Security-constrained optimal power flows
Advanced power system analysis

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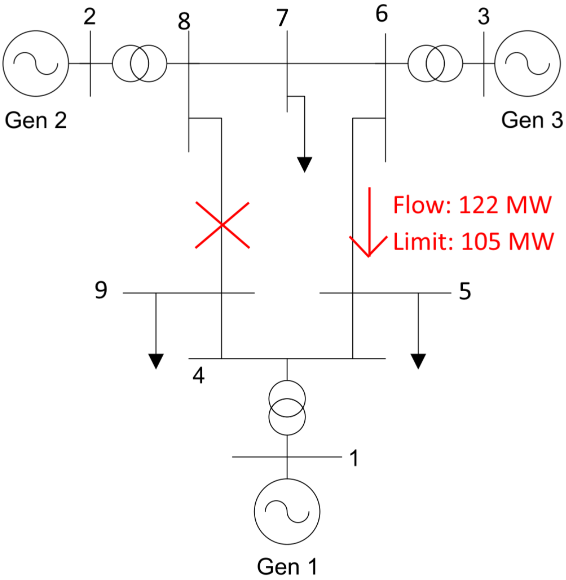
Agenda

Perspectives

"Today, 50 years after the problem was formulated, we still do not have a fast, robust solution technique for the full ACOPF. Finding a good solution technique for the full ACOPF could potentially save tens of billions of dollars annually." (Cain, O'neill, and Castillo 2012)

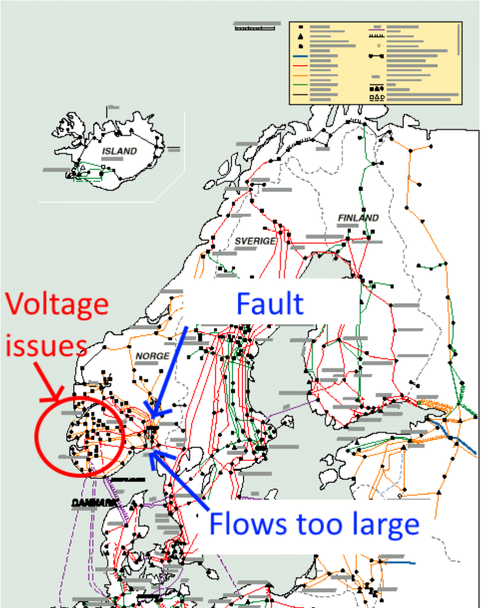
"Recommendation 1: The Department of Energy should develop and test a full ac optimal power flow (ACOPF) model with an optimization algorithm using all nodes in the market area, taking advantage of supercomputers and parallel processing and respecting all thermal and voltage constraints." (2016, Analytic Research Foundations for the Next-Generation Electric Grid)

Example



What do you do?

Example 2



What do you do?

SCOPF - General formulation

Security-constrained optimal power flows are **optimization problems** of the following form:

$$\min \quad \text{Cost of preventive and corrective actions} \tag{1}$$

$$\text{subject to} \quad \text{The system is secure} \tag{2}$$

That is, we want to find **preventive** and **corrective** actions that make the system secure.

Outline

Topics to discuss today:

- What is security?
- When do transmission system operators need SCOPF?
- What are preventive and corrective actions?
- How to translate the power system problem "ensuring security" to mathematical equations that can be used in an optimisation framework?

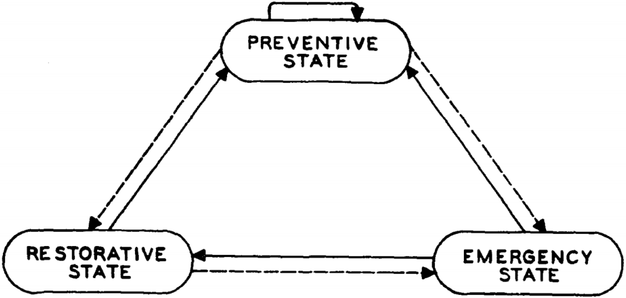
Agenda

What is security?

Operational security is defined for all European transmission system operators in *ENTSO-E network code on operational security*:

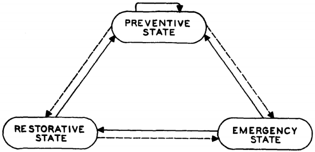
"**Operational Security** means the Transmission System capability to retain a Normal State or to return to a Normal State as soon and as close as possible, and is characterized by thermal limits, voltage constraints, short-circuit current, frequency limits and stability limits" (From ENTSO-E 2013)

Dy Liacco's security diagram



(From Dy Liacco 1967)

Dy Liacco's security diagram - State description



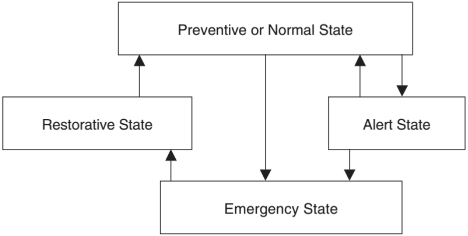
Preventive (normal) state All components within operating constraints[1]. Preventive control actions: anticipate threats (changes in load, RES production, outages of generators, lines, etc).

Emergency state Stability lost or some operating constraints violated. Emergency control actions: Stop the degradation of services.

Restorative state Service outages (interruptions of supply for some customers) Restoration control actions: Restore electricity supply to all customers.

[1] what are typical operating constraints?

