MANAGING VOLATILITY IN DISTRIBUTION NETWORKS WITH ACTIVE NETWORK MANAGEMENT

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ABSTRACT

The traffic light concept of the German Association of Energy and Water (BDEW) to coordinate and market power in the distribution system level defines different mechanisms to ensure network stability in dependence of the criticality of the system state. But what is a critical network condition and how is it possible to detect a critical network condition timely, effective, and possibly also at distinct locations? Especially when facing the insufficient number of measuring devices at medium and low voltage levels. A possible solution for this problem are modern techniques for network state estimation, which determine a realistic picture of the actual network conditions with the aid of a limited number of real time measurements. This paper shows how network state estimation can be applied to detect critical network states and how the right conclusions for grid stability can be derived with respect to the traffic light concept of the BDEW.

CHALLENGES TO IMPLEMENT THE BDEW TRAFFIC LIGHT CONCEPT

The traffic light concept is designed to coordinate grid and market on distribution level and defines several approaches to ensure network stability depending on the severity of the network state. The question is what is a critical network state and how can such a critical network state be predicted early enough in an efficient manner with sufficient localization.

Current situation in German distribution grid

Looking more closely on the degree of transparency in the German distribution grid, we experience a well monitored – means measured - 110 kV level while the 20 kV level and below in most cases lacks any information. Measuring equipment is mainly limited to the large transformer substations while the medium voltage grid is not automated at all. However, the growing number of distributed energy resources is leading to unclear power flow directions and volatility. The traffic light concept is an approach to manage those problems.

Possible solution with network state estimation

Possible counter measures are new concepts to estimate the network state despite the limited number of real-time measurements [1]. These algorithms use active and reactive power measurements as well as all available current and voltage magnitude measurements in combination with the static network model, load profiles and generation forecast to calculate the most probable network state given the input data. The algorithms incorporate repeated power flow executions. The distributed energy resources (wind, photovoltaic and bio mass ...) should be aggregated per distribution substation and the respective power supply should be either calculated based on measured reference systems or modelled based on generation forecast data. With this approach a detailed view of the network state can be obtained independent of the availability of real-time measurements at each single station. In addition the power flow based algorithms provide the information about availability of flexibilities on market level (yellow traffic light). As at the same time those counter measures can be simulated and evaluated, it is possible to initiate further measures as early as possible (red traffic light). Thus the network state estimation provides a sound base to identify critical network states and to calculate and evaluate counter measures.

CALCULATION OF THE EXPECTED NETWORK STATE

The following sections show how modern algorithms for network state estimation can be used to detect in a systematic way whether the network state is reaching a critical state and consequently to calculate counter measures. The network state estimation is typically an integrated component of the power control system for distribution grids. This application calculates network state information in real-time and is re-calculating whenever the network topology changes or significant measurement changes occur. It calculates voltage magnitude and angle at each network node. The following information is presented to the operator as comprehensive results:

- Alarms to indicate critical network states that need immediate attention.
- Limit violations to indicate areas of problems
- Total active and reactive power as well as power factor as key figures representing the energy exchange with the transmission grid
- Voltage reserve to indicate available flexibilities

Network state estimation algorithm

The network state estimation algorithm in [1] works with measurement areas and load groups. Measurement areas are network subsections bordered by measurements or open switches. Load groups are loads with similar weighting factors within one measurement area.

The estimation problem is solved using Weighted Least Squares (WLS) approach defined as a minimization of the objective J described by the equation (1). The goal is to provide nearest estimates to a given measurement set consisting of power measurements (1st row), pseudo power measurements at load groups (2nd row), current magnitude measurements (3rd row) and voltage magnitude measurements (4th row). Additionally, for each measurement area the following equality constrains must be fulfilled:

- Sum of estimated active power within the area including estimated power at real and pseudo measurements and active power contributed by generators covers power losses (2)
- Sum of estimated reactive power within the area including estimated power at real and pseudo measurements and reactive power contributed by capacitors covers power losses (3)
- For each measurement area having a P and Q pair calculated from current magnitude measurement estimated Pc E , Qc E , Ic E and Vc must fulfil (4).

