Czech Technical University in Prague

Faculty of Electrical Engineering

Intelligent transmission and distribution systems

Habilitation thesis

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Abstract

The thesis focuses on the issues of advanced methods to achieve security and reliability of electrical power systems, mainly focusing on transmission systems. Advanced principles and techniques in monitoring systems are discussed. The key part of the thesis deals with Smart Grids and WAMPaC systems (Wide Area Monitoring, Protection and Control) application possibilities. Assessment criteria are explained in mathematical form and demonstrated in terms of case studies. Significant power system states were analyzed in the case studies.

For methods and algorithms verification purposes various power system models were established. Based on simulation outputs appropriate algorithms and their parameters were found to create the local automatics. The issue of local automatics functions is described using the general abstract layer model. One of the local automation principles is described in details - the Automatic Power System Stabilizer (PSS). Results indicate that simulated PSS in this case significantly increase the stability of the connected power plant. Due to the impedance characteristics and time constants in this case PSS does not influence the behavior of the sources under nearby fault conditions. In the final part od the thesis there are requirements on information and communication technologies which are analyzed and evaluated in the terms of transmission and distribution networks operation.

The benefit of this work is mainly the model of local automation increasing the stability of the connected source. For monitoring and automation purposes synchrophasor measurements are used. For algorithm verification purposes the model with parameters close to the real power system with real sources was created. The implementation part consists of the construction of the local automatics model – power system stabilizer and its verification under various states and system operation conditions. The model was created in the general environment, so it would be easily implemented into larger models in the future.

Keywords

Power System Safety and Reliability, Synchrophasor measurement, Local Automation, Power System Stabilizer, Power System Stability.

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Contents

1. Introduction

Advanced power systems equipped with all the usual protection functions and systems were affected by significant failures in recent years. These events had a number of accompanying phenomena from frequency oscillation to large system collapses. The development and dynamic deployment of new sources (especially renewable) carry unusual system states in comparison with previous conditions. The complexity and size of the interconnected systems entail the need to deploy additional technologies to monitor the system state.

The current trends in the transmission and distribution of electricity in convergence with the development of information and telecommunication technologies toward integration of technologies are commonly used in the field of IT in the energy sector. This leads to the enrichment of the traditional concept of the network operation of new, previously unfeasible, approaches and opportunities. The transition from the traditional concept of networks of concepts WAMPaC and Smart Grids course brings a number of negative aspects - the connection of multiple technologies has a significant impact on the reliability and security - networks are usually operated closer to the border of stability, characterized by greater penetration of energy sources, etc.

The deployment of new technologies and concepts in energy is traditionally more tied to the current situation than in other rapidly evolving fields (IT, CT). Due to the complexity of network construction and resources it is not possible to build a new system to "scratch" in developed countries. This is due to the economic and legal demands. In the development of new concepts and technologies in the transmission and distribution there is a rule that is based on the existing power network topology; New elements are usually seeded in the communication and control layers as an extension of the existing power technologies.

In the transmission systems area the most developed technologies belongs to the group WAMPaC (Wide Area Monitoring, Protection and Control System). The most discussed issue in this area is called the synchrophasor measurement (PMU - Phasor Measurement Unit).Synchrophasor measurements are based on The Phasor Measurement of quantities in major network nodes, the key is to complement these measurements with accurate timestamps (in practice use a satellite or synchronization protocols). Within Europe, the implementation of various pilot projects is in progress concentrating usually on one particular issue.As a key to the operation of power systems in the future it appears to be deepening of mutual cooperation of network operators - close interconnection of systems it will be necessary to realize not only the power lines, but the data lines with guaranteed parameters.

In the distribution systems area the current trend is the so called SmartGrids. SmartGrids are technologically equivalent of the WAMPaC in transmission systems. The development and implementation of these technologies encounter most of the economic aspects of investment required by "upgrade" of the existing system. Since the initial phase of this concept there are not yet available standards for individual elements/technologies (or power or telecommunications). Especially for this reason there is a confusing number of elements with proprietary characteristics and protocols. Each grid therefore often uses incompatible systems and their bonding is at least difficult.

The above-mentioned aspects can in many cases improve the efficiency, safety and stability of electricity supply, but their dysfunction may cause a collapse. In particular, this is closely related to the conditions associated with outages of the measurement and actuators, system failures, and last but not least, human failure.

2. Current state-of-the-art in WAxS and Smart Grids

Currently, the power of most of the plants is directly connected into the UHV and HV networks. The grid at these voltage levels is typically operated as a loop or meshed systems, which is fully ready for the bidirectional flow of electricity. The basic type of protection at voltage levels of 400 kV, 220 kV and 110 kV are directional distance protections which do not require time delay for obtaining required selectivity. These networks are fully equipped with the necessary tele-mechanics and automation, such as automatic voltage regulation. All substations at these voltage levels are equipped with the necessary technological and communication infrastructure.

The distribution at the HV and LV voltage levels mainly has a passive character. In these networks there are prioritized traffics in the so called "normal connection". Most of the topology changes are done manually. Automation functions are used very rarely. HV and LV networks are designed for radial operation in which it is assumed that there are unidirectional power flows. The basic type of overcurrent protection is implemented by a simple function that is non-directional.

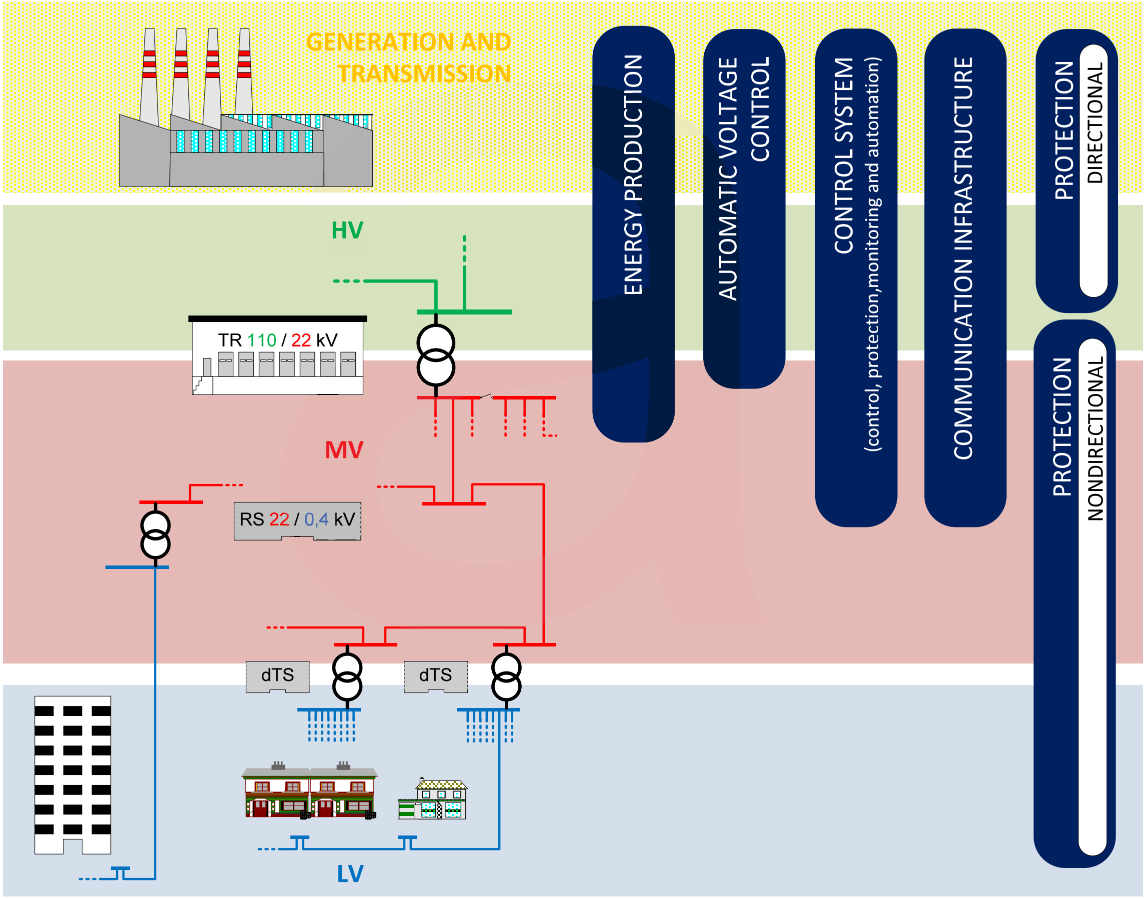


Fig. 1: Current distribution system model

Information from the lower levels of the distribution system are usually not transmitted to the dispatch center. Energy parameters at lower distribution levels are derived from measurements in parent substations, which is due to the radial DS operation partly possible and meaningful.

The development of the distributed generation will lead to structural changes in the distribution of electricity in particular MV and LV voltage levels. Basic and fundamental changes from the status quo will result in bidirectional power flows in HV and LV networks, which would completely change the operational characteristics of the DS.

To maintain the viability of the distribution network in the new conditions we are talking about the necessity of implementation of the Smart Grid concept. The MV and LV network fulfilling the basic principles of Smart Grid should be as close as possible to the network with loop or mashed shapes.

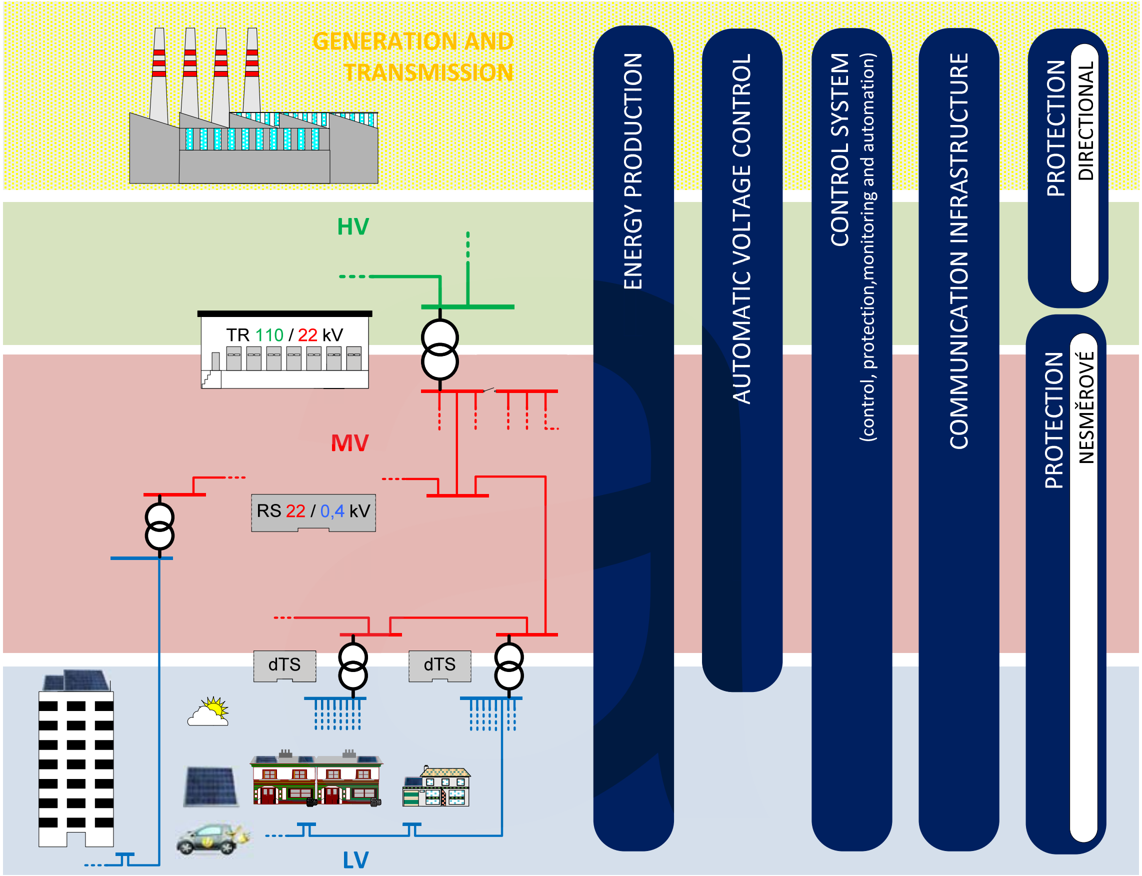


Fig. 2: Future distribution system model

The concept of Smart Grid is also associated in particular with the development of systems providing monitoring, control, protection and automation for lower voltage levels of the distribution network. Strict requirements on communication infrastructure are related with the developement of these systems. Deployment of this technology is a prerequisite for ensuring the functionality of "smart grid".