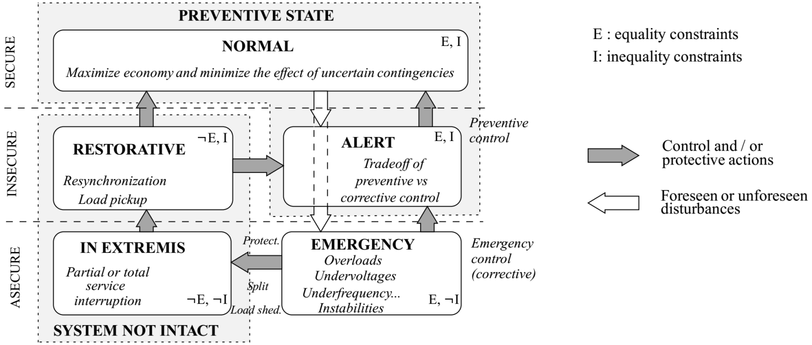
Cihlar's security diagram



(From Cihlar et al. 1969)

Alert state = Potential emergency. Operating constraints still satisfied (like in the normal state) but some operating constraints would be violated in case of a contingency (we would go to the emergency state should that contingency occur).
Preventive control actions: Actions to return to the normal state.

Fink and Carlsen's security diagram



(From Fink and Carlsen 1978)

In extremis state Partial or total system collapse = Interruption of supply. Corrective actions: Stop the collapse, and prevent the system from further degrading.

Today's security diagram

- Fast forward almost 40 years to today: the same five states are still pivotal to the definition of security.
- See Article 8 in ENTSO-E network code on operational security (2013)

a) Normal State:

i. voltage and power flows are within the Operational Security Limits defined according to Articles 10 and Article 12 in accordance with Article 8(5) and frequency is within the frequency limits for the Normal State as defined in [NC LFCR];

ii. Active and Reactive Power reserves are sufficient to withstand Contingencies from the Contingency List defined according to Article 13; and

iii. operation of its Responsibility Area is and will remain within Operational Security Limits even after a Contingency from the Contingency List defined according to Article 13 and after effects of Remedial Actions;

Today's security diagram

- Fast forward almost 40 years to today: the same five states are still pivotal to the definition of security.
- See Article 8 in ENTSO-E network code on operational security (2013)

b) Alert State:

i. voltage and power flows are within their Operational Security Limits defined according to Articles 10 and 12 in accordance with Article 8(5); and

ii. at least one of the following conditions is fulfilled:

a. Active Power Reserve requirements are not fulfilled with lack of more than 20% of the required amount of any of the following: FCR, FRR and RR according to the dimensioning in the [NC LFCR], for more than 30 minutes and with no means to replace them;

b. frequency is within the frequency limits for the Alert State as defined in [NC LFCR];

c. at least one Contingency from the Contingency List defined according to Article 13 can lead to deviations from Operational Security Limits, even after effects of Remedial Actions;

Today's security diagram

- Fast forward almost 40 years to today: the same five states are still pivotal to the definition of security.
- See Article 8 in ENTSO-E network code on operational security (2013)

c) Emergency State:

i. there is at least one deviation from Operational Security Limits and times defined according to Articles 10 and 12 in accordance with Article 8(5); or

ii. frequency is outside the frequency limits for the Normal State and outside the frequency limits for the Alert State as defined in [NC LFCR]; or

iii. at least one measure of the System Defence Plan is activated; or

iv. there is a complete loss of all tools and facilities defined according to Article 8(15) for more than 30 minutes;

Today's security diagram

- Fast forward almost 40 years to today: the same five states are still pivotal to the definition of security.
- See Article 8 in ENTSO-E network code on operational security (2013)

d) Blackout State:

   i. loss of more than 50% of load in the TSO Responsibility Area; or

   ii. total absence of voltage for at least 3 minutes in the TSO Responsibility Area and triggering Restoration plans;

Today's security diagram

- Fast forward almost 40 years to today: the same five states are still pivotal to the definition of security.
- See Article 8 in ENTSO-E network code on operational security (2013)

e) Restoration:

i. Procedures are implemented to bring frequency, voltage and other operational parameters within the Operational Security Limits defined according to Articles 9, 10 and 12 in accordance with Article 8(5); and

ii. Demand Facilities are connected at a pace decided by the TSOs in charge of Restoration, depending on the technical capability and feasibility of the Transmission System resources and Significant Grid Users which are Power Generating Facilities.

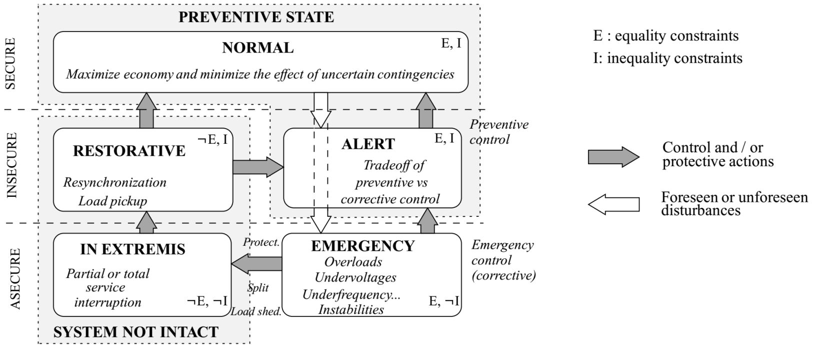
Definition of security (Again)

Operational security is defined for all European transmission system operators by *ENTSO-E network code on operational security*:

"**Operational Security** means the Transmission System capability to retain a Normal State or to return to a Normal State as soon and as close as possible, and is characterized by thermal limits, voltage constraints, short-circuit current, frequency limits and stability limits" (From ENTSO-E 2013)

