecurities
  - Because correcting constraint violations often creates new violations which, if ignored, can be even worse.

Usable engineering results when not all violations are enforceable (infeasibility)

- This issue almost always arises
- It is among the most difficult solution aspects, if practical results are to be obtained
  - It requires sophisticated analytical and heuristic techniques.
  - It includes constraint relaxation
  - It includes priority levels for constraints and controls

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Sample Objective Function

A typical objective can be expressed as the function:

$$\min \underbrace{\sum_{t=1}^{T} w_{1,t} \cdot \sum_{k=1}^{NControls} \left| u_{k,t} - u_{k,t}^{*} \right|}_{\textit{Keep controls close to a target}} + \underbrace{\sum_{t=2}^{T} w_{2,t} \cdot \sum_{k=1}^{NControls} \left| u_{k,t} - u_{k,t-1} \right|}_{\textit{Reduce control movements between consecutive periods}}$$

where *u* are the optimized controls, *w* are weightings, *t* is a period and * denotes target values.

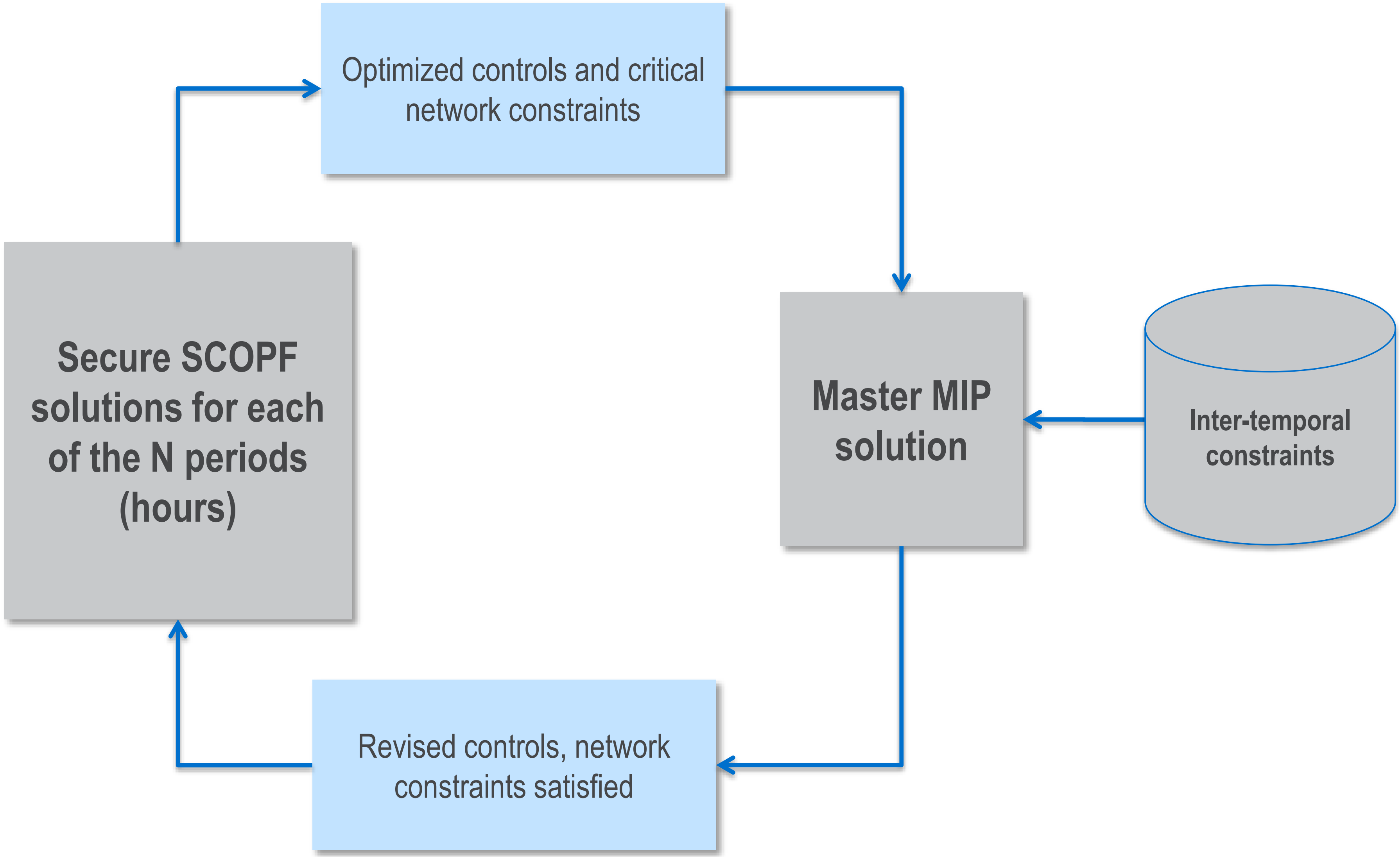
Nature of the Problem and Solution