The concept of Smart Grid is also characterised by a distribution of process control networks into system layers. An important role is held by a central management process, which is nowadays fully applied to the voltage level of the EHV and HV level. This process is further extended to the lower levels of the distribution network. These aspects lead to new process requirements providing the following functionality:

- voltage regulation and stabilization
- Balance automation
- Automatic self-healing
- Automatic islanding
- adaptable protection system
- monitoring of electrical and non-electrical quantities at substations terminals (HV and LV)
- information preprocessing (for supervisory systems)

VPP and PPP are characterized by considerable variability in power supplied to the grid.Smart Grid enables flexible management of the balance of power at a distribution level. Smart Grid thus allows minimizing of the need for auxiliary services provided by the transmission system operator. This leads to the minimization of losses in the grid.

A specific area in the presented PS scheme is the final consumer.Power management is provided by the concept of Smart Metering. Specifically, the link between the processes of Smart Grid and Smart Metering.

3. Intelligent grids Trends and Technologies

The task of this distribution network is to create conditions for the electricity distribution under new conditions that are characterized by many aspects listed below:

- higher rate of local electricity sources applications;
- a certain part of local sources has the character of renewable energy sources (RES);
- selected parts of the distribution network can be operated and managed as a more or less autonomous region;
- areas autonomy is understood as the ability of operation and management tasks realization which uses the complex of all the installed devices that allows e.g.:
  - automatic network reconfiguration after a failure (self-healing aspect);
  - maximal power and energy balance, especially with regard to minimize negative effects on the superior network levels;
  - balanced voltage profiles in all modes of the network operation;
  - optimization (minimization) of the needs of system services is related with the local sources operation (system operation needs compensations at the local level);
  - defining the area operation in a critical state with limitation of consumption/supply to costumers to the so-called security minimum;
  - allowing the island area operation using only local sources of electrical energy;

The mentioned aspects are only examples of the basic characteristics of the Smart Grid concept. The further developed final architecture is designed to cover or to create conditions for future coverage a wide range of evolving aspects of the Smart Grids concept. Not only in its guidelines (core aspects) but also in those which are known as side effects and also those that are multiplying benefits (synergistic effects) of the concept.

3.1. Distribution systems

The structure and content of the document follows the structure and content of the entry:

- **Distribution system model** – architecture topology design by layers (including changes in ICT, management of DS, links to the AMM and to existing systems)
- **Distribution network general structure description**, including all related parts, represented by above-mentioned layers
- **Functions of distribution system** – the list of functions and necessary changes in the distribution system

The specification of all usual functions at all distribution system levels with a special focus on:

- Requirements and parameters of new technological elements (components) by layers of distribution system for ensuring required functionality of the Smart Grid
- Requirements for networks protection
- Requirements for network management and technological equipment in the island operation
- Requirements for sources control

- **Application of standards** – the requirements for distribution system solutions from the perspective of standardization oriented on implementation of the Smart Grid concept
- **List of specific standards by various layers of the distribution system** – all understood as a framework for the Smart Grid concept with respect to the current state for further development

MV System Concept

Outgoing feeders led to transformers must be equipped so that they fulfil conditions for all operation modes. It means that the outgoing feeder must be functional both in the 10 kV system and in the 35 kV system. At the same time it must satisfy the operation conditions within the feeding from the superior system and also in the island operation. These above mentioned operation states are so much different that it is almost impossible to dimension the fuse so that it fulfils the conditions for safety disconnection of the transformer outgoing feeder in case of internal transformer fault. This shows that the transformer outgoing feeders must be equipped by circuit breakers with appropriate IED, which can be parameterized in accordance with the system requirements. This solution is of course more expensive then the solution with a fuse and a disconnector.

In case that there will be a change of island definition in the future it is possible to extend this solution by logical functions to avoid a dangerous state. The solution of logic can be solved by using of appropriate IED that would be needed just to make quick commands on LV side of station.

LV System Conception

It is possible to use the same solution during the second stage as in the first one in particular nodes at the expense of higher costs. The selection of these nodes is closely related to the importance of involved take-offs (critical infrastructure, public lighting and buildings of public importance). It is possible to employ the classical solution in the rest of the system.

To fulfil basic principles of Smart Grids the topology of a low voltage network should be as close as possible to the nodal topology. Due to the needs to preserve the current low voltage net topology, it is necessary to save fully functional weak coupling – for both the areas powered by only one DTS, eventually mutual connection of power distribution transformer stations at the low voltage level. It can be necessary to use parameterizable LV protections in such cases. The utilization of this type of interconnection is limited by the transmission capacity of existing cable splices. This limitation can be improved by the supplementation of the existing LV network with new LV interconnections placed into reconstructed MV corridors and serving mainly during supply failure at the MV level. It is actually analogy of the bridging used at higher levels, where the bridges must be disconnected during common operation (see Fig. 5). It is always necessary to verify the solution suitability by model evaluation of a particular station and topology. Utilization of bridge connections is advised mainly during the second project stage. The existing interconnections are likely satisfactory within the first stage (see Fig. 4).

This alternative provides only very limited opportunities for changes of low voltage network configuration. It must be always supplemented by a handmade reconfiguration of classical protection elements (fuses) in the case of fundamental change in the network configuration from the point of view of power flow directions and preserving of protection selectivity. A partial automation together with a higher systems software support in combination with suitably adjusted project (inputs for the project should be partial results and conclusions from concurrently being solved studies of dynamical model and of island operational state) facilitates the same reliability and similar operational functionality as the remaining parts of the system.

For island operation severance and controlling the following components and technologies are available in the scope of Smart Region:

- Circuit breakers in split-up points with appropriate telecommunication infrastructure
- Synchrotacts for subsequent connection of an island to the network
- Automation of low voltage outlets for the balance control
- Possibility of access to the AMM centre for "slow control"

Another option is to extend the island by other selected DTS, respectively DTS outputs. An example of such an island is in figure 20. For the implementation of this concept it is necessary to provide individual integrated DTS by:

- Remote-controlled circuit breaker or disconnector for MV side – the possibility to pin or unpin a DTS
- Remote-controlled circuit breaker or disconnector on LV outlets – the ability to control the outputs from DTS (e.g. output for public lighting, hospital or another building of public importance)
- The area must be for all situations balanced – i.e. some outlets will be disconnected in island operation

The version of the island expansion (figure 20) is one of the options for future system expansion. Decision about possible equipment of involved stations should be based on experiences with island operation in the first stage. For now it is not economical to fully equip DTSs with low-voltage circuit breakers and IEDs.

One of the solutions is a stand-in automatic that can be applied in both project stages. The existing connection is fully used in the first stage and it is expected that these weak coupling points will be connected in the normal state of the system. Flows and protection parameters must be checked in the scenario.

The second stage of realization offers a solution to extend the existing LV system that new cable connections will be put between selected DTSs in terms of MV corridors reconstruction. These connections must be always switched off when powered from both sides because the load influences both DTSs.

Within judgment of the possibility of linking the AMM and the Smart Grid control system a version of the control system connection with AMM concentrators was considered. This option is no longer used because of the concentrator's interconnection impossibility due the usage of proprietary protocols on these elements. If it is possible to communicate with the concentrators in DTS directly on the control system level, this solution can also be used.

3.2. Wide Area Systems

One approach bringing new possibilities for system deployment are WAMS, WAPS and WACS (Wide Area Monitoring System, Wide Area Protection System and Wide Area Control System). These systems are sometimes not very well understood only as synchrophasors measurement systems. To use advanced features information from existing systems are required (range of system states can be observed using conventional measurements with higher accuracy) as well as some information hitherto not entering the monitoring and control systems (in particular synchronously measured values of voltage and current phasors). A number of applications can be significantly refined using additional means (eg, monitoring of mechanical vibrations for ampacity monitoring).

Phasor Measurement Units (PMU - Phasor Measurement Unit) are considered one of the most important measuring devices in the transmission systems in the future. Their uniqueness is in the ability to measure, communicate and collect data including measured voltage and current phasors in different electrical network substations. Time synchronization is performed using the GPS system. Requirements for phasor measurement units PMU are described the standard IEEE C37.118, currently valid regulation does not define the behavior of the PMU units in transient states. In the future I expect direct waveform measurement and processing, which better describes the dynamic behavior of the system, and advanced methods application to identify the basic components of a transient.By using the phasors only a substantial part of the information is lost.

The safety and reliability of the power system operation should be monitored by both the voltage and transmission stability criteria (ie,. module voltage criteria, Load angles monitoring and frequency module monitoring).

At the beginning of a common strategy for the development of the European electricity system was a document entitled "Vision and Strategy for the European electricity system of the future," published in 2006. It presented "future" direction of development of energy networks. One of the possible concepts are called systems WAMPaC and "SmartGrids".

As part of a larger integration of renewable energy sources (RES) can be expected that there will be further changes in the power flow. The change in the calculation of the power system state (state estimation, load flow, voltage profiles) will be directly binded with these changes. Control strategies based on deterministic methods will be replaced by control elements on the basis of power electronics. With the renewable energy sources energy storage systems development would be required to solve problems with high production during consumption downturns and vice versa. It will therefore be necessary to develop devices that will be used to accumulate electrical energy. These devices may be used within the concept of virtual power stations.

3.3. Voltage and Power Flow Control

Voltage control in the power system is physically closely linked to the management of reactive power Q.

In the power grid there are several types of devices providing U / Q control:

- Transformers with tap changer
- Control of reactive power provided by power plants
- Compensation equipment, reactive power compensation for donations - Volt / Var control devices
- Power electronics devices

The classical distribution transformers can not change the transfer ratio under the load. For selected applications, however, transformers with on load tap changer OLTC (On-Load Tap Changer) is tested.