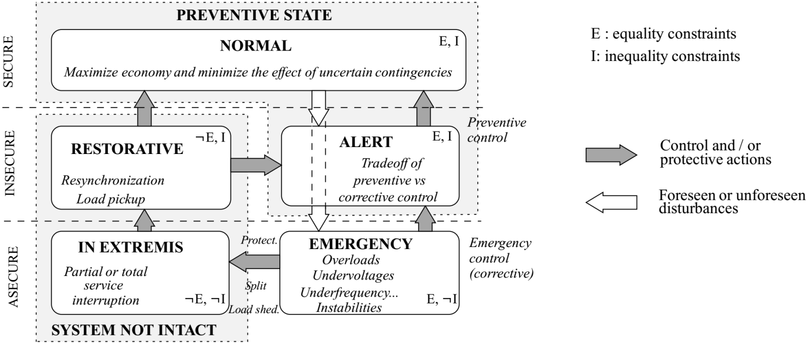
Operational security limits are cornerstones of the definition of security. Also called security constraints ("constraints" is a mathematical term used in optimization).

Question 1



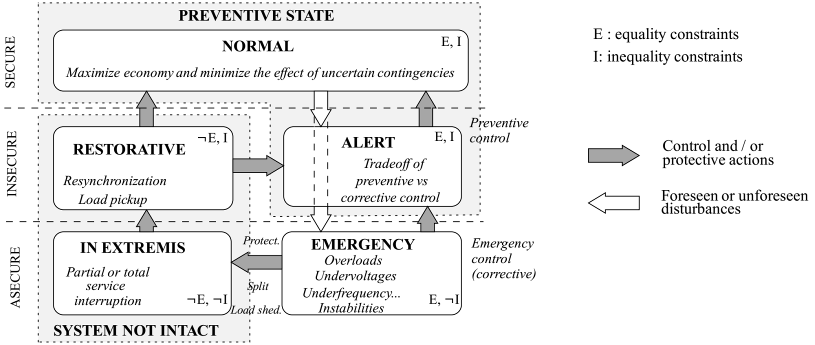
- Suppose that no contingency has occurred. Contingency analyses show that the flow limits of one line would be exceeded if one specific contingency occured. In which state is the system?

Question 2



- Suppose that a contingency has occurred and voltages in one area exceed their limits. In which state is the system?
- Suppose further that no load shedding was necessary. In which state is the system?

Question 3

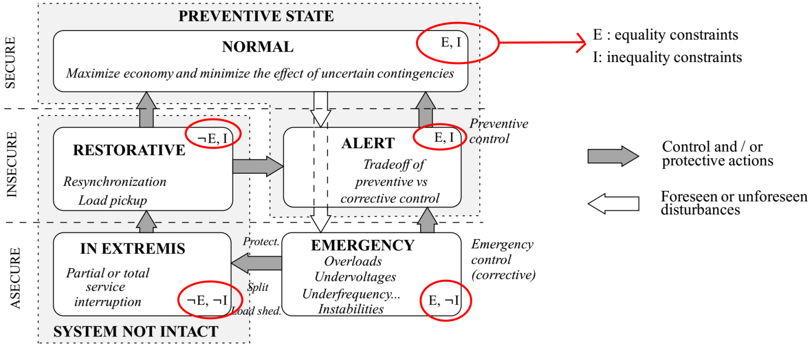


- Suppose that a contingency has occurred and all limits are fulfilled. In which state is the system?

Agenda

Fink and Carlsen's security diagram

Getting closer to a mathematical formulation:



(From Fink and Carlsen 1978)

- What are equality and inequality constraints?

Security constraints in SCOPF

> "**Operational Security** means the Transmission System capability to retain a Normal State or to return to a Normal State as soon and as close as possible, and is characterized by thermal limits, voltage constraints, short-circuit current, frequency limits and stability limits" (From ENTSO-E 2013)

Typically:

- Short-circuit currents are dealt with by protection systems.
- Frequency limits are dealt with by frequency control reserves.

Security constraints left:

- Thermal limits.
- Voltage constraints.
- Stability limits.

Thermal limits

Power system perspective

Thermal limits (or thermal ratings) are limits on loading of components such as lines, cables and transformers.

Two types of limits:

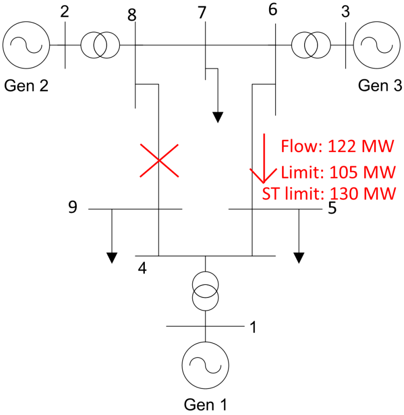
- Long-term (or continuous) limits: components can operate a long time without problem if these limits are fulfilled.
- Short-term limits (or emergency limits): These limits can be sustained by components only for a short time (e.g. 15 minutes).

Math formulation

$$P_l \leq P_l^{\max}, \ \forall \text{ lines } l.$$

Question for later: How to distinguish long-term and short-term limits in the mathematical formulation?

