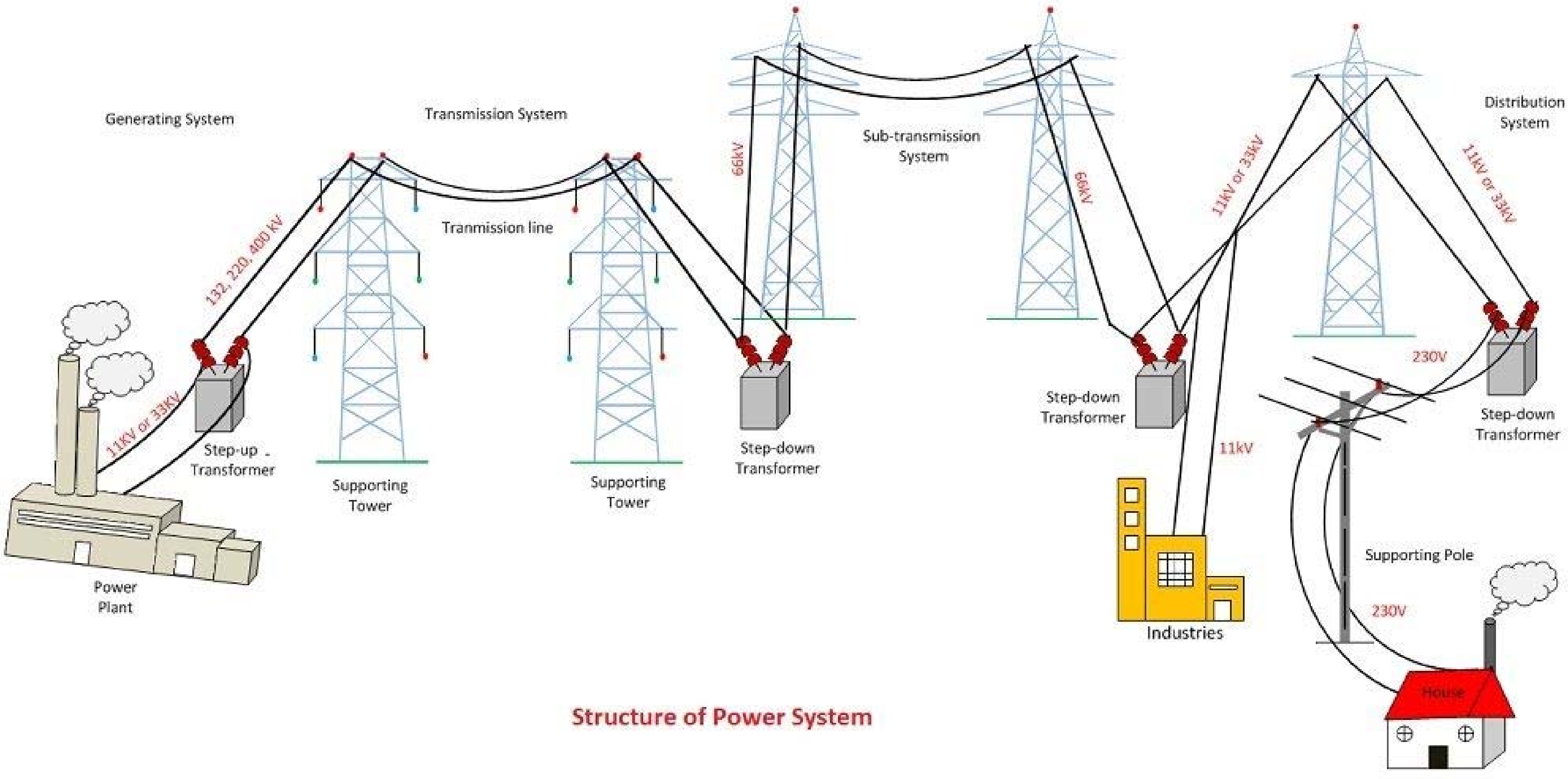