For the control of the reactive power resources it is especially required to coordinate the management of both the supply and consumption of the reactive power between the distributed resources.

Distributed generation for microgrids

Distributed energy sources for microgrids includes loads and sources, including distributed generation and advanced methods of storing energy to operate as individual systems providing both electrical power and heat. Most of the dispersed sources are equipped with power electronics to provide the required flexibility to ensure the operation as the aggregate of individual systems. Distributed generation systems include high-frequency AC source (microturbines) and DC systems (solar, fuel cells, etc.).

High efficiency and Distributed generation from renewable sources

The customer requires distributed energy sources, including the deployment of high-efficiency and renewable energy in civil, commercial and industrial equipment. These technologies include both commercial and appropriate technology as photovoltaics, microturbines, and engines and gas turbines. Future technologies will include advanced low cost technologies for PV, fuel cells and energy storage based on electric vehicles.Typical conversion systems will be based on power electronics (inverter).

Methods of energy storage

NaS batteries are available for energy storage for 8 hours at price levels 3 500 USD / kW. Redox batteries are suitable for smaller units with the price level of 2 800 USD / kW. These batteries can be used to cover peak loads and improve voltage stability during transient phenomena. Covering peak loads from batteries can be spared the cost of constructing additional transformer stations or other transformers.

Superconducting systems for the storage of magnetic energy are based on magnetic field created by a flow of DC current in the superconducting coil which is cryogenically cooled to a temperature below the critical temperature of superconductivity. These systems can provide not only the stability of the voltage, but have sufficient capability to dampen oscillations of the system and to mitigate transient instability.

Ultracapacitors are high energy, electrochemical devices with high energy density, which are easily charged and discharged. They have the ability to store energy like a battery for an extended period of time, but it can be released quickly as capacitors. Progress in their development can have a significant impact on the possibilities for energy storage.

Measures to increase the reliability on the part of customers

Numerous technologies and approaches responding to power deviations are commercially available. Some specific resources include:

The network-friendly device that monitors system parameters such as frequency and voltage and automatically shut down all or part of the load / generation from the network.

Integrated load management using the customer portal, which reduces consumption by dispatching instructions or according to customer defined parameters.

Integration of connected hybrid electric vehicles, fuel cells and other forms of distributed generation and advanced methods of energy storage and other restrictive options subscriptions on the customer side.

Advanced equipment for network management

Developments in the field of semiconductors, such as silicon carbide (SiC), gallium nitride (GaN), gallium arsenide (GaAs) and vacuum technology provide materials for fast switching high voltage, high current and high power electrical equipment such as FACTS, HVDC terminals, electronic transformers and circuit breakers for power electronics.

New types of switches to ensure the uninterrupted supply delivery from two independent power supplies.

D-VAR or DSTATCOM are small mobile FACTS devices. They use air cooling, IGBT transistors, and work with high efficiency with low harmonic content. They are placed at the interface of the transmission and distribution system at the entrance to the industrial enterprises to support voltage, flicker reduction, improve power quality, reduce impacts of wind power on distribution and transmission systems.

High-temperature superconducting synchronous capacitors are now available in size 10 MVAr as a competitive source of support dynamic voltage at the transmission and distribution system management flicker. These devices immediately respond to actual voltage conditions, may, if necessary, release of reactive energy reserve 2 to 4 times greater for seconds to minutes. These devices are cost effective and highly reliable source of voltage support in the grid.

New types of wires with high data transmission capability

Composite reinforced aluminum conductor costs 5 to 8 times more than a traditional aluminum wire, but its thermal resistance is 1.5 to 3 times larger. Aluminum conductor with composite core arranged in a trapezoid can be 3 to 5 times more expensive than a traditional aluminum wire, but its carrying capacity can be increased by 100%.

High temperature cables for HVAC applications can be used to transmit the high power of high voltage to the high voltage at high currents with low losses and a small warming. These cables have lower storage requirements in the ground and can be competitive with conventional underground cables with copper core. High temperature cables can carry an increased power for emerging areas in large cities.

High temperature cables can also be used for low voltage DC applications with a large reduction in cost to DC converters.

Fault current limiters (FCL) are thyristor-switched capacitor banks and reactors that are designed for fault currents up to 110 kA and operating voltages higher than 500 kV.

3.4. State estimation

Improving the accuracy of measurement requires collection and processing of additional information such as: correction curves, detailed static and dynamic models, the processing of the measured information, etc. For these conditions the concept of "Supercalibrator" is suitable.

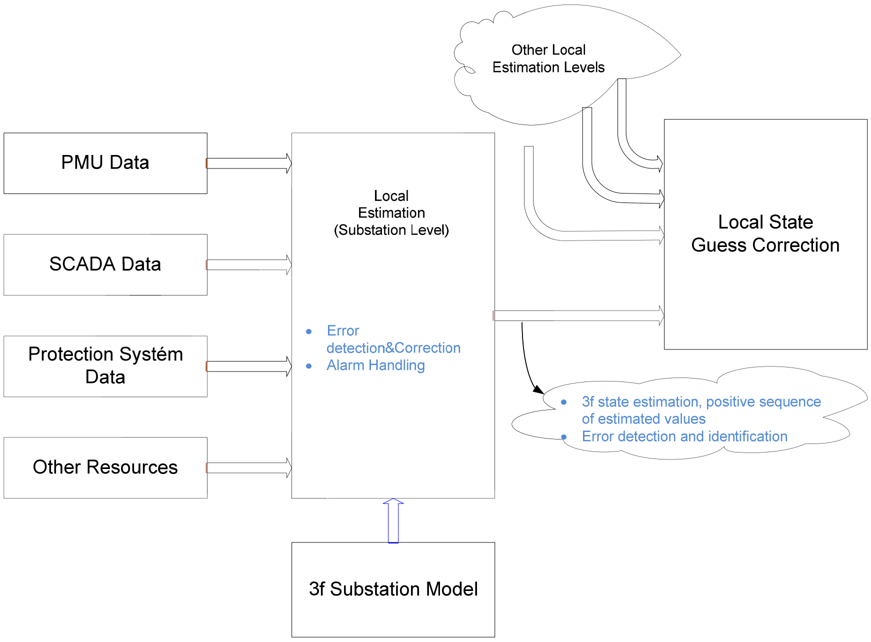


Fig. 3: Supercalibrator concept

Objective:

Eliminate errors in measuring chains and achieve high measurement accuracy

Means:

- elimination of systematic errors in measuring chains
- use of PMU measurements and all available measurements
- 3f model station and transfer function measurement channels

-
- synchronous parallel measurement and estimation in various local systems
- coordination of parallel distributed estimation methodology results

The sample applications are ranked in the measuring chain software calibration that corrects the "raw measurement" containing systematic errors "on calibrated measurements" as:

$$m_c = f\left(m_s, \bar{\mu}\right)$$

m_c… calibrated measured value

m_s… raw measured value

$\bar{\mu}$… calibration parameters vector

(1)

Measurements are performed as a three phase and in selected nodes also zero-point voltage is measured. If there are none of them the values are replaced with the pseudomeaured value.Vector of measured voltage *related to* the ith node is assumed to be of the form:

$$\hat{U}_k = \left[\hat{U}_{k,A} \quad \hat{U}_{k,B} \quad \hat{U}_{k,C} \quad \hat{U}_{k,N}\right]^T \tag{2}$$

The current in the branch between nodes *k* - *m* is thus:

$$\hat{I}_{k\_m} = \begin{bmatrix} \hat{I}_{k\_m,A} \\ \hat{I}_{k\_m,B} \\ \hat{I}_{k\_m,C} \end{bmatrix} = \left[\widehat{Y}_{ABC}\right]\left[\hat{U}_{k,A} \quad \hat{U}_{k,B} \quad \hat{U}_{k,C} \quad \hat{U}_{m,A} \quad \hat{U}_{m,B} \quad \hat{U}_{m,C}\right]^T \tag{3}$$

$\left[\widehat{Y}_{ABC}\right]$...... tř Three phase admitance matrix of the branch

The apparent power in the node:

$$\widehat{S}_{k\_m} = \begin{bmatrix} \widehat{S}_{k,A} \\ \widehat{S}_{k,B} \\ \widehat{S}_{k,C} \end{bmatrix} = \begin{bmatrix} P_{k,A} + \mathrm{j}Q_{k,A} \\ P_{k,B} + \mathrm{j}Q_{k,B} \\ P_{k,C} + \mathrm{j}Q_{k,C} \end{bmatrix} = \begin{bmatrix} \hat{U}_{k,A} & 0 & 0 \\ 0 & \hat{U}_{k,B} & 0 \\ 0 & 0 & \hat{U}_{k,C} \end{bmatrix} \begin{bmatrix} \hat{I}_{k,A} \\ \hat{I}_{k,B} \\ \hat{I}_{k,C} \end{bmatrix}^* \tag{4}$$

Estimation equation is solved according to the nature of the measurements to be linear or hybrid.

The advantages of supercalibrator:

- Three-phase model better describes reality than the model only positive sequence.
- Allows to effectively detect erroneous measurements
- More accurate measurement calibration
- Estimation submodel is very fast

Associated estimations are based only on the nodal voltages and branch currents values.

Summary table of estimation values

Estimation	**Measured values vector**	**Measurement equation**	**The state vector**
global	$\overline{m}$	$\overline{m} = \overline{\Phi}\left(\overline{x}\right) + \overline{v}$	$\overline{x}$
primary	$\overline{m}^{\{k\}}$	$\overline{m}^{\{k\}} = \overline{\Phi}^{\{k\}}\left(\overline{x}^{\{k\}}\right) + \overline{v}^{\{k\}}$ $k \in \langle 1, N \rangle$	$\overline{x}^{\{k\}}$
secondary	$\overline{m}_s^T = [\overline{m}_\delta^T, \overline{x}^{\{h\}T}]$	$\overline{m}_s = \overline{\Phi}_s\left(\overline{x}_s\right) + \overline{v}_S$	$\overline{x}_s^T = [\overline{\delta}_b^T, \overline{x}^{\{h\}T}]$

The results of the primary estimation $\overline{x}^{\{h\}}$ are used as a input into the secondary estimation as quasimeasurement