The voltage/VAr scheduling problem is a complex, multi-period mixed-integer (MIP) optimization problem, whose solution can be approached by a decomposition process comprising:

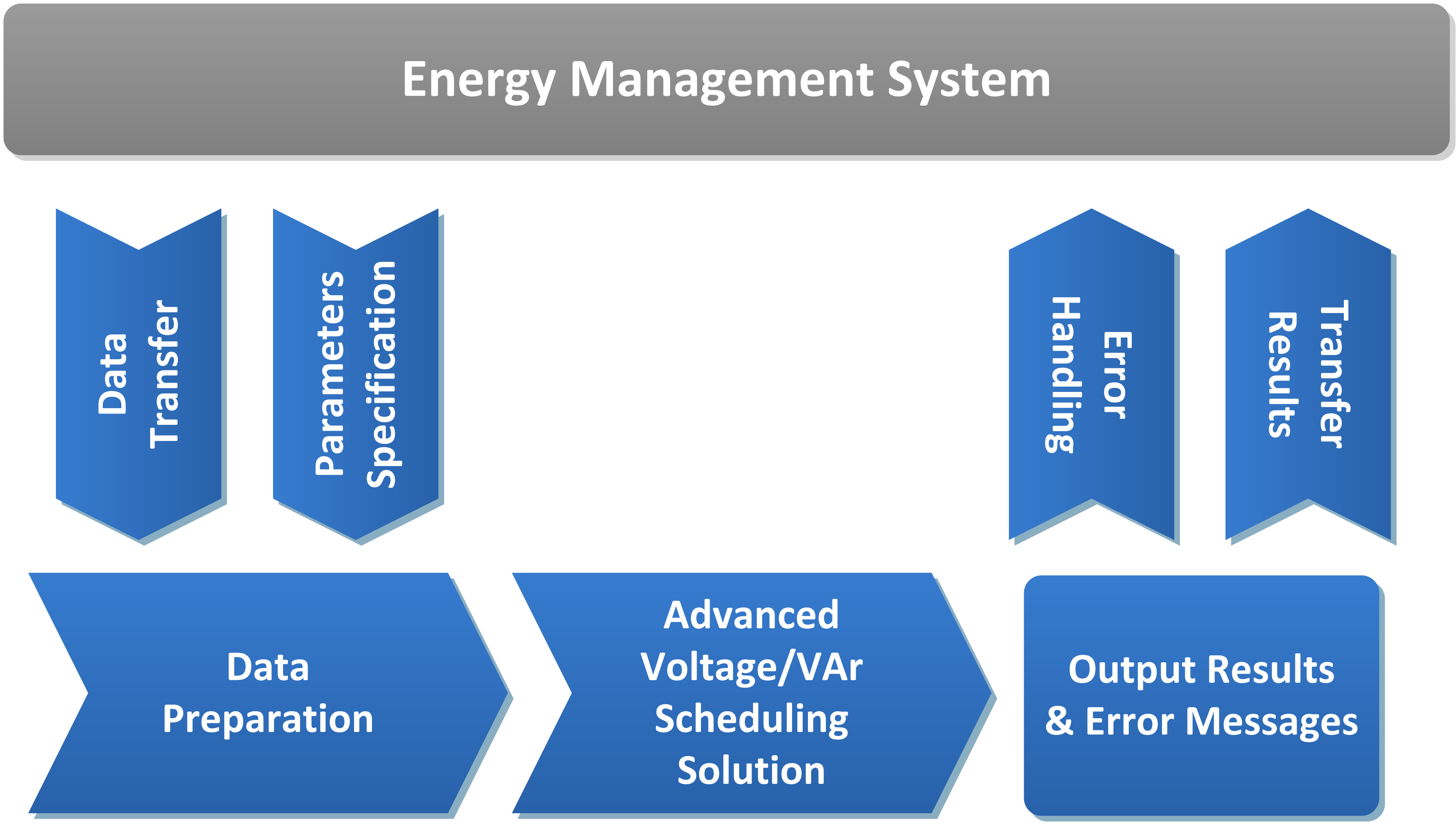
- **The Sub-Problem Solutions**: Optimal network-constrained control-variable dispatch for each period (SCOPF)
- **The Master Level Solution**: A MIP calculation that couples all periods (hours), imposing constraints to limit control actions between periods and over all periods, and subject to the critical network constraints from the base case and all contingency cases for all periods