Example



- The flow is acceptable for 15 minutes
- TSO would have to take actions within 15 minutes

Voltage constraints

Power system perspective

From ENTSO-E network code on operational security:

Synchronous Area	Voltage range	Time duration
Continental Europe	0.90 pu – 1.05 pu	unlimited
Nordic	0.90 pu – 1.05 pu	unlimited
Great Britain	0.90 pu – 1.05 pu	unlimited
Ireland Ireland offshore	0.90 pu – 1.05 pu 0.90 pu – 1.10 pu	unlimited
Baltic	0.90 pu – 1.10 pu	unlimited

Table 10.2: Voltages ranges for reference voltages defined by TSOs between 300 kV and 400 kV

Math formulation

$$V_i^{\min} \leq V_i \leq V_i^{\max}, \ \forall \text{ buses } i.$$

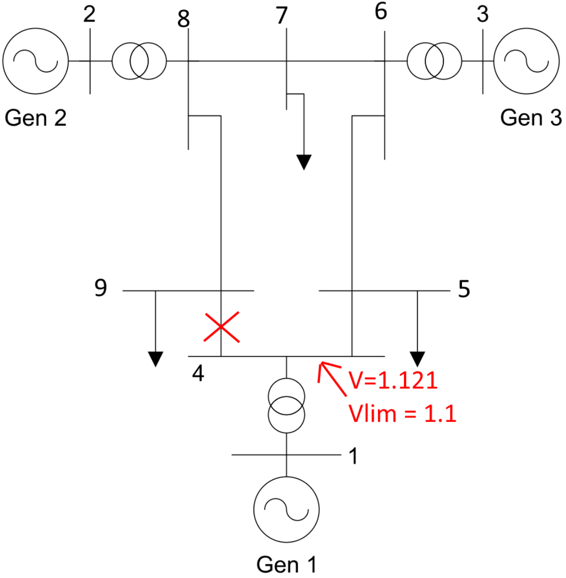
Voltage constraints - 2

What happens if voltages exceed the range?
The answer is in *ENTSO-E network code on Requirements for Grid Connection Applicable to all Generators (RfG) of 2016*:

Synchronous area	Voltage range	Time period for operation
Continental Europe	0,85 pu-0,90 pu	60 minutes
	0,90 pu-1,05 pu	Unlimited
	1,05 pu-1,10 pu	To be specified by each TSO, but not less than 20 minutes and not more than 60 minutes
Nordic	0,90 pu-1,05 pu	Unlimited
	1,05 pu-1,10 pu	To be specified by each TSO, but not more than 60 minutes
Great Britain	0,90 pu-1,05 pu	Unlimited
	1,05 pu-1,10 pu	15 minutes
Ireland and Northern Ireland	0,90 pu-1,05 pu	Unlimited
Baltic	0,88 pu-0,90 pu	20 minutes
	0,90 pu-1,097 pu	Unlimited
	1,097 pu-1,15 pu	20 minutes

The table shows the minimum time periods during which a power-generating module must be capable of operating for voltages deviating from the reference 1 pu value at the connection point without disconnecting from the network where the voltage base for pu values is from 300 kV to 400 kV.

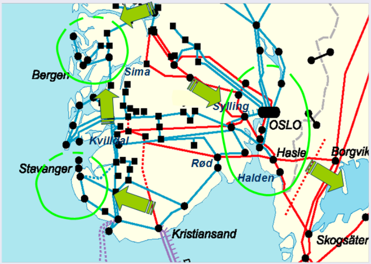
Example

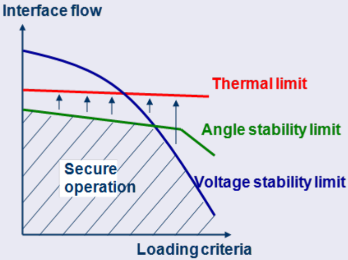


Stability constraints

Power system perspective

Typically, stability constraints take the form of active power limits on critical interfaces (=transmission corridors / lines).





Math formulation

$$P_l \leq P_l^{\max}, \ \forall \text{ critical interfaces } l.$$

Note: *same math formulation as thermal limits but fundamentally different constraints!*

Contingencies

Remember:

"**Operational Security** means the Transmission System capability to retain a Normal State or to return to a Normal State as soon and as close as possible, and is characterized by thermal limits, voltage constraints, short-circuit current, frequency limits and stability limits" (From ENTSO-E 2013)

a) Normal State:

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iii. operation of its Responsibility Area is and will remain within Operational Security Limits even after a Contingency from the Contingency List defined according to Article 13 and after effects of Remedial Actions;

Contingency list and N-1 criterion

From ENTSO-E network code on operational security (again ...):

2. In addition the following definitions shall apply:

(N-1)-Criterion means the rule according to which elements remaining in operation within TSO's Responsibility Area after a Contingency from the Contingency List must be capable of accommodating the new operational situation without violating Operational Security Limits;

(N-1)-Situation means the situation in the Transmission System in which a Contingency from the Contingency List has happened;

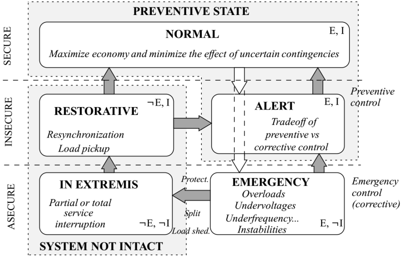
In practice, the contingency list contains all single outages and some critical double contingencies (such as double-circuit overhead lines).

N-1 and N-2 contingencies

Single-circuit = N-1 contingency

Double-circuit = N-2 contingency, still included in the contingency list.

Security constraints - a summary

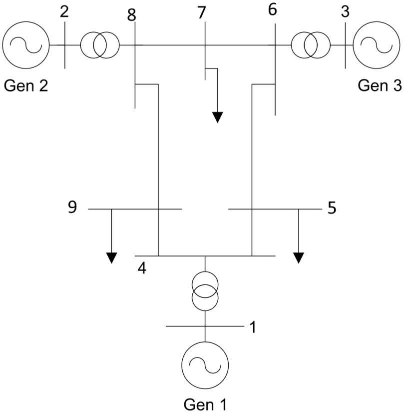


In normal operations, a TSO's responsibility is to enforce the following constraints:

- Short-circuit constraints
- Frequency limits
- *Bus voltage constraints*
- *Thermal limits*
- *Stability limits*

for all contingencies in its contingency list.