The overall structure is shown in **Fig. 4.**

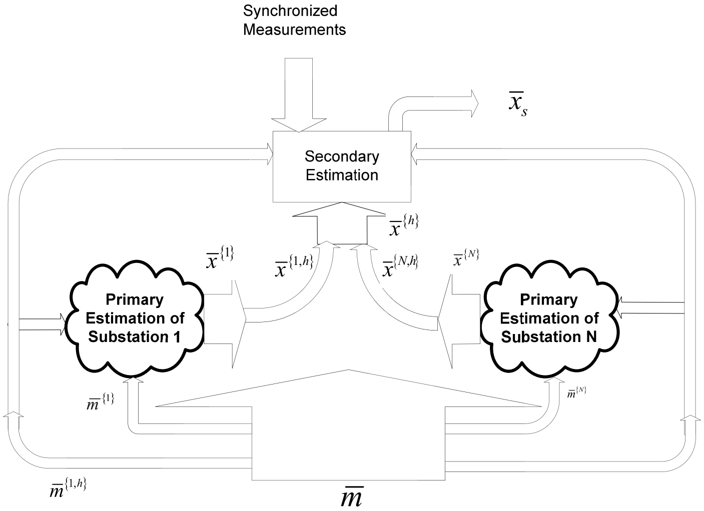


Fig. 4: Structure of distributed estimation

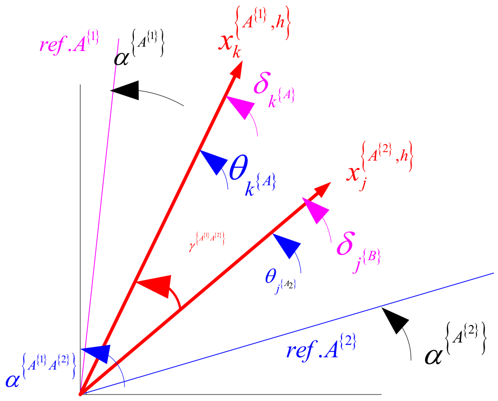


Fig. 5: Subsystems phasors in the complex plane and coordinate systems

Tab. 1: The importance of values

Value	Description
$ref.A^{\{1\}}$, $ref.A^{\{2\}}$	Refrence axes of the subsystem A and B
$\alpha^{\{A^{\{1\}}\}}, \alpha^{\{A^{\{2\}}\}}$	Angles of the refrence axes measures from the real axe of the comlex plain
$\alpha^{\{A^{\{1\}}A^{\{2\}}\}}$	Voltage phasors of the boundary nodes of the subsystems
$x_k^{\{A,h\}}, x_j^{\{B,h\}}$	Angles of the voltage phasors measured from the refrence aze of the systems
$\delta_{k\{A\}}, \delta_{j\{B\}}$	Angles of the voltage phasors measured from the refrence aze of the system $ref.A^{\{1\}}$
$\theta_{k\{A\}}, \theta_{j\{B\}}$	Angles of the voltage phasors measured from the refrence aze of the system $ref.A^{\{2\}}$
$\gamma^{\{AB\}}$	Voltage phasor shift at boundary nodes caused by the power flow

3.5. Automation in T&D Systems

The control system of local automatics is generally divided into several layers **(Figure 7-1),** which always perform a specific aktivity

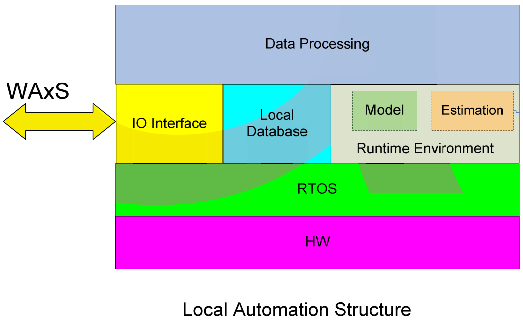


Fig. 6: The proposed concept of the internal architecture of the automatic local / distributed estimator

Hardware

Hardware level provides sufficient computing resources and connections to surrounding equipment.

RTOS (Real-Time Operating System) - real-time system

- Unlike commercially available systems for office applications such as Microsoft Windows, or other common distributions there are several major fundamental differences that RTOS has such as:
- Under RTOS there are more priorities runtime, or part thereof, compared to conventional operating system unreal time.
- Individual tasks (applications) are planned in deterministic time, ie., It is possible to determine exactly when and how that calculation, or other operations take place. For systems other than RTOS it is not quite clear and it depends on the "way of planning" that the operating system uses.
- Low resolution timer. The timer resolution determines the minimal quantum of time which may be granted individual application. This parameter is related to the planned task.
- Speed of context switching.

An example of real time operating system are: RTAI, RTLinux, VxWorks, PikeOS, QNX, and many others.

Computational runtime

Mathematical environment enabling data processing and calculations.This may include Scilab environment that is by French companies INRIA and ENPC. In the Scilab environment, it is possible to compute the system dynamics and evaluate its behavior in time.It is also possible to perform estimation and process measured data. Substitute environment of Scilab could be commercial MATLAB. The Scilab environment is extensible by Scicos, which offers system design like MATLAB-Simulink. Scilab environment allows import code from MATLAB.

Local database

The Local database is used to store the current local data collected for calculations and as a cache. The number of data in the cache should be with regard to the computational requirements, technical considerations and effectiveness limited in history depth.

Processing output and input data

The purpose of this module is to collect and interpret data from the measurement units PMU and the preprocessing before sending data to other systems.

Evaluation of data

Algorithms for data evaluation use supportive data from the internal data model of a database or other external data. This group also includes alarm settings and specific events.

Fault data storage

OPC server provides storage of process data such as synchronous phasors, system status, and the next available value. If necessary, the amount of data and the depth of their history could be set. The main advantage of this technology is easy connection to any future systems, which is secured by the unification of the connection. Unlike conventional servers that are not used for storing process data, it is possible to obtain priority of access and speed of access to the database.

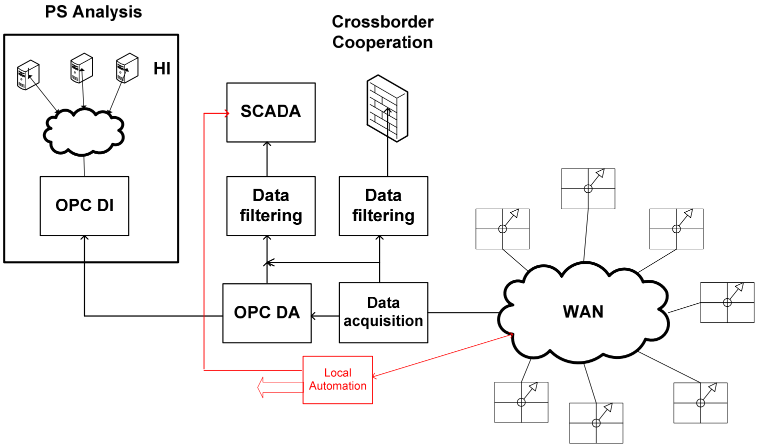


Fig. 7: Cooperation between local automation system and WAMS

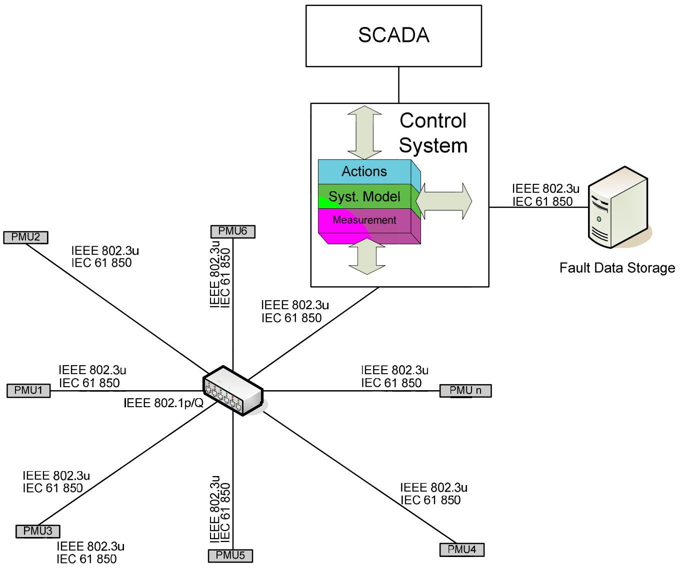


Fig. 8: The logical network topology for local automation (using an WAMS infrastructure)

The algorithm of local automatics is based on a mathematical model equivalents using a scalar amplitude measurements and angles of voltage and current vectors in the complex time-shifted by ΔT_1, thus obtaining a number of vectors. The matrix vector is multiplied by its own transpose matrix and eigenvalues are determined. Non-dominant eigenvalues indicate the presence of abnormal states. Automation has two sets of eigenvalues - calculation of the model and calculation of measured values. This is achieved by increasing the reliability of signaling exceptional conditions.

3.5.1. System Stabilizers

The system stabilizer (Power System Stabilzer - PSS) is a voltage regulator phase compensation device, which is responsible for the control of active power during oscillations within the power system. These oscillations can cause restrictions in the network transmission capacity or may have a negative impact on maintaining a safe and stable operation of the network. Oscillation can be divided into three basic groups:

- System Oscillation (Inter-Area Oscillation) is caused by the swinging of large electrical energy production areas. Typically occurs in the frequency range 0.1 - 0.7 Hz.
- Local Oscillation (Local Oscillation Mode) are created by swinging of one or more generators simultaneously. The oscillation frequency is normally in the range 0.7 - 2 Hz.These oscillations mostly are among generators equipped with very fast excitation sets (High Initial Response Excitation System), which creates a significant component of the generator rotor negative damping torque.
- Oscillations in the same local generation area (Inter-Unit Oscillation) during parallel operation of two or more machines in one plant or within nearby stations.Frequency band oscillations there is a 1.5-3Hz.

3.5.2. The principle of PSS

The system stabilizer is a part of the voltage regulator generator, whose task is to create the generator rotor torque components with positive damping effect and using the superimposed signal to the control deviation alarm controller. Fig. 9 shows a basic diagram of voltage regulator incorporating a PSS.

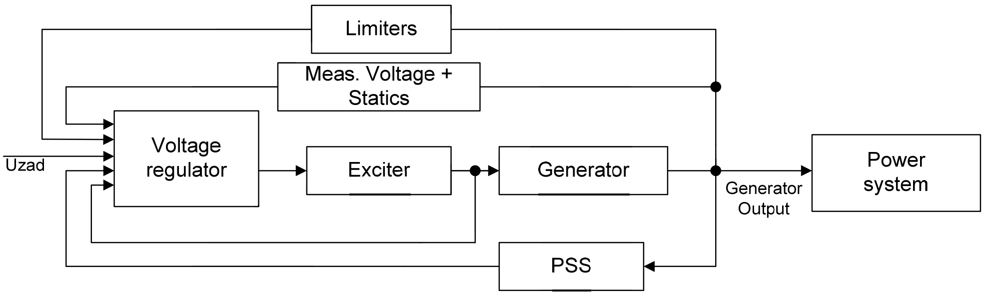


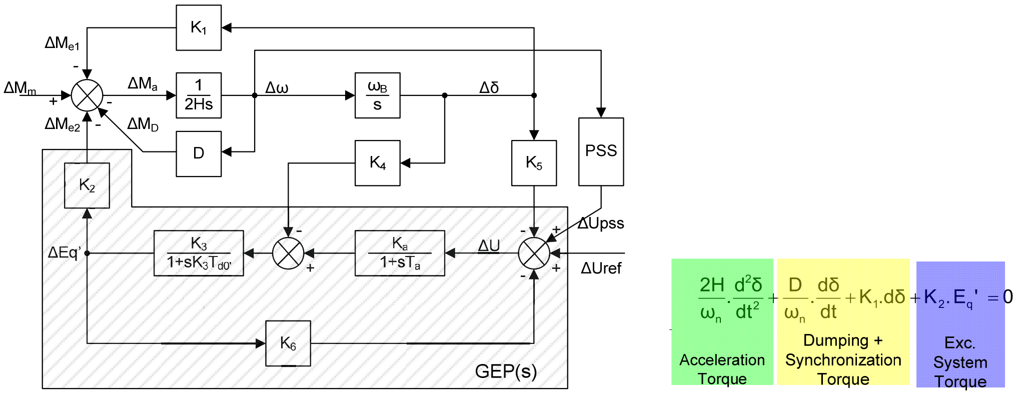
Fig. 9: Wiring of voltage regulation is incorporated PSS

On Fig. 10 is a diagram of a simple linearized dynamic model of one-machine system with voltage regulator operating on the grid. The model is based on the motion equation shown in Fig. 7-9, the structure of the control loop voltage generator. The model is valid for small deviations from equilibrium values and the constant supplied mechanical shaft torque.