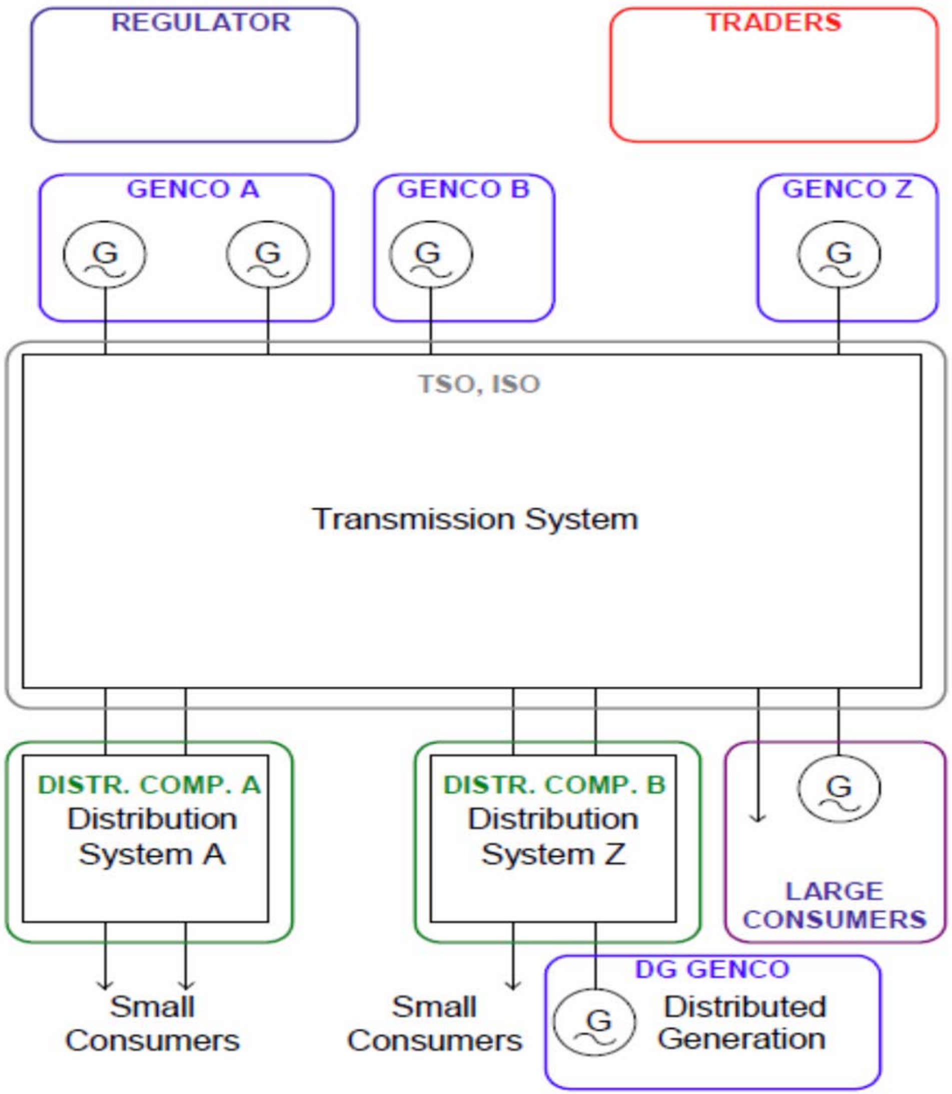
Power System Monitoring and Control