Question



- What contingencies are included in the N-1 contingency list of this system?

Agenda

Examples of problems a TSO faces

Day-ahead problem

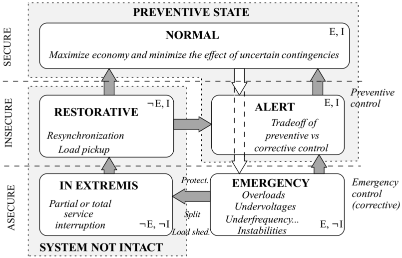
- Do the market generation and consumption plans comply with the security requirements? $\Leftrightarrow$ contingency analyses
- What actions must be taken now if they do not? $\Leftrightarrow$ SCOPF.

Real-time operation

- Does the current system comply with the security requirements? $\Leftrightarrow$ contingency analyses.
- What actions must be taken now if they do not? $\Leftrightarrow$ SCOPF.

SCOPF is one possible tool (not the only one) to answer these questions

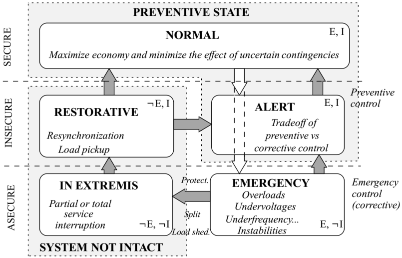
SCOPF for real-time decision making



Assumption: no contingency has happened yet.

What is our “problem formulation”?

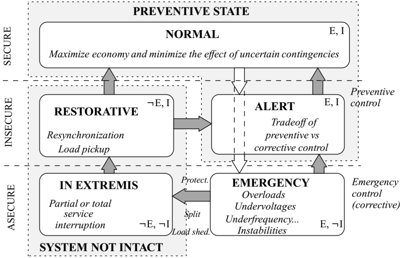
SCOPF for real-time decision making



Power system problem:

- are we in the normal or alert state? $\Rightarrow$ contingency analyses
- If we are in the alert state, what actions should we take now? $\Rightarrow$ SCOPF

SCOPF for real-time decision making

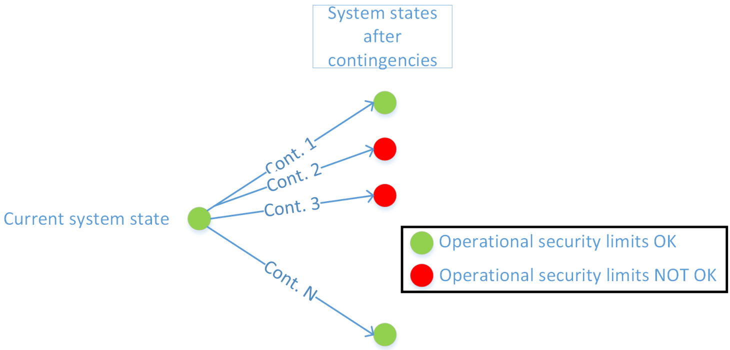


Formulating the problem

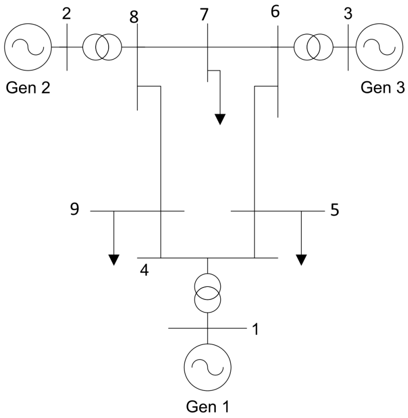
We need to decide:

- What is the contingency list?
- What are the security constraints?
- What are available actions if necessary?
- What are the costs of these actions?

Contingency analysis - Illustration

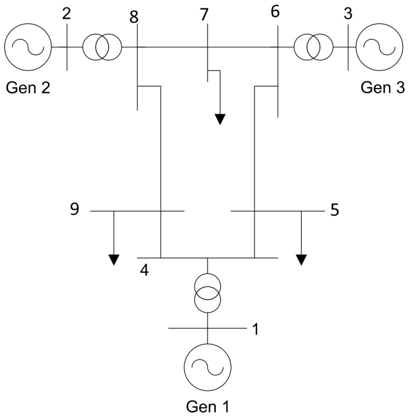


Example



- Contingency list: N-1 contingency list
- Security constraints: Voltage limits and line ratings
- Actions: Re-dispatch of generators
- Cost: Re-dispatch cost

Example - contingency analysis

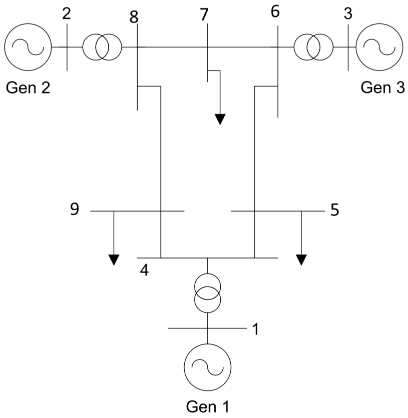


For all contingencies in the contingency list:

- Apply contingency.
- Simulate system response. (How?)
- Check the security constraints.

See example in MATPOWER.

Example - contingency analysis



For all contingencies in the contingency list:

- Apply contingency.
- Simulate system response. (How?)
- Check the security constraints.

System in alert state $\Rightarrow$ actions must be taken.