The model shows that the rotor operates at total of four torque components (moments accurately deviations from equilibrium):

ΔM_D – damping torque generated mainly by induced currents in the damper windings (in phase with $\Delta\ \omega$)

- ΔM_{e1} – synchronizing torque (in phase with $\Delta\ \delta$)
- ΔM_m – mechanical torque (due to the turbine and the controller)
- ΔM_{e2} – torque generated by a predetermined current to the excitation winding



$$\frac{2H}{\omega_n}.\frac{d^2\delta}{dt^2}+\frac{D}{\omega_n}.\frac{d\delta}{dt}+K_1.d\delta+K_2.E_q'=0$$

Fig. 10: The linearized dynamic model of one-machine system with a voltage regulator working to the grid and the motion equation

Their sum determines the resulting acceleration torque Δ *M*. Phasor diagram of the torque components valid for very fast excitation systems is shown in Fig. 7 -10.The yellow shows the resulting torque phasor for constant excitation, ie. without a voltage regulator. In this case, the resultant phasor is in the stable region. Adding the torque generated by the excitation current from a very quick excitation system (blue phasor), we get the final torque turned into an unstable region (purple phasor). The torque component with a positive torque dampening effect should be created, ie in phase with *Δ* ω (red phasor) and large enough that the resulting moment would be able to stay in the stable area.

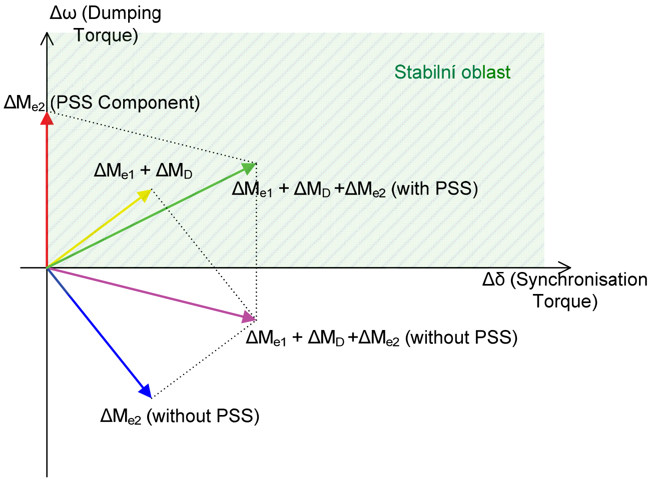


Fig. 11: Phasor diagram of torque components

This requirement is ensured by system stabilizer which injected the signal into the added element of voltage rebulator and an excitation circuit of a generator produces torque in the generator rotor. Typically, PSS input is speed deviation *Δ* ω or active power deviation Δ *P*. The phase difference between these quantities is 90 °. Since the PSS torque component of the generator rotor must bein phase with *Δ* ω, PSS must compensate the phase delay of adder controller up to the torque component Δ *M* e2. This determines the transmission phase delay hatched in Fig. 11, which includes sub-transmissions BS, the controller circuit and the parameters of the generator system, and is sometimes abbreviated as (+ Generator excitation system + power system).

Fig. 12 shows the GEP phase delay in the reference range of frequencies and an example of setting the phase characteristics of PSS, which provides phase lead such that the resulting delay from input PSS (ie from *Δ* ω) to the folder torque Δ M_{e2} was close to 0 ° in the desired frequency band.

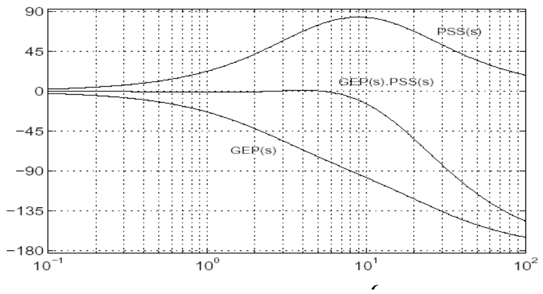


Fig. 12: Phase delay GEP (a) setting the PSS phase characteristics (s) and the resulting GEP offset (s).PSS (s)

3.5.3. Methods for PSS functions verification

A commonly used measuring method to verify the PSS is determined by the Code of PS and PS CR based on Std.IEEE 421. They use measurements in the time and frequency domains.

In the time domain waveform is measured as a response to a step change in setpoint voltage RB, event. response to defined change in the network. This method will verify the effectiveness of the control of local swings.

In the frequency domain it determines the frequency characteristics of variables Pg, Qg, Ug in response to harmonic signal superimposed to the control deviation of excitation controller. This method can evaluate the influence of damping of the local swings and system swings.

Fig. 13 shows a comparison of the time course of active power response to a step change in setpoint voltage for active and inactive PSS for very fast static excitation systems. The picture shows a very effective damping of oscillations using a PSS.

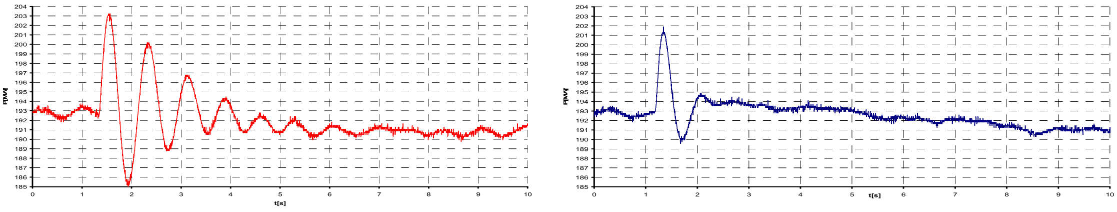


Fig. 13: Comparison of the active power waveform in response to a step change in setpoint voltage for active (left) and inactive (right) PSS

3.5.4. PSS Case Study

Limiting operating conditions of the generator, see points in the machine PQ diagram (Fig. 14)		
Point 1	[Pgmax [MW], Qgmax [MVAr]]	[230, 150]
Point 2	[Pgmax [MW], Qgmin [MVAr]]	[230, -50]
Point 3	[Pgmin [MW], Qgmax [MVAr]]	[10,-125]
Point 4	[Pgmin [MW], Qgmin [MVAr]]	[10, 205]

Case #	**Grid Sk**	**[Pg,Qg]**
1	**Sk1**	**Point 1**
2	**Sk1**	**Point 2**
3	**Sk1**	**Point 3**
4	**Sk1**	**Point 4**
5	**Sk2**	**Point 1**
6	**Sk2**	**Point 2**
7	**Sk2**	**Point 3**
8	**Sk2**	**Point 4**

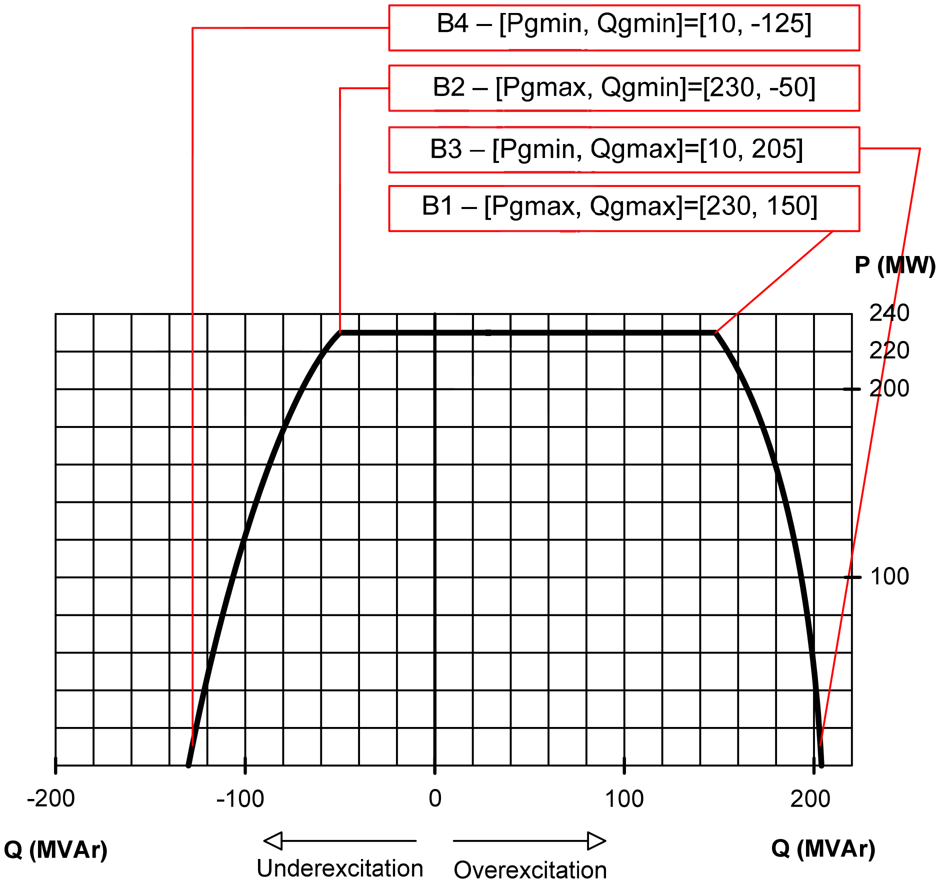


Fig. 14: **Machine limit states**

For network short-circuit power Sk'' = 25,595 MVA:

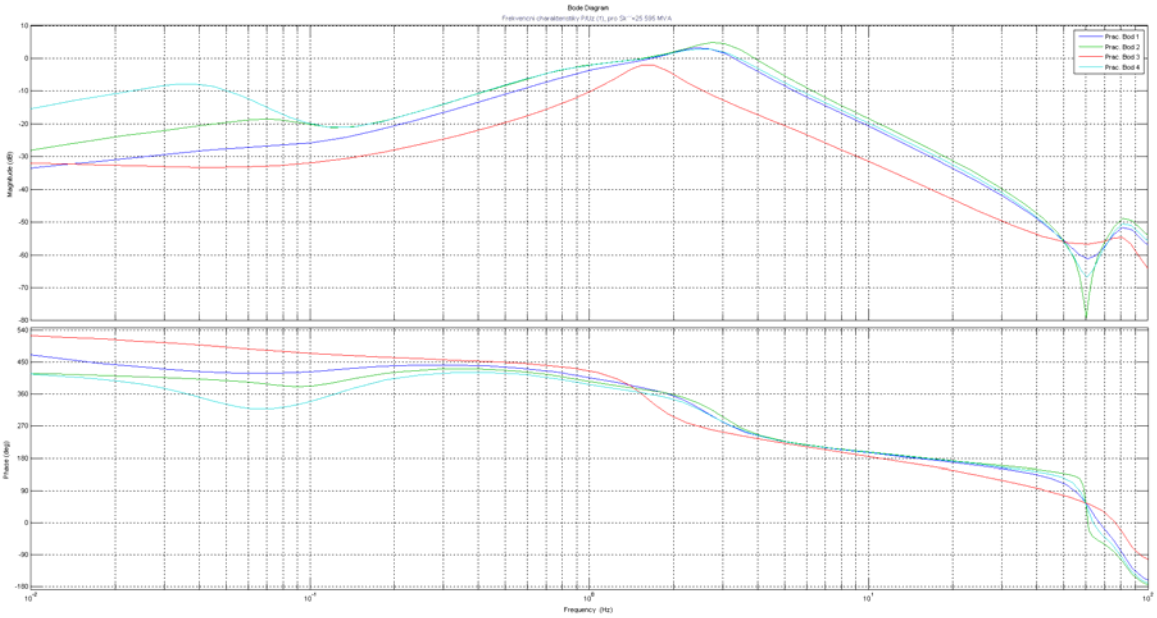


Fig. 15: Frequency responseP/U_z (f)

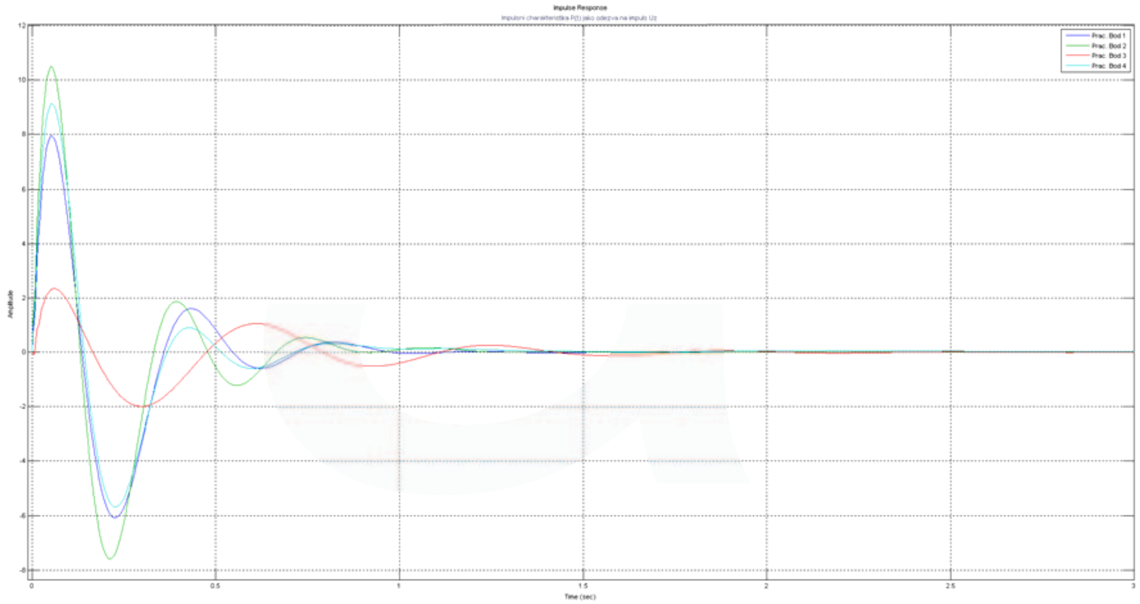
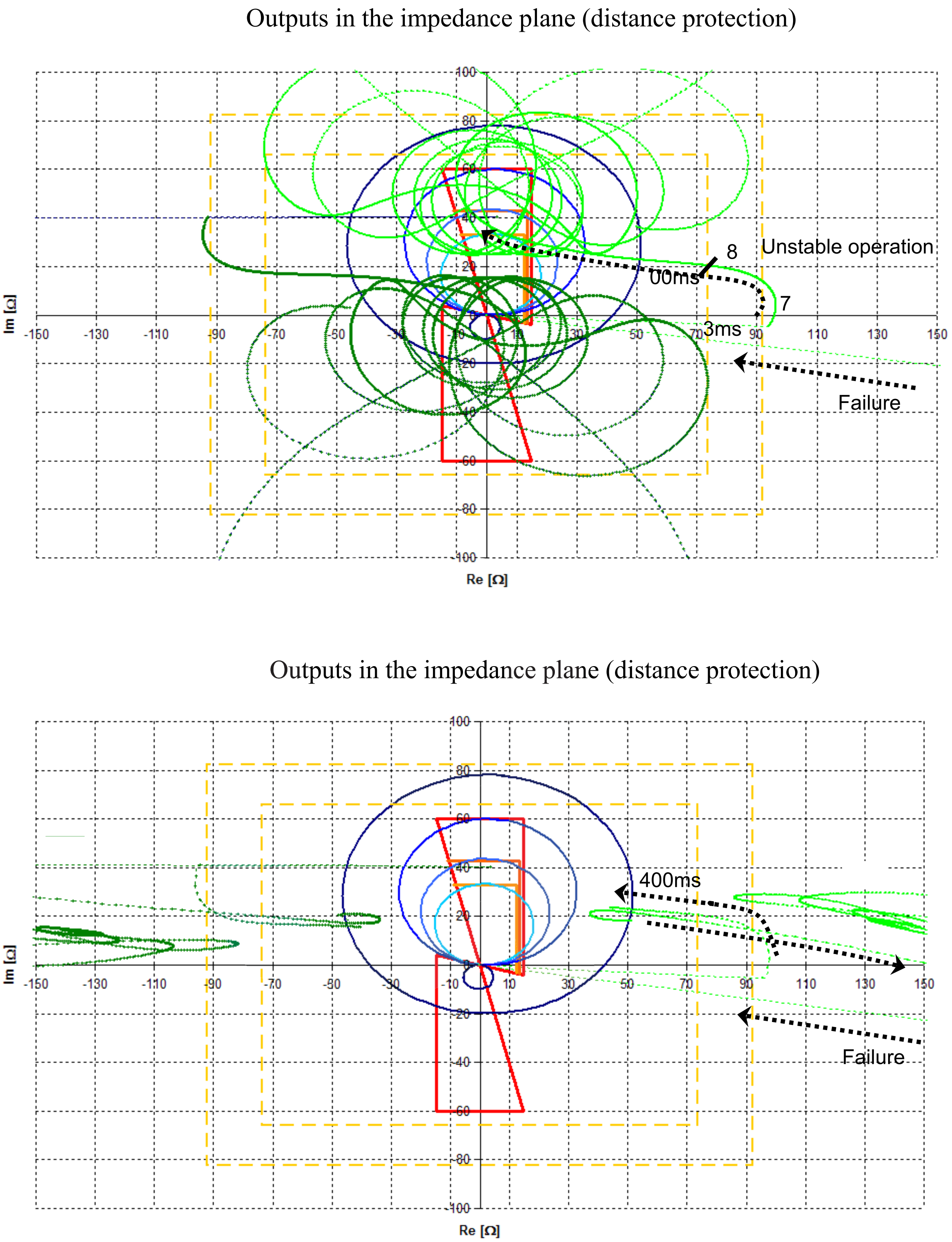


Fig. 16: Impulse response $P(t)$


Outputs in the impedance plane (distance protection)

Outputs in the impedance plane (distance protection)

Fig. 17 a,b: Example of time behavior calculation (the short circuit impedance (a) unstable, b) steady state))

3.6. Evaluating Model Simplifications

3.6.1. Motivation

Modeling and solving stability issues of real complex network can be often time and computationally demanding. It is therefore reasonable to use model simplifications in order to reduce the number of state space equations. This can be achieved by substituting of several generators with a single one while similar dynamic behavior of the new (reduced) state space model is preserved.

3.6.2. Evaluation on Eigenvalue Basis

Taking into consideration eigenvalues of the original *n*-th order dynamic state space model $\lambda_1, \lambda_2, ..., \lambda_n$, eigenvalues of the new simplified model are $\tilde{\lambda}_1, \tilde{\lambda}_2, ..., \tilde{\lambda}_m$, where $m < n$. Degree of how dynamic behavior of the simplified model fits to its original can be expressed via maximum eigenvalue deviations.

Let us define eigenvalue deviation as

$$\delta_{\lambda ij} = \frac{\left|\lambda_i - \tilde{\lambda}_j\right|}{\left|\lambda_i\right|} \tag{5}$$

where $i = 1...n$ and $j = 1...m$. The total number of all the deviations is thus $m \times n$. The “closest” eigenvalue of the simplified model to *i*-th eigenvalue of the original model has minimal value of eigenvalue deviation for the all possible *j*, and can be written as

$$\delta_{\lambda \min i} = \min\left(\delta_{\lambda i1}, ..., \delta_{\lambda ij}, ..\delta_{\lambda im}\right) \tag{6}$$

Maximal deviation $\delta_{\lambda \max}$ among $\delta_{\lambda \min i}$ expresses the most different mode of the simplified model compared to its original.

$$\delta_{\lambda \max} = \max\left(\delta_{\lambda \min 1}, ..., \delta_{\lambda \min i}, ..\delta_{\lambda \min n}\right) \tag{7}$$

Above mentioned considerations are demonstrated on 14 node network case study. In following figure can be seen the original model, which contains three generators of the same parameters connected in unit arrangement in parallel.

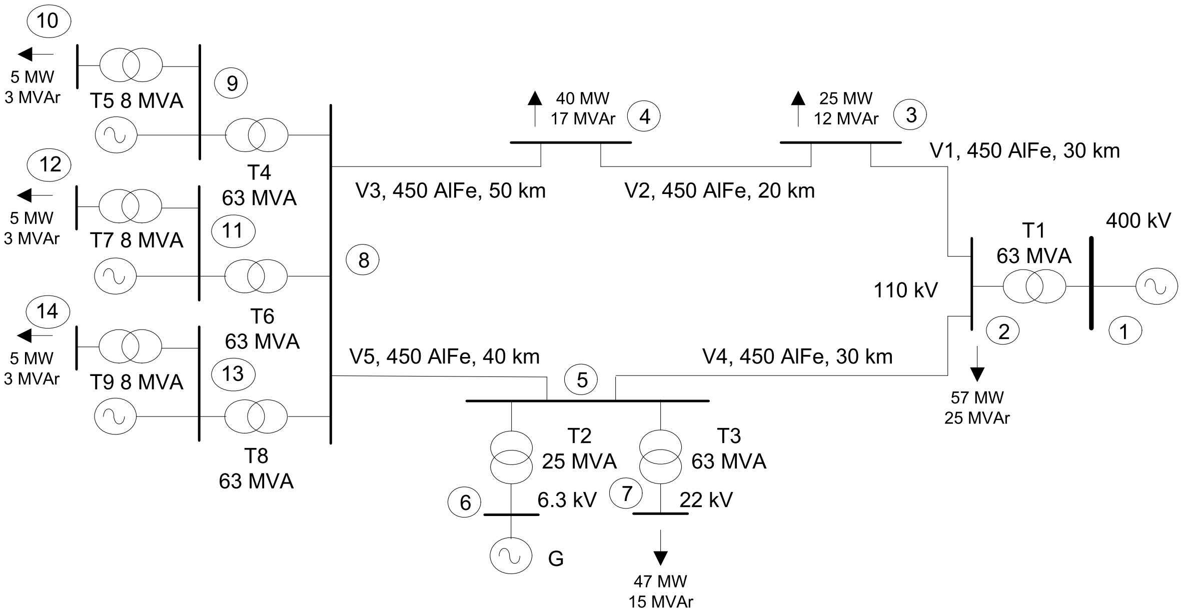


Fig. 18: Model of the original network

Let us assume often used simplification, which consists in substituting of three identical units connected in parallel by one with triple nominal parameters as it is depicted in the Figure 18. Tested generator (range 0-6 MW) is connected to the node No. 6.