Structure of power systems



Structure of power systems



Structure of power systems

- Traditionally, power systems have been administered by a single entity.
  - Such an utility is called a Vertically Integrated Utility.
  - The entity covers the whole chain starting from power production and transmission to distribution and final delivery.
- This company bears responsibility for system reliability and thus also secure operation.
  - This includes coordination of transmission and generation (both operation as well as long-term planning and investment).
- The regulatory authority is usually a government agency.
  - Approves final electricity price,
  - Approves procedures for larger investments of the Vertically Integrated Utility, such as acquisition of new transmission assets and extensions of the power system (building new power plants, transmission lines etc.).

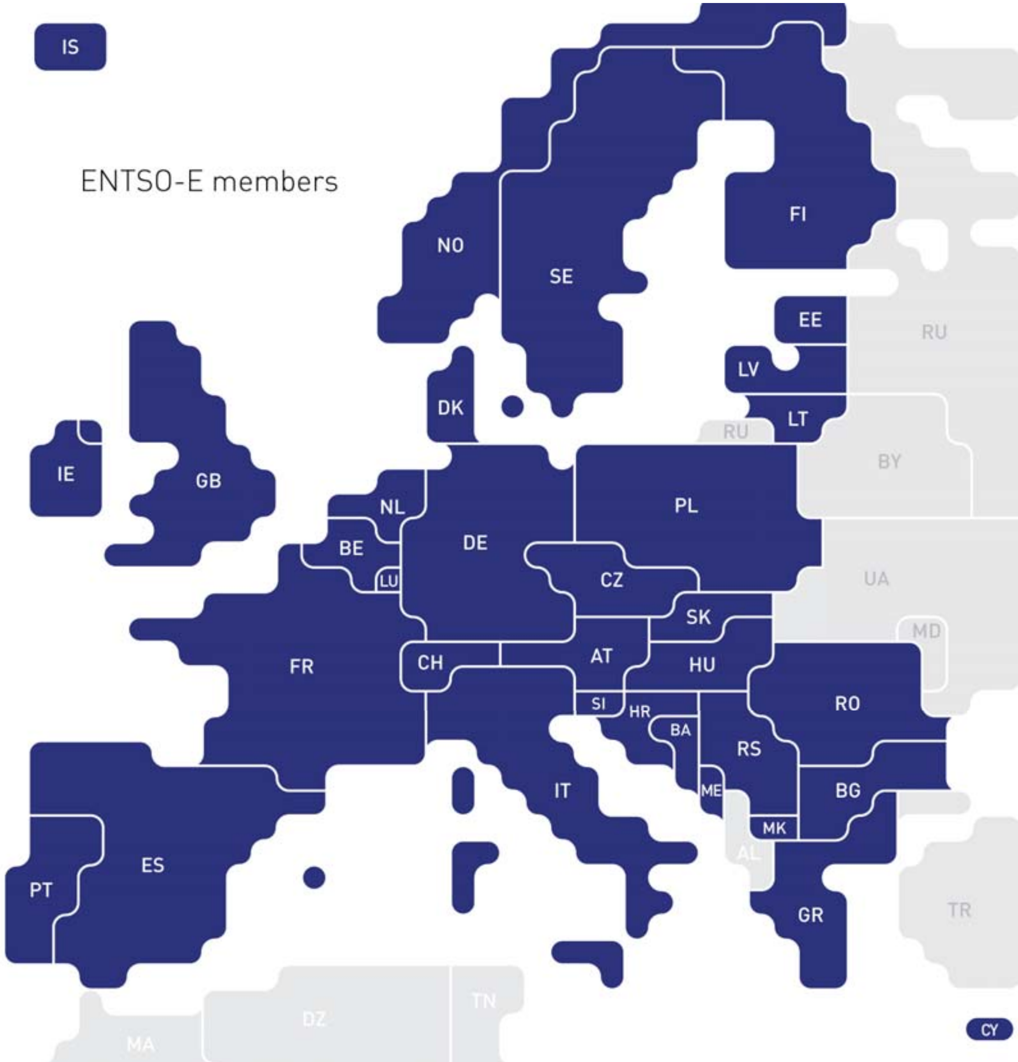
Structure of power systems

- Liberalization of electricity industry has brought about changes into the organizational framework of power systems
- The liberalized market calls for the splitting up of the Vertically Integrated Utility into its constituent parts, namely generation, transmission and distribution.
  - This process is referred to us unbundling.
- The task of the regulatory authority in the liberalized market environment is to create a fair and sustainable environment for the electricity market.
  - Approves transmission pricing policies and long-term monitoring of the market so that manipulation and misuse of the market by market participants do not take place.
- New actors in the liberalized electricity market, who do not necessarily possess physical assets, are traders.