$$J = \min \left\{ \begin{array}{ll} \sum_{i=1}^{NPQ} \left[w_i^{PM} \left(P_i^E - P_i^m \right)^2 + w_i^{QM} \left(Q_i^E - Q_i^m \right)^2 \right] & + \\ \sum_{i=1}^{NLG} \left[w_i^{P,LG} \left(P_i^{E,LG} - P_i^{LG} \right)^2 + w_i^{Q,LG} \left(Q_i^{E,LG} - Q_i^{LG} \right)^2 \right] & + \\ \sum_{i=1}^{NI} w_i^{IM} \left(I_i^E - I_i^m \right)^2 & + \\ \sum_{i=1}^{NI} w_i^{VM} \left(V_i^E - V_i^m \right)^2 & + \end{array} \right\} \tag{1}$$

$$\sum_{i=1}^{NMK} P_i^E + \sum_{i=1}^{NGK} P_i^{Gen} - \sum_{i=1}^{NLGK} P_i^{E,LG} - P_{loss}^k = 0 \tag{2}$$

$$\sum_{i=1}^{NMK} Q_i^E + \sum_{i=1}^{NGK} Q_i^{Gen} + \sum_{i=1}^{NCK} Q_i^{Cap} - \sum_{i=1}^{NLGK} Q_i^{E,LG} - Q_{loss}^k = 0 \tag{3}$$

$$\left(P_c^E \right)^2 + \left(Q_c^E \right)^2 - (V_c\, I_c^E)^2 = 0 \tag{4}$$

NPQ , NI	Total number of power and current measurements respectively
NLG , NLGK	Total number of load groups and load groups in area k
NMK	Number of P-/Q- pairs converted from currents in area k
NGK , NCK	Number of generators and capacitors in area k respectively
$w_i^{PM}, w_i^{QM}, w_i^{IM}$	Weighting factors for active, reactive power and current measurements
$P_i^E, Q_i^E, I_i^E, V_i^E$	Estimated active and reactive power, current and voltage related to measurement i
$P_i^m, Q_i^m, I_i^m, V_i^m$	Measured active and reactive power, current and voltage respectively
$w_i^{P,LG}, w_i^{Q,LG}$	Weighting factors for active and reactive power of load group i
k_i^P, k_i^Q	Estimated scaling factors for power of load group i
P_i^{LG}, Q_i^{LG}	Active / reactive power of load group i
P_i^{Gen}, Q_i^{Gen}	Active / reactive power of generator i
P_{loss}^k, Q_{loss}^k	Power losses in area k
V_c, P_c^E, Q_c^E, I_c^E	Voltage and estimation results for a current converted to power

The estimation algorithm has additionally to satisfy inequality constraints, i.e. load groups scaling factors have to be kept within specified limits.

As proven in [2] already with P, Q, I, V measurements at substations and a limited set of additional measurements along the feeders an accurate result can be obtained.

LOAD AND GENERATION MODELLING

Data sources

Load data is usually obtained from several different sources such as Accounting data, Sampling and load classification, Automated Meter Readings (AMR) and Advanced Metering Infrastructure (AMI). Except for the AMR and AMI sources which are accurate but come late to the system, load data is mostly unreliable, and not well maintained. Although the State Estimator handles even very large discrepancies between initial load values and the real/estimated measurements, this difference should be as small as possible. The Short Term Load Scheduler (STLS) is utilized to reduce the number of iterations in the subsequent estimation process. Most important to note is that STLS works with real time Distribution System State Estimation (DSSE) in negative feedback, see Figure 1. STLS is also considering the reliability of DSSE results by calculated trust factor.

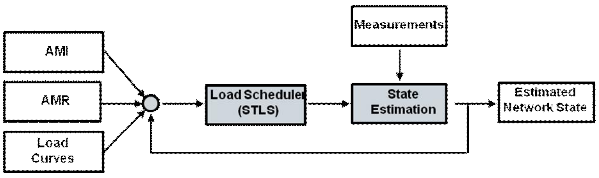


Figure 1 - Load data preparation in STLS

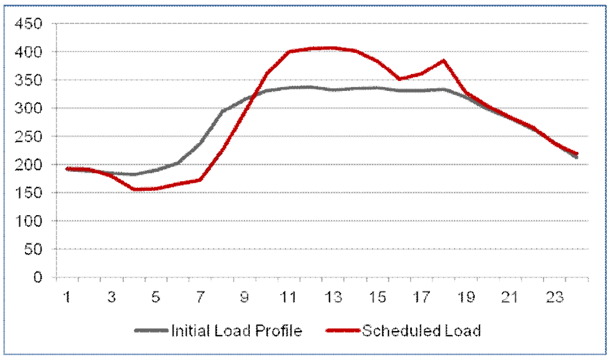


Figure 2 - Comparison Graph showing the difference between scheduled and STLS data after several weeks