Note: This is a problem in which the number of critical network constraints (i.e. those potentially binding) is potentially huge. Benders Decomposition is able to impose these constraints efficiently at the master level.

Voltage/VAr Scheduling Decomposition Solution



Typical EMS Implementation



An Illustrative Real-Life Test Case

Study timeframe

- 24 equal time periods with different network topologies

System size

- 5,000+ buses
- 5,000+ contingency cases

Optimized Controls

- 1000+ transformer taps, switchable shunts and generator voltage setpoints

Network Constraints

- Voltage limits for base case (0.95 – 1.05 p.u.) and post-contingency (0.9 – 1.1 p.u.) scenarios across all periods
- Equipment limits

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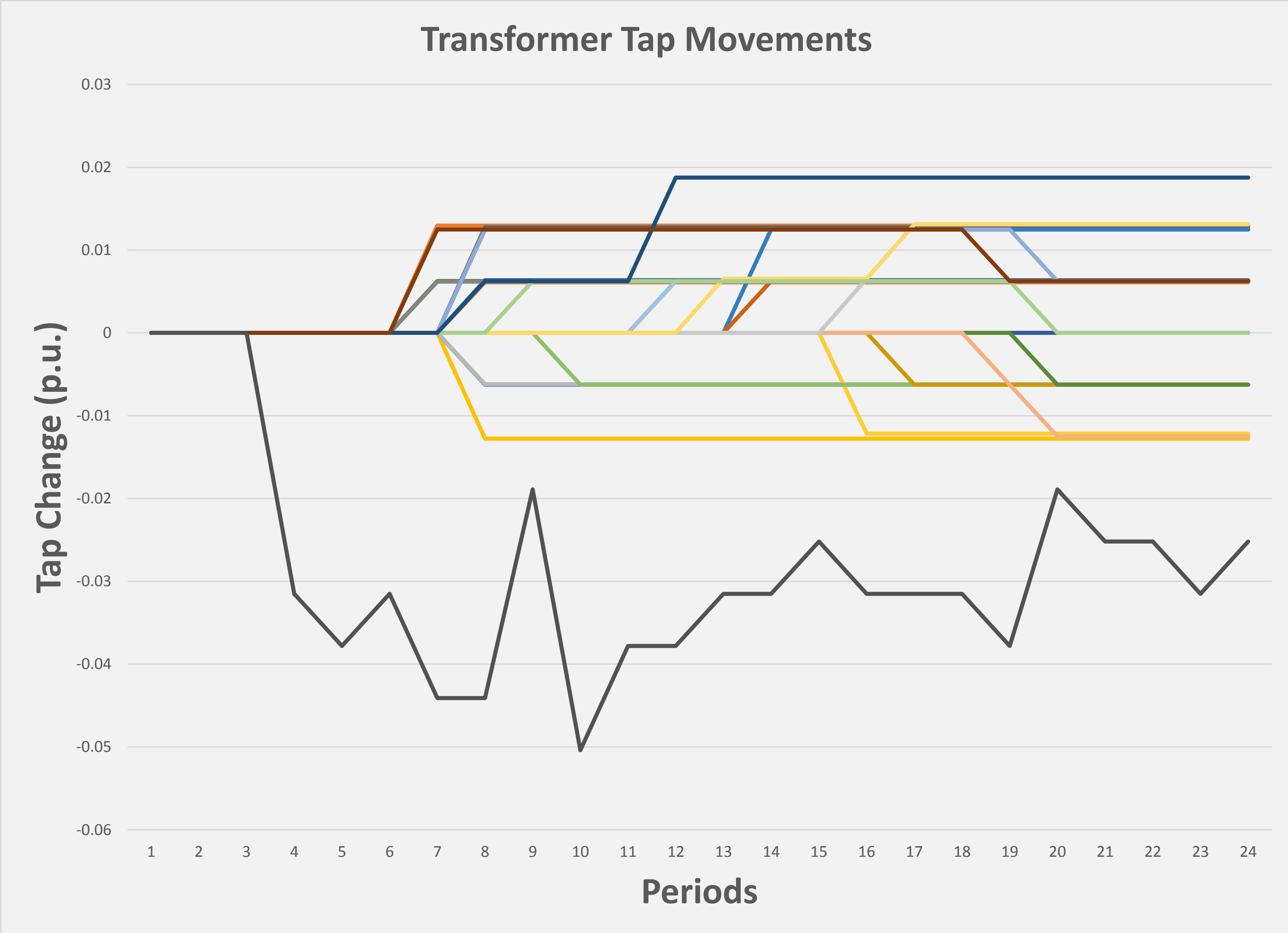
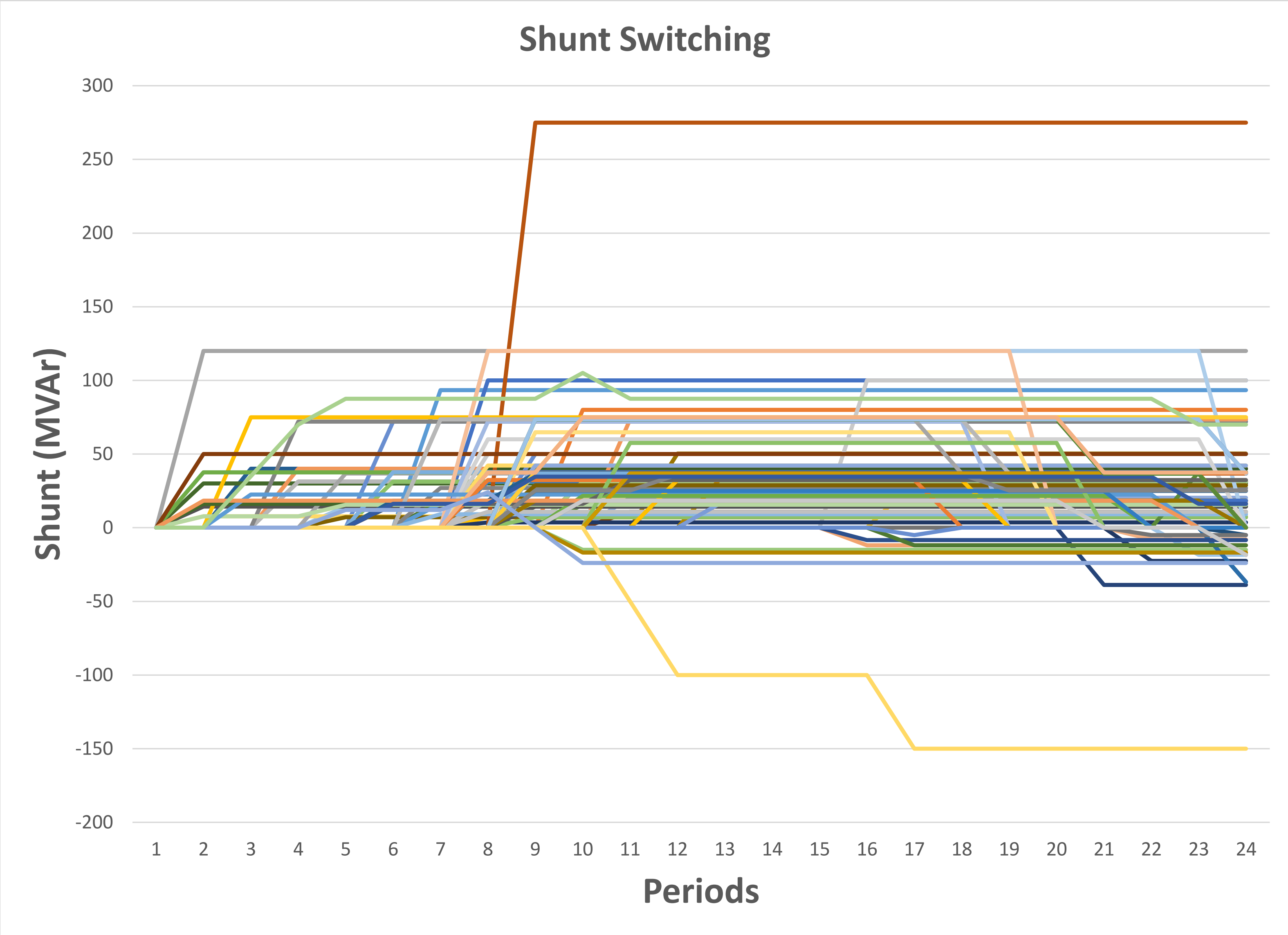
Summary of Results