Cross-border interconnections

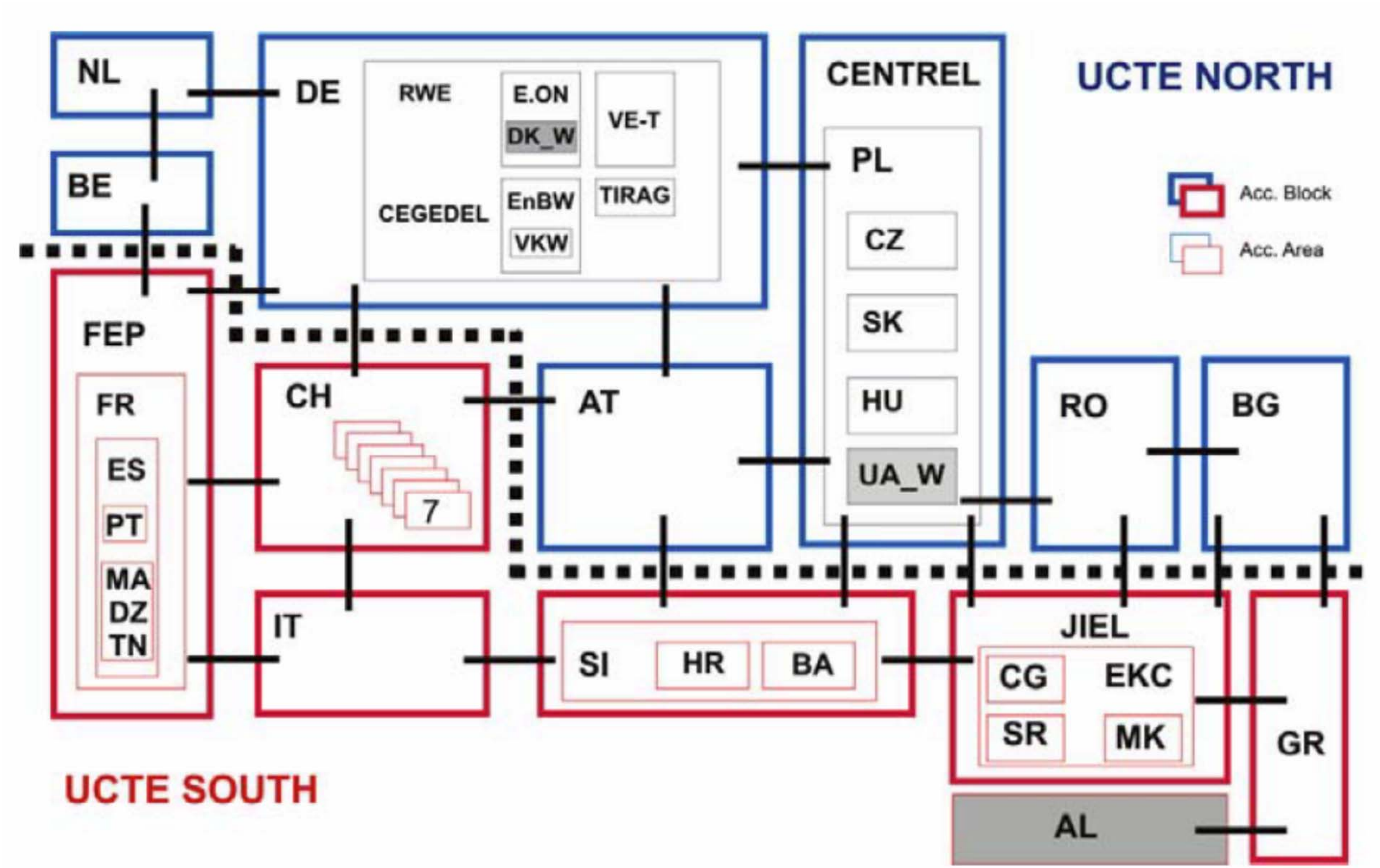
- Many power systems are independent self-sufficient systems, which typically cover their respective service territories.
- But a larger number of power systems are interconnected with their neighboring systems. These connections are mostly established at the transmission system level.
- Interconnecting links (frequently called tie-lines) originally built for power exchange under emergency assistance, but now more and more for electricity trading
- Incentives for interconnection are of both security and economical nature:
  - Coordinated use of power plants and resources
  - Sharing emergency reserves
  - Higher system security
  - Possibility for energy trading

Control structure of UCTE (example)



UCTE: Union for Coordination of Transmission of Electricity
Now: ENTSO-e : European Network of Transmission System Operators - electricity

Control structure of UCTE (example)



UCTE: Union for Coordination of Transmission of Electricity
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Control structure of UCTE

- Most of the continental European power systems are interconnected with each other forming a large interconnected power system
  - covers 34 countries
  - a total of 210,000 km of HV transmission lines,
  - serves a population of around 500 million people
  - an installed capacity of 530 GW.
- Nordic countries form a separate interconnected system called Nordel.
- Baltic countries are connected to the transmission system of the Russian Federation.
- There are DC connections between the listed AC interconnected power systems. They do not share technical issues, such as frequency control etc., but they are ideal for trading, since a better controllability is provided and thus physical flows equal contractual ones.

Classification of power system equipment

- Primary and secondary equipment together make up a complete power system.
- Components which carry the full load current and subjected to the full voltage are referred to as the primary equipment.
- Secondary equipment, on the other hand, are components and systems used for monitoring, protection and control.
- Transmission and distribution lines
- Substation equipment (transformers, circuit breakers, voltage and current transformers, busbars)
- Busbars may have various configurations, most common are single busbars, double busbars and one and half circuit breaker busbars.