Generation Model

While in the past all loads were supplied by large central plants, nowadays more and more generation is available in the distribution grids due to increasing wind, photovoltaic and biomass generation. Therefore it is not sufficient anymore to model this distributed generation using a static curve model, since this is not accurate enough and doesn't consider weather factors which have a very big impact on this kind of generation. Integration of generation forecast data into the DSSE provides high additional value with regard to accuracy of results.

ADVANCED ANALYSIS

General considerations

While Distribution System State Estimation provides the most probable status of the grid, Active Network Management (ANM) determines which network parts may suffer from instabilities and how to resolve these. The main application of the ANM is the Volt/Var Control (VVC) [3] [4]. VVC is formulated as an optimization problem with different goal functions such as minimization of power losses or minimization of reactive power flow while considering limits on control and state variables. Control variables are remote load tap changers, capacitors, batteries, controllable loads and distributed energy resources. State variables are voltage magnitude and angles at each network node.

VVC is solved by the steepest gradient method. The objective function value is determined from the power flow solution given the settings of the control variables.

The optimization is based on minimizing a multiple term objective function. The main optimization criterion "Minimal limit violations" can be freely combined with the following sub-criteria (sub objectives):

- Minimal power losses.
- Minimal active power consumption.
- Minimal reactive power consumption.
- Maximal revenue / voltage reserve

Minimal limit violation as the basic sub-criterion considers voltage deviations, transformer and feeder overload, power factor violations and cost of corrective actions.

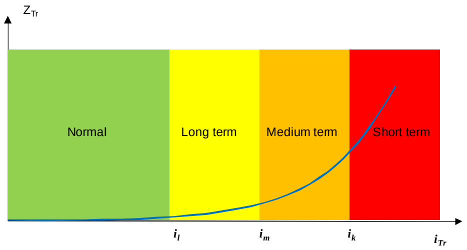


Figure 4 - Minimal Transformer overload sub-criterion

Based on this sub-criterion, the quantification of deviations from optimal values is performed. Optimal values are considered to be the ones that are within allowed limits (e.g. within technical limits). Figure 4 shows transformer violation areas. Violations can be classified as follows:

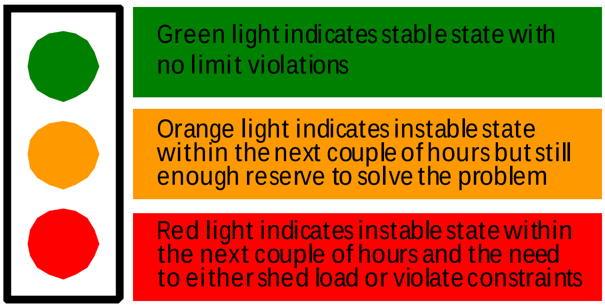
- Long-term limits may be violated for long period
- Medium-term limits may be violated for a specified period
- Violation of short-term limits requires immediate correction

Penalty factors (e.g. cost) are defined based on how serious deviations from optimal values are considered. The highest penalty factors are defined for short term areas.

VISUALIZATION CONCEPT

General approach

A semaphore model is used both as logical and visual presentation to mediate the obtained network state information in a user friendly and comprehensive way. The three discrete states reflect the network state and Distribution System Operator's ability to resolve the actual and anticipated volatility. This semaphore model is reflecting the so-called traffic light concept of the German Association of Energy and Water (BDEW) and is both concerned about the current and the near future (predicted) state. The single states can be defined as follows:



Green light indicates stable state with no limit violations

Orange light indicates instable state within the next couple of hours but still enough reserve to solve the problem

Red light indicates instable state within the next couple of hours and the need to either shed load or violate constraints

The calculation of the traffic light status is shown in Figure 5. As long as the network state is in green zone, only DSSE simulation is done (Step 1). If a potential volatile network state is determined, VVC is simulating counter measures by engaging available controllers, such as remote load tap changers, capacitors, batteries as well as controllable loads and distributed energy resources. If these countermeasures resolve the network state the traffic light is set to orange. If it is not possible to resolve the network state, an alarm is issued for the operator and all necessary information is provided for further analysis. The process of generating the semaphore can be expressed mathematically through a discrete objective function as shown in (5). The total objective function is calculated as normalized figure and based on the predefined border value G_{zone} a semaphore state is determined.