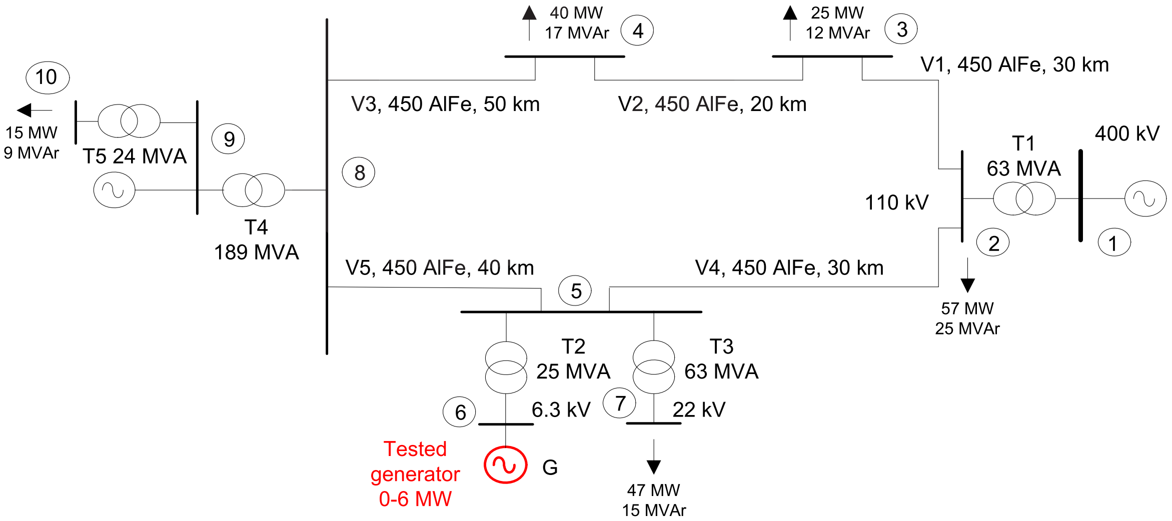


Fig. 19: Model of the substituted network with tested machine connected to the node No. 6

Following figures show the results.

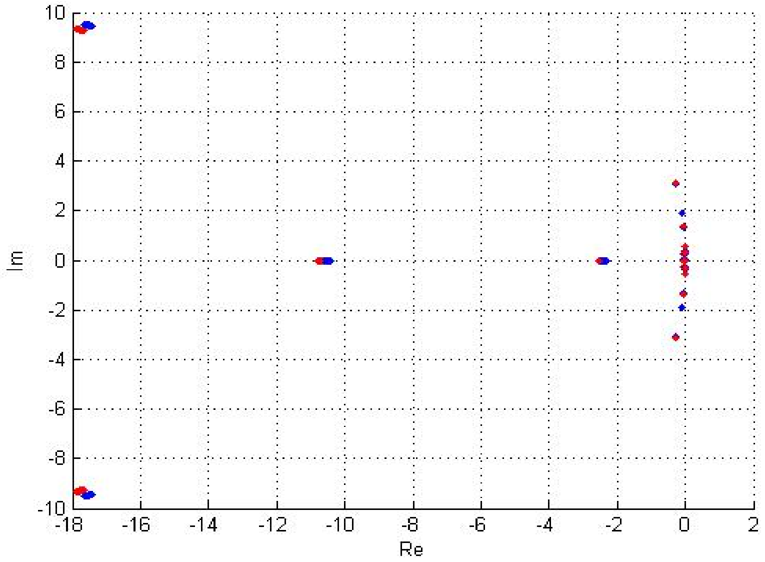


Fig. 20: Original and simplified model eigenvalues (blue – original, red – simplification)

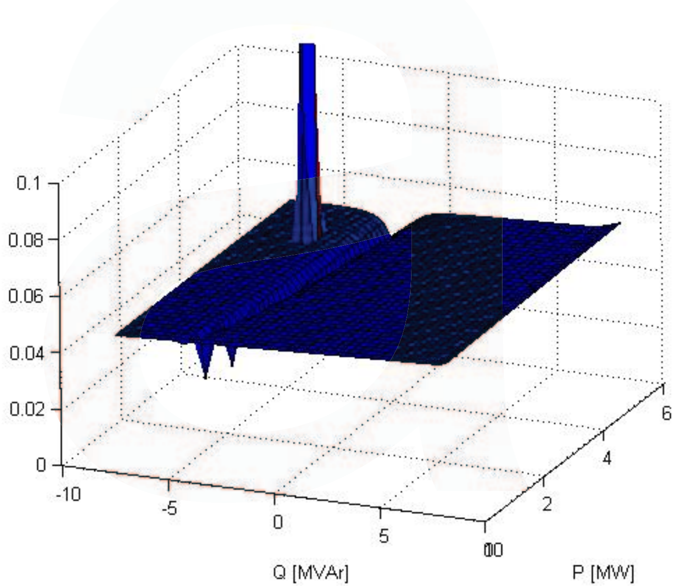


Fig. 19: Maximum deviations [%] of the original and simplified model eigenvalues

The results show, that maximal eigenvalues' deviations in the whole operable region of the machine at node No. 6 are less than 5%. Usage of this simplification can be thus recommended.

Next simplification can be seen in the Figure 20. In this case is analyzed operable region (range 0-60 MW) of the machine connected to the node No. 9. The Figures 21-24 bellow show the main analysis outputs.

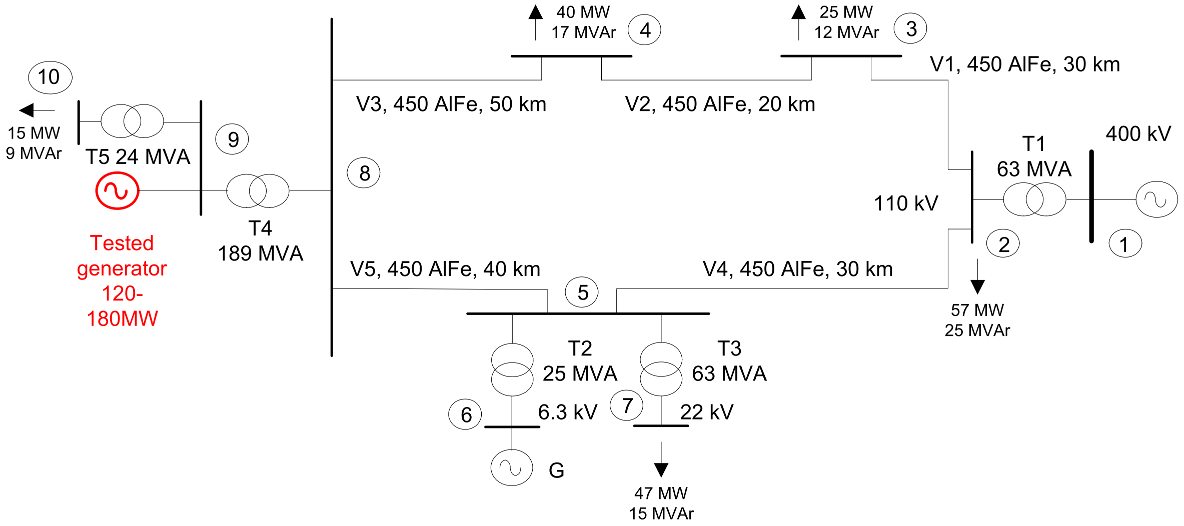


Fig. 20: Model of the substituted network with tested machine connected to the node No. **9**

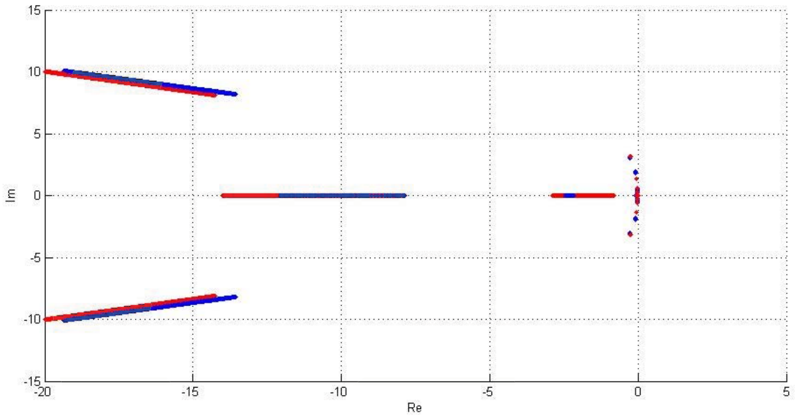


Fig. 21: Original and simplified model eigenvalues (blue – original, red – simplification)

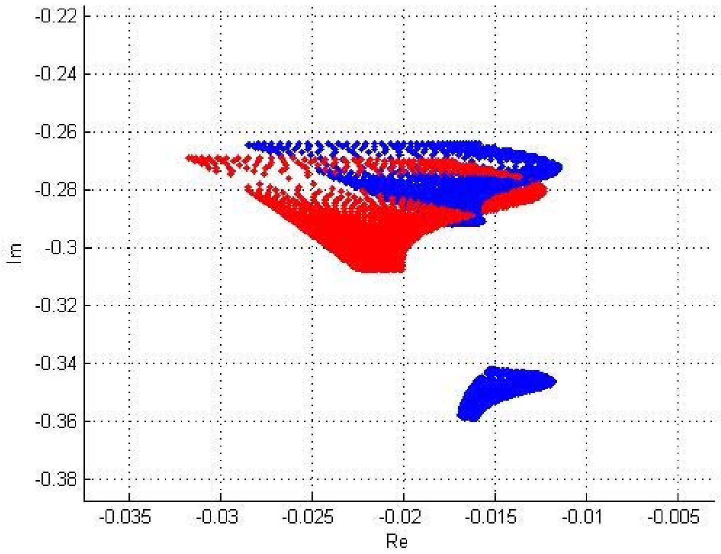


Fig. 22: Original and simplified model eigenvalues (detailed show)