Classification of power system equipment

- Instrument Transformers are used to scale down the measured quantity to a level that can be safely and easily processed by electronic equipment.
  - The nominal secondary voltage of voltage transformers is 100 V and
  - the secondary side current of the current transformer is 1 or 5 A.
- Switches:
  - Circuit Breaker
  - Disconnector
  - Earth Switch

Control devices

Voltage Control Devices:

- Shunt Capacitor, Shunt Reactor, Static VAR Compensator, Tap-changing Transformer

Power Flow Control Devices:

- Phase-shifting Transformer, Controlled Series Capacitor, Unified Power Flow Controller

Control devices

- Shunt components are connected between the bus and ground (thus shunt) and their objective is to either absorb or produce reactive power in order to compensate for either excess or lack of reactive power in the network.
  - Their advantage is simplicity, but their control possibilities are very limited, they can be switched in stages until completely switched on or off.
- Tap-changing transformers are equipped with tap-changer to keep the voltage on the secondary side within the desired operation range.
- Phase-shifting transformers control the voltage phase angle between primary and secondary side, can thus significantly influence the active power flow.

Control devices

- Most common type of series (series because it is connected in series with a line) control device is Thyristor Controlled Series Capacitor (TCSC).
  - Just like in the case of the SVC, TCSC capacitance can be changed to compensate line reactance, which strongly affects active power flow in the line.
- The general term FACTS device refers to devices and systems containing power electronics elements
  - Examples are SVC, TCSC and Unified Power Flow Controller
- Allow a fast control, in addition to influencing the damping of oscillations, which may occur in the system.

Monitoring and control of power systems

- The monitoring and control structure in power systems is hierarchical.
- The coordination is achieved by different speed of operation and the covered area,
  - the lower the position of the process and task in the hierarchy, the faster the execution time and the more local the scope of the action.
- It proved to be a suitable concept for several reasons, including robustness, scalability and most of all a simple philosophy/principles for coordination of different tasks.

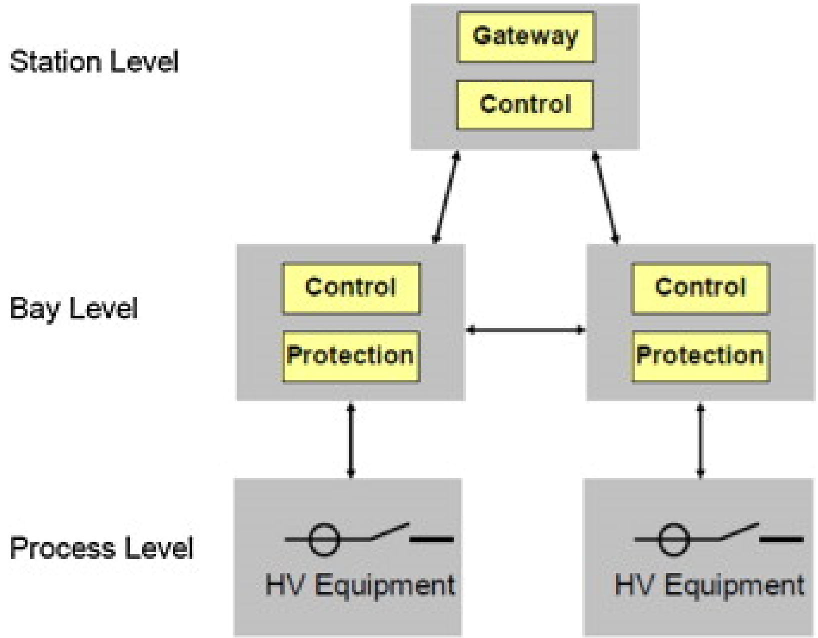
Classification by location

- Tasks crossing hierarchical layers
  - provide a platform for system-wide supervision by providing information to operators in Regional and Network Control Centers and enabling control actions by operators.
  - from the technological viewpoint, devices and technology implementing these tasks belong to SCADA.
- Local autonomous tasks
  - The information they process and the control action they execute is local, but the impact of their control action may be system-wide, which may sometimes have a very negative effect on the whole system, for example, in the case of protection malfunction.
  - Typical representative is protection
  - They usually pose very high requirements in terms of performance (mostly speed).

Classification by layers in the hierarchy

The hierarchical concept incorporates the following layers:

- Process Level
- Bay Level
- Substation Level
- Regional Control Center Level
- Network Control Center Level



Process layer