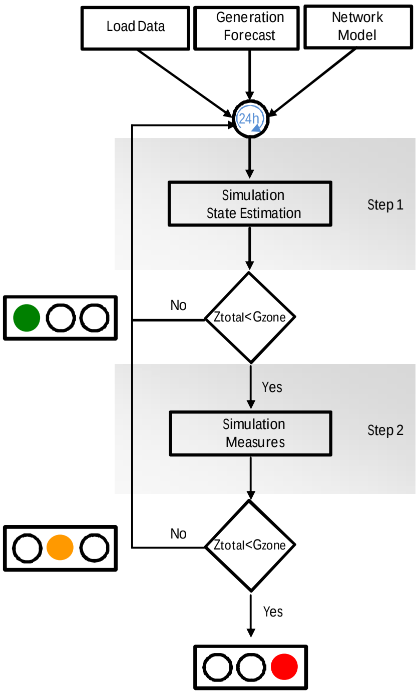


Figure 5 Calculation of semaphores

$Z_{tot} = W_{li} * F_{limits} + W_{lo} * F_{loading} + W_R * F_R + W_{PF} * F_{PF}$ (5)

Where:

$W_{li}, W_{lo}, W_R, W_{PF}$:	weighting factors
F_{limits}:	*U*, *I*, *P*, *Q* and $\cos(\varphi)$ limit violations
$F_{loading}$:	Total loading of network
F_R:	Reserve status (e.g. battery state of charge, capacitor and load tap changer potential)
F_{PF}:	Power factor at the injection

Sample Visualization for Operator

The traffic light can be presented to the operator as shown in Figure 6.

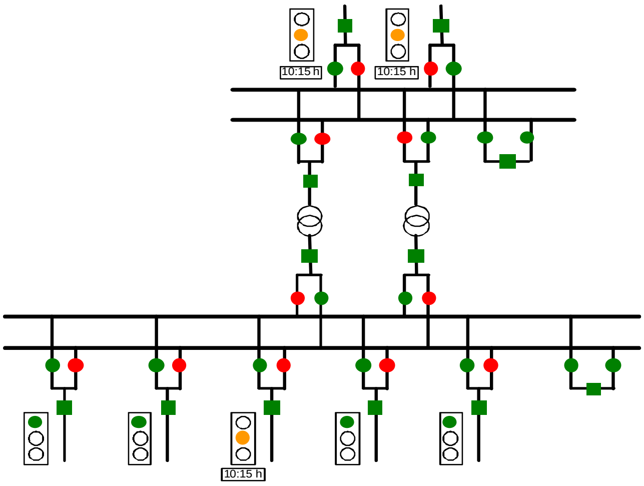


Figure 6 Operator Overview

The most detailed level is the feeder. Typically you can find feeder that will face more likely critical situations than others. Therefore it is very important to point the user's attention to those feeders where problems are expected. At the injections the traffic light can be calculated as logical "or" combination of the states of the single feeders. The traffic light should always show the worst case situation, means a red traffic light is shown as soon as any of the feeders is in a critical state.

Finally the State Estimation can be visualized in the most optimal way as shown in Figure 7 as overlay of time, state and geography to provide a comprehensive overview as base for further decisions. The contouring is done with the color code used for the traffic light.

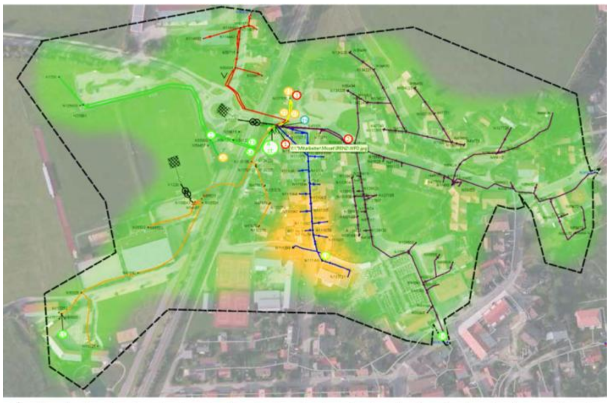


Figure 7 Geographical representation of the network situation (08:30 AM)

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