For all 24 periods	In the Initial Power Flow & Contingency Analysis	After Time-Decoupled Voltage/VAr Scheduling	After Time-Coupled Voltage/VAr Scheduling
Violations of voltage range in base case	174 voltage violations involving 18 buses. Largest violation of 0.08 p.u.	None	None
Violations of voltage range in contingency cases	582 voltage violations involving 54 buses. Largest violation 0.25 p.u.	Total of 20 limit relaxations (for infeasibility) involving only 10 buses. Largest violation 0.006 p.u.	Total of 34 limit relaxations (for infeasibility) involving only 15 buses. Largest violation 0.006 p.u.
Total number of transformer tap movements over all periods		137 movements involving 17 transformers	55 movements involving 32 transformers
Total number of shunt device switchings over all periods		325 shunt switchings involving 142 shunt devices	188 shunt switches involving 138 shunt devices

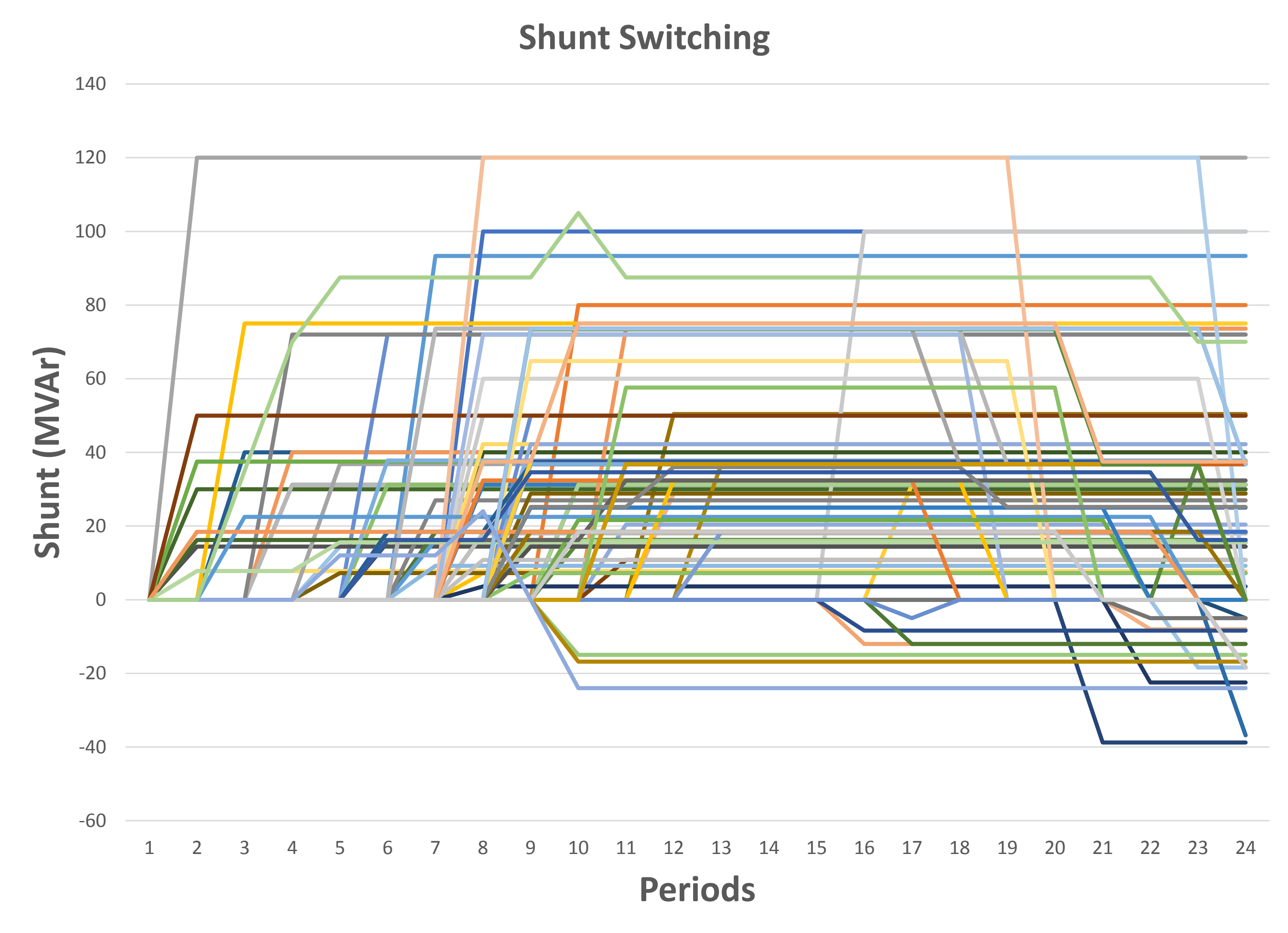
Time-Coupled Tap Movements over the Study Period



Time-Coupled Shunt Switching over the Study Period



Time-Coupled Shunt Switching over the Study Period (Zoomed)