Preventive SCOPF

$$
\begin{aligned}
&\min_{u_0, x_c} \; C(u_0) \\
&\text{subject to } g_c(x_c, u_0) = 0, \; c = 0, \ldots, n_c \\
&\qquad\qquad h_c(x_c, u_0) \leq h_c^{\max}, \; c = 0, \ldots, n_c
\end{aligned}
\qquad \text{(P-SCOPF)}
$$

- $c = 1, \ldots, n_c$ are contingencies, $c = 0$ is the pre-contingency case.
- x_c is the state of the system (typically voltage angles and magnitudes), after contingency c occurs.
- u_0 are the preventive actions.
- g_c are the power flow equations.
- $h_c^{\max}$ are the security limits.

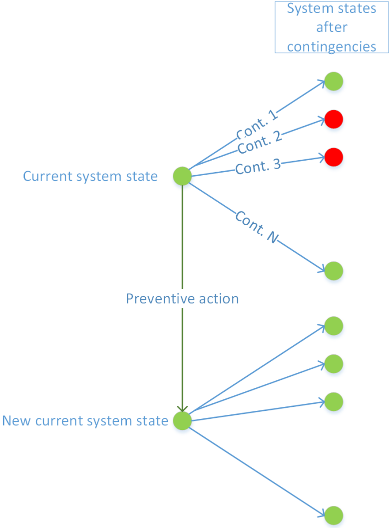
The optimal solution u_0^* is the cheapest set of preventive actions that enforces the security limits for the considered contingency list.

Preventive SCOPF - discussion

$$\begin{aligned} \min_{u_0, x_c} \; & C(u_0) \\ \text{subject to } & g_c(x_c, u_0) = 0, \; c = 0, \ldots, n_c \\ & h_c(x_c, u_0) \leq h_c^{\max}, \; c = 0, \ldots, n_c \end{aligned} \tag{P-SCOPF}$$

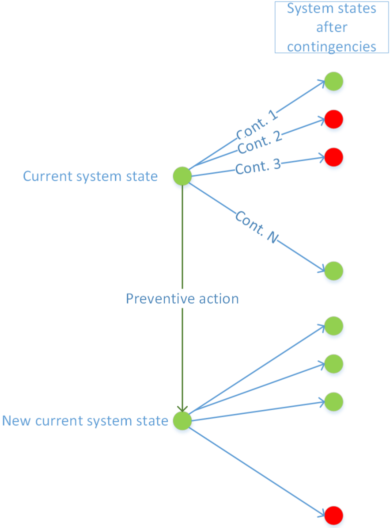
- The control actions u_0 are applied <u>now</u>
- They apply to <u>all</u> pre- and post-contingency systems, thereby the name "preventive"
- We take actions before the contingencies occur.
- We take necessary actions <u>now</u> so that the security limits are fulfilled even if one of the contingencies c occurs.
- <u>Note:</u> we do not know what happens with contingencies outside the contingency list (maybe secure, maybe not).
- <u>Limitation</u>: P-SCOPF does not consider the possibility of using corrective actions after contingencies occur.

Preventive action - illustration

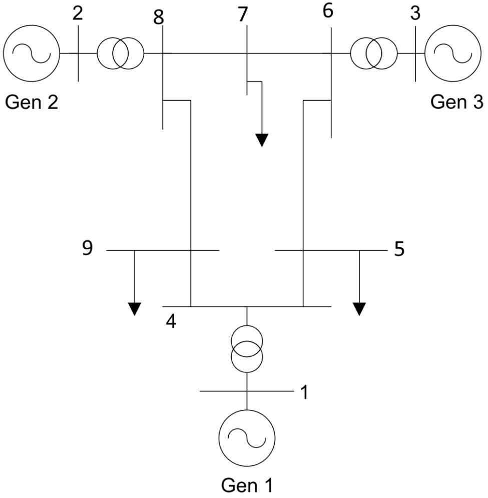


Preventive action - illustration

This can also happen if contingencies are not explicitly/properly considered when finding preventive actions!



Examples



See examples in MATPOWER

Preventive-corrective SCOPF

$$
\begin{aligned}
\min_{x_0, x_c, u_0, u_c} \quad & C(u_0) \\
\text{subject to } & g_0(x_0, u_0) = 0, \\
& g_c(x_c, u_c) = 0, \; c = 1, \ldots, n_c \\
& h_0(x_0, u_0) \leq h_0^{\max}, \\
& h_c(x_c, u_c) \leq h_c^{\max}, \; c = 1, \ldots, n_c \\
& \|u_c - u_0\| \leq \Delta u_c^{max}
\end{aligned}
\qquad \text{(PC-SCOPF)}
$$

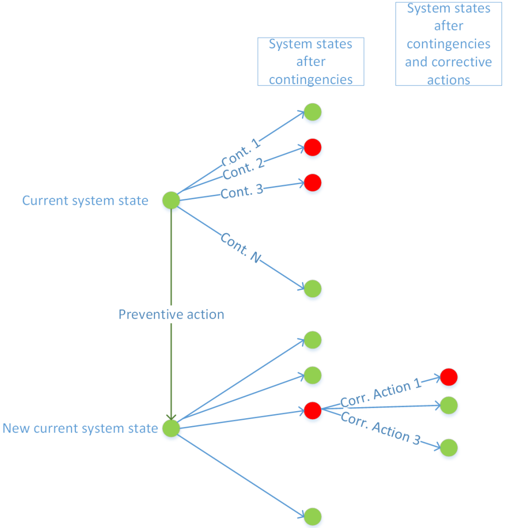
- u_c are the corrective controls. Note that they apply only in the corresponding contingency c.
- As many different u_c as contingencies.
- The last equation limits the possible range of corrective actions. For example: $\Delta u_c^{\max} = T_c R$, with T_c the time available to corrective control to react (say 10 minutes), and R the ramp rates of power plants (say 20 MW/min).