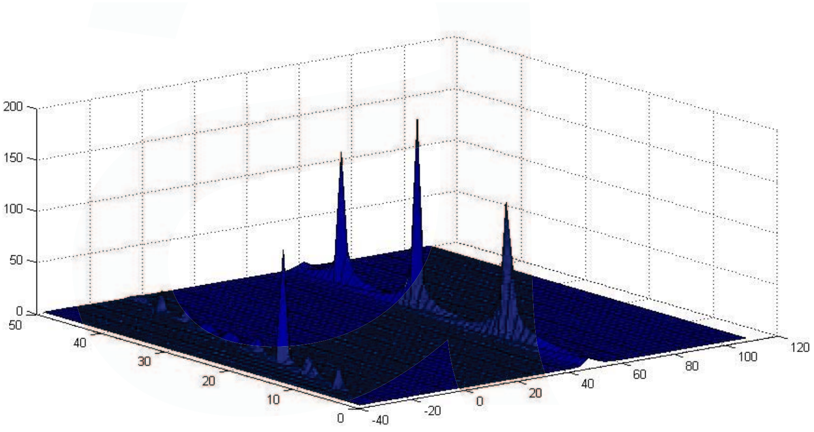


Fig. 23: Maximum deviations [%] of the original and simplified model eigenvalues

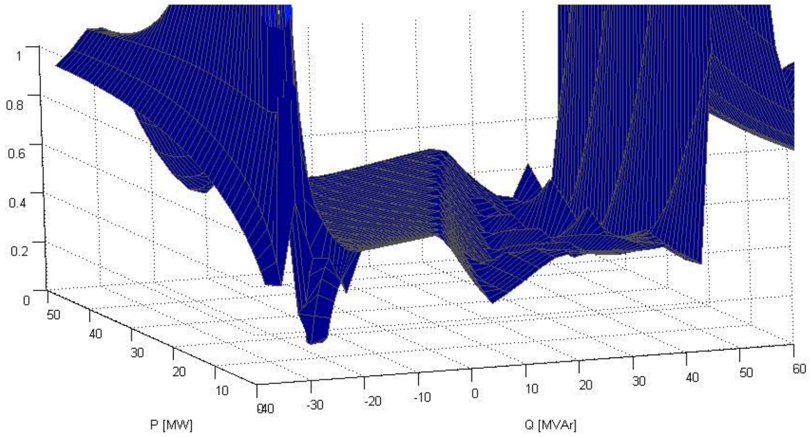


Fig. 24: Maximum deviations [%] of the original and simplified model eigenvalues (detailed show)

From these results can be concluded, that usage of this simplification is improper because maximal deviation is significantly higher than in previous case especially in stability borders.

4. The applicant contribution

The thesis focuses on the problems of future advanced elements in electric power systems, namely synchrophasor measurement (commonly called WAMS - Wide Area Monitoring, WAPS - Wide Area Protection System, WACS - Wide Area Control System, and most recently WAMPaC - Wide Area Monitoring, Protection and Control) in the transmission system and other technology concept called smart grids (in recent years this concept has seen the name "SmartGrids").

The basic blocks of WAxS include the PMU (Phasor Measurement Unit). One of the key aspects of application units PMU is the quality of the measured data and the resulting usefulness in applications. For future real deployment it is also important to analyze the WAxS requirements in the context of the communication environment.

The basic goals of this work include an analysis of the possibilities of mentioned elements in advanced systems based on new methods of measuring and monitoring. The utilization synchrophasor measurement appears promising. This research is concentrated on the applicability of this concept particularly in the area of monitoring and control of active and reactive power, transmission system parameter estimation, ampacity and last but not least, transmission stability. The utilization of modern monitoring and control elements can achieve a more efficient use of the entire system, ie it is possible ways to optimize the entire chain of production and - transmission and distribution - consumption.

To properly perform the above analysis was developed a range of mathematical models:

- Model of the transmission and distribution system (a very good example of just electricity interconnection topology as the national grid in combination with neighboring interconnected systems).
- Mathematical models of selected resources.
- Models measuring elements (for WAxS will discuss the above PMU).

The above models were analyzed in possible states of the system and their observability using mentioned means. Requirements for the accuracy of the measuring chain for each application were analyzed in this context. New advanced applications allow to maximize the use of existing elements grids for each specific conditions and in the future due to a combination of modern technical means (eg. FACTS, HVDC) systems facilitating flexible operation. These technologies will also contribute to a better use of renewable resources and, last but not least, removes some technical limitations preventing effective function of the free electricity market.

Achieving these goals would be followed by furhter research such as:

- Development of the theory of stability in electric power systems (nonlinear systems, chaos) and the possibility of its analysis and monitoring.
- Analysis of the measuring chain, key features and requirements. Error correction applicable for known errors.
- Analysis of WAxS system capabilities on the data model of the transmission grid.
- Analysis of the feasibility of new advanced features (such as virtual power plants, virtual protections based on local automation).
- The definition of local structures for automations.

- Implementation of the conclusions to the requirements of the appropriate ICT infrastructure, depending on the criticality of the function application (protected vs. Vs control. Monitoring).

5. Upcoming challenges

One of the basic preconditions for sustainable development of human civilization is the security and reliability of the electrical supply with respect to the economical and environmental aspects. An electricity system includes an extensive set of equipment production, transmission, distribution and use of electrical energy that has to meet very high demands on quality control, safety and reliability and eliminate any adverse accompanying phenomena. Functional parameters of the system must also be sufficiently high and constantly adapt to new knowledge, technology, manufacturing and distribution facilities and the composition and nature of the demand.

Issues associated with the development of the system, operation reliability and safety and adaptability of large-scale power systems can be structured using different aspects creating not strictly separated groups, and in many aspects may strongly overlap, eg. upgrading existing resources and identifying and utilizing alternative sources, increasing the operating parameters of power, control and safety devices, modeling, simulation and evaluation of static and dynamic processes in the system and ensuring the quality and reliability of electricity supply based on microelectronics , power electronics and semiconductor technologies.

With the upcoming technologies it will be necessary to solve the aforementioned problems, especially for transmission systems because of their close interconnection with other system operators. The new concept will certainly contribute to the analysis of the actual system failures, and mathematical models. In terms of monitoring, control and protection it is very perspective the deployment of virtual resources (virtual power plants, virtual protection ...) .

Virtual power plants, ie . coordinated operation and management of the generation group, or other devices connected to the grid (especially compensation and electricity storage devices), are one of the key elements of the new concept.

Virtual protection and other virtual instrumentation are also some of the possible solutions of the future. Combination of protection and other measuring elements create new functional units. In many cases it is possible to use existing equipment with new software and of course communication connection.

The interconnected national system of today is a single entity within ENTSO- E . Given the increasingly close cooperation between the systems rapid exchange of information between network operators with the possibility of immediate intervention in case of an emergency appears as a necessity.

6. List of Research Projects

Public research (Active participation):

- Local Automation in WAMPaC Systems
- Partnership in Nucelar Power Engineering of New Generation
- Research and Development of Effective CHP Generation
- CANUT
- Nonlinear Dynamic Loads Negative Effects Mitigation
- Distribution Systems with Dispersed Filters for Safety and Quality Increasement
- WAMPaC Systems with synchrophasor support

Non-public sponsored research:

- Local automation in transmission systems (as a support technology for nuclear power plants)
- Smart Region Architecture
- Asset Management in transmission systems (5 projects in five different countries)
- AMM infrastructure application possibilities and AMM data processing (2 projects)
- WAMS applications in transmission systems
- Protection system optimization (2 projects)

7. Summarized list of the applicant published papers:

1. Kasembe, A. - Müller, Z. - Müller, M.: Assessment of Power Systems with Doubly Fed Induction Generator Based Wind Turbines. *Advanced Science Letters*. 2013, vol. 19, no. 3, p. 811-815. ISSN 1936-6612.
2. Mareček, P. - Müller, M. - Müller, Z. - Švec, J. - Tlustý, J.: Electromobility and the Possibility of its Use in the Czech Republic. *Energetika*. 2013, roč. 63, č. 10, s. 576-581. ISSN 0375-8842. (in Czech).
3. Müller, M. - Müller, Z. - Tlustý, J.: Overhead Line Mechanical Behaviour - Dynamic Model. *Przeglad Elektrotechniczny*. 2013, vol. 89, no. 10, p. 221-224. ISSN 0033-2097.
4. Švec, J. - Müller, Z. - Kasembe, A. - Tlustý, J. - Valouch, V.: Hybrid power filter for advanced power quality in industrial systems. *Electric Power Systems Research*. 2013, vol. 103, p. 157-167. ISSN 0378-7796.
5. Fandi, G. - Švec, J. - Müller, Z.: The Converter Choice and its Control Circuit Design for Synchronous Generators. In *Electric Power Engineering 2013*. Ostrava: VŠB - Technical University of Ostrava, 2013, . ISBN 978-80-248-2988-3.
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10. Čepa, L. - Kocur, Z. - Müller, Z.: Migration of the IT Technologies to the Smart Grids. *Elektronika ir Elektrotechnika*. 2012, vol. 7, no. 123, p. 123-128. ISSN 1392-1215.
11. Kasembe, A. - Müller, Z. - Švec, J. - Tlustý, J. - Valouch, V.: Synchronous Phasors Monitoring System Application Possibilities. In *27th Convention of Electrical and Electronics Engineers in Israel*. Piscataway: IEEE, 2012, p. 1-3. ISBN 978-1-4673-4680-1.
12. Mareček, P. - Šrom, J. - Švec, J. - Müller, Z.: Dispersed Generation Impact on Faulted Currents in Distribution Systems. In *Proceedings of the 13th International Scientific Conference EPE 2012*. Brno: Vysoké učení technické v Brně, Fakulta elektrotechniky a komunikačních technologií, 2012, p. 749-752. ISBN 978-80-214-4514-7.
13. Müller, Z. - Špetlík, J. - Švec, J. - Tlustý, J.: Stability of Operation with Small Hydropower Plants in Islanded Network. In *16. konference ČK CIRED*. Praha: CIRED, 2012, p. 1-8. ISBN 978-80-905014-1-6.

14. Müller, Z. - Švec, J. - Čerňan, M. - Kyncl, J.: The Use of Regression Methods for Measurement and Diagnostics in Electrical Power Engineering. In *Proceedings of the 13th International Scientific Conference EPE 2012*. Brno: Vysoké učení technické v Brně, Fakulta elektrotechniky a komunikačních technologií, 2012, p. 413-417. ISBN 978-80-214-4514-7.
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16. Müller, Z. - Švec, J. - Tlustý, J. - Valouch, V.: Generalized Non-Active Power Theory for Non-Periodic Disturbances. In *Proceedings of the 13th International Scientific Conference EPE 2012*. Brno: Vysoké učení technické v Brně, Fakulta elektrotechniky a komunikačních technologií, 2012, p. 407-411. ISBN 978-80-214-4514-7.
17. Soibelzon, H. - Vernieri, J. - Salzman, C. - Müller, Z. - Švec, J. - et al.: Methodology for Lightning Protection of Medium and High Voltage Networks. In *ELEN 2012*. Praha: vydavatelství ČVUT v Praze, 2012, p. 1-10. ISBN 978-80-01-05096-5.
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