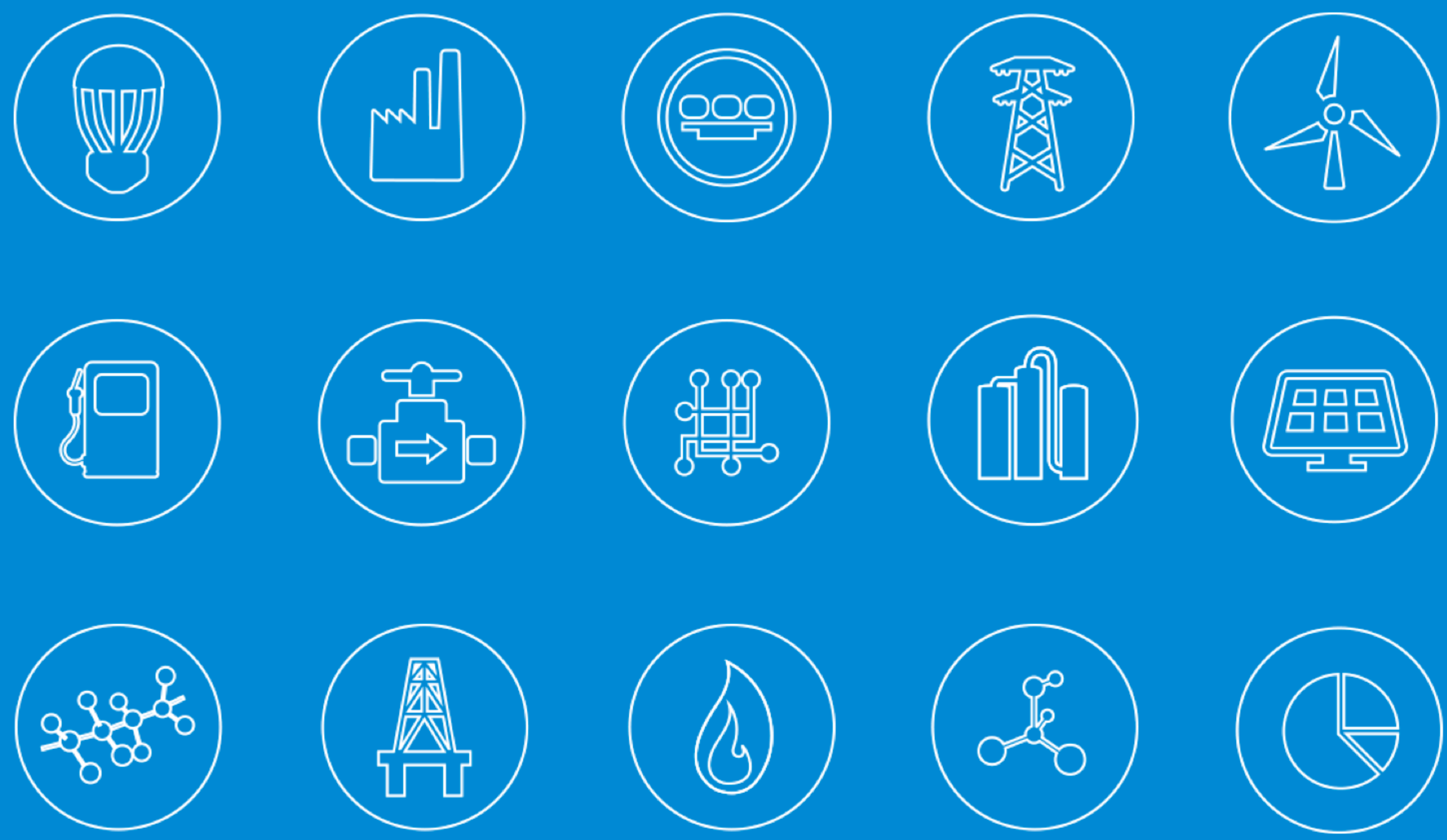


Comments on the Illustrative Solution

- The time-coupled solution here moves the controls considerably more smoothly than in the time-decoupled case.
- By altering the objective and preferences, different engineering outcomes can be obtained, for example fewer controls are rescheduled with more limits “softly” enforced.
- There is almost always a trade-off in the solution between control movement and the degree, number and locations of limit relaxations (constraints that are impossible or impractical to enforce).

Concluding Remarks

- The industry is entering the era where advanced scheduling calculations for voltage/VAr management are becoming operationally possible.
- The problem is very complicated and requires sophisticated solution techniques and appropriate computing power.
- There is considerable scope for variations in problem formulation and requirements, particularly in the areas of inter-temporal constraints and criteria for desirable/acceptable engineering voltage/VAr schedules.



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