Preventive-corrective SCOPF - discussion

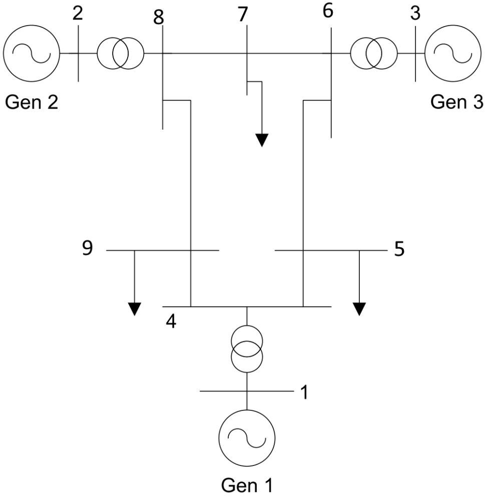
$$
\begin{aligned}
\min_{x_0, x_c, u_0, u_c} \quad & C(u_0) \\
\text{subject to } & g_0(x_0, u_0) = 0, \\
& g_c(x_c, u_c) = 0, \; c = 1, \ldots, n_c \\
& h_0(x_0, u_0) \leq h_0^{\max}, \\
& h_c(x_c, u_c) \leq h_c^{\max}, \; c = 1, \ldots, n_c \\
& \| u_c - u_0 \| \leq \Delta u_c^{max}
\end{aligned}
\qquad \text{(PC-SCOPF)}
$$

- u_0 is now the cheapest set of preventive actions that enforces security limits, knowing that corrective actions are available
- Remember, corrective actions u_k are not taken now.
- Preventive actions u_0 affect all pre- and post-contingency systems. The corrective action u_c affects only the system after contingency c.

Preventive and corrective actions - Illustration



Example



See examples in MATPOWER

Preventive-corrective SCOPF - discussion 2

$$\begin{aligned}
\min_{x_0, x_c, u_0, u_c} \quad & C(u_0) \\
\text{subject to} \quad & g_0(x_0, u_0) = 0, \\
& g_c(x_c, u_c) = 0, \; c = 1, \ldots, n_c \\
& h_0(x_0, u_0) \leq h_0^{\max}, \\
& h_c(x_c, u_c) \leq h_c^{\max}, \; c = 1, \ldots, n_c \\
& \| u_c - u_0 \| \leq \Delta u_c^{max}
\end{aligned} \tag{PC-SCOPF}$$

What is the problem with this formulation? (Hint: corrective controls react in, say, 10 minutes)

Corrective actions and short-term limits

From the network code on operational security, Article 8:

a) Normal State:
   i. voltage and power flows are within the Operational Security Limits defined according to Articles 10 and Article 12 in accordance with Article 8(5) and frequency is within the frequency limits for the Normal State as defined in [NC LFCR];
   ii. Active and Reactive Power reserves are sufficient to withstand Contingencies from the Contingency List defined according to Article 13; and
   iii. operation of its Responsibility Area is and will remain within Operational Security Limits even after a Contingency from the Contingency List defined according to Article 13 and after effects of Remedial Actions;

and Article 12

5. In the (N-1)-Situation in Normal State each TSO shall keep power flows within the Transitory Admissible Overloads, preparing and executing Remedial Actions including Redispatching, to be applied within the time allowed for Transitory Admissible Overloads.

- Remember: emergency limits can be sustained for a short while (say 10-15 minutes)
- If the flow on a line is larger than the continuous limit but smaller than the emergency limits ⇔ "Transitory admissible overloads"
- TSOs have a certain amount of time (10-15 minutes) to implement corrective actions.

Preventive actions = pre-fault remedial actions; corrective actions = post-fault remedial actions.

Improved preventive-corrective SCOPF

$$
\begin{aligned}
\min_{x_0, x_c, u_0, u_c} \quad & C(u_0) \\
\text{subject to } & g_0(x_0, u_0) = 0, \\
& g_c(x_c, u_c) = 0, \; c = 1, \ldots, n_c \\
& h_0(x_0, u_0) \leq h_0^{\max, LT}, \\
& h_c(x_c, u_0) \leq h_c^{\max, ST}, \; c = 1, \ldots, n_c \\
& h_c(x_c, u_c) \leq h_c^{\max, LT}, \; c = 1, \ldots, n_c \\
& \|u_c - u_0\| \leq \Delta u_c^{max}
\end{aligned}
\tag{PC-SCOPF}
$$

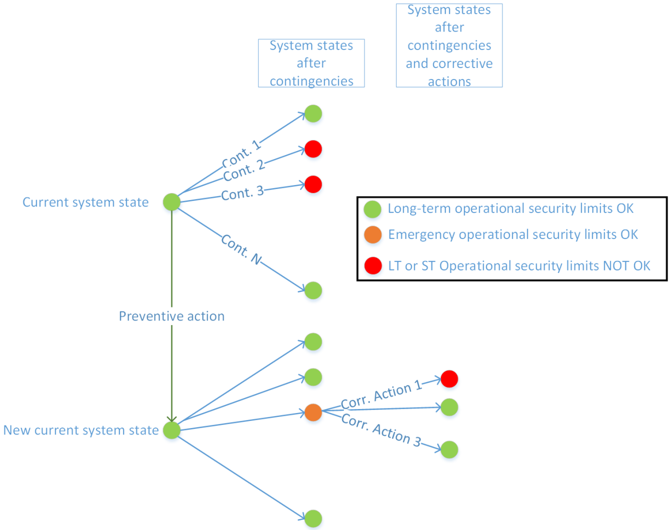
- $h_c^{\max,ST}$ and $h_c^{\max,LT}$ are the emergency and continuous ratings.
- Preventive actions ensure that the post-contingency systems are within the emergency limits while corrective actions can be called upon to bring the system back within the continuous limits.

Improved preventive-corrective SCOPF

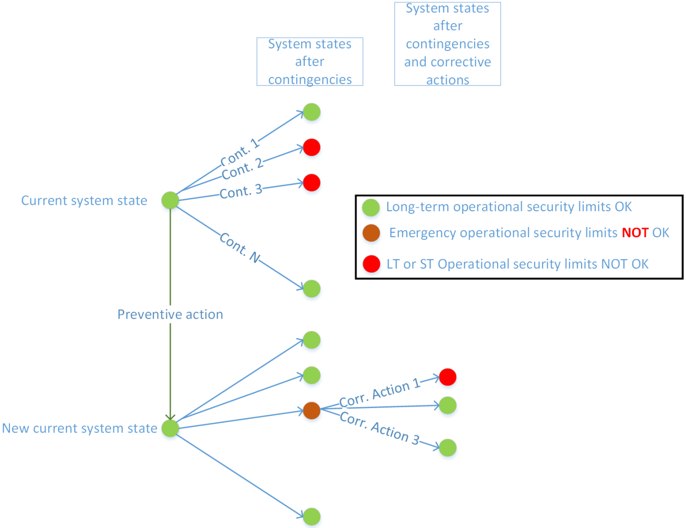
$$
\begin{aligned}
\min_{x_0, x_c, u_0, u_c} \quad & C(u_0) \\
\text{subject to} \quad & g_0(x_0, u_0) = 0, \\
& g_c(x_c, u_c) = 0, \;\; c = 1, \dots, n_c \\
& h_0(x_0, u_0) \leq h_0^{\max, LT}, \\
& h_c(x_c, u_0) \leq h_c^{\max, ST}, \;\; c = 1, \dots, n_c \\
& h_c(x_c, u_c) \leq h_c^{\max, LT}, \;\; c = 1, \dots, n_c \\
& \| u_c - u_0 \| \leq \Delta u_c^{max}
\end{aligned}
\qquad \text{(PC-SCOPF)}
$$

- Proposed in Capitanescu and Wehenkel (2007), “Improving the statement of the corrective security-constrained optimal power-flow problem”

Improved preventive-corrective SCOPF - illustration



Improved preventive-corrective SCOPF - illustration



Questions

- What do we mean by "system state"? How to determine it?
- What is the difference between OPF and SCOPF?
- Two examples of situations in which TSOs can make use of SCOPF.

Agenda

Challenges

- SCOPFs are nonlinear nonconvex optimization problems.
- Needless to say, there are challenging to solve.
- Challenge 1: Size of the problem (number of constraints and number of variables)
- Challenge 2: Nature of the problem for the full AC formulation (nonlinear nonconvex) $\Rightarrow$ Solving such problems is hard.
- Challenge 3: Including all possible types of control (including discrete control actions such as tap changer actions and line switching) $\Rightarrow$ Mixed integer optimization problem $\Rightarrow$ Even harder problem!

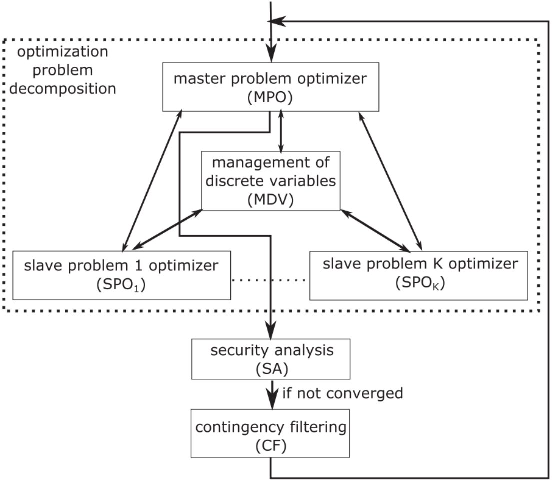
State-of-the-art

Read these three excellent sources:

- Capitanescu, "Critical review of recent advances and further developments needed in AC optimal power flow," 2016.
- Stott and Alsaç, "Optimal power flow–basic requirements for real-life problems and their solutions," 2012.
- FERC, "Optimal power flow and formulation papers", `https://www.ferc.gov/industries/electric/indus-act/market-planning/opf-papers.asp`

Solution method

General solution method:



From Capitanescu, "Critical review of recent advances and further developments needed in AC optimal power flow," 2016.

In use today

- DC-SCOPF implemented today by many independent system operators in the US for clearing the market.
- Some European TSOs have an implementation of an AC-SCOPF for real-time security optimization (every 15 minutes) (see for example López, 2015, "Swiss TSO experience with an ac security-constrained optimal power flow application for real-time security management").

Agenda

Take-home messages 1

- Security = making sure that the system fulfils operational security limits even after contingencies occur.
- Contingency list to be considered = at least the N-1 contingencies.
- Preventive actions affect the system now and after any contingency occurs.
- Corrective actions affect the system only after a contingency occurs.

Take-home messages 2

- SCOPF is one tool to find preventive actions to apply now.
- Corrective actions are included in SCOPF to avoid being too conservative when finding preventive actions.
- Corrective actions determined by SCOPF can of course be used should contingencies actually occur.
- Preventive versus Preventive-Corrective versus Improved Preventive-Corrective SCOPF.
- AC SCOPF is a hard problem to solve.
- SCOPF is a mathematical tool for solving a power system problem. Don't lose the underlying power system problem (when does it arise? why do we want to use SCOPF? What are the physical phenomena involved? . . .)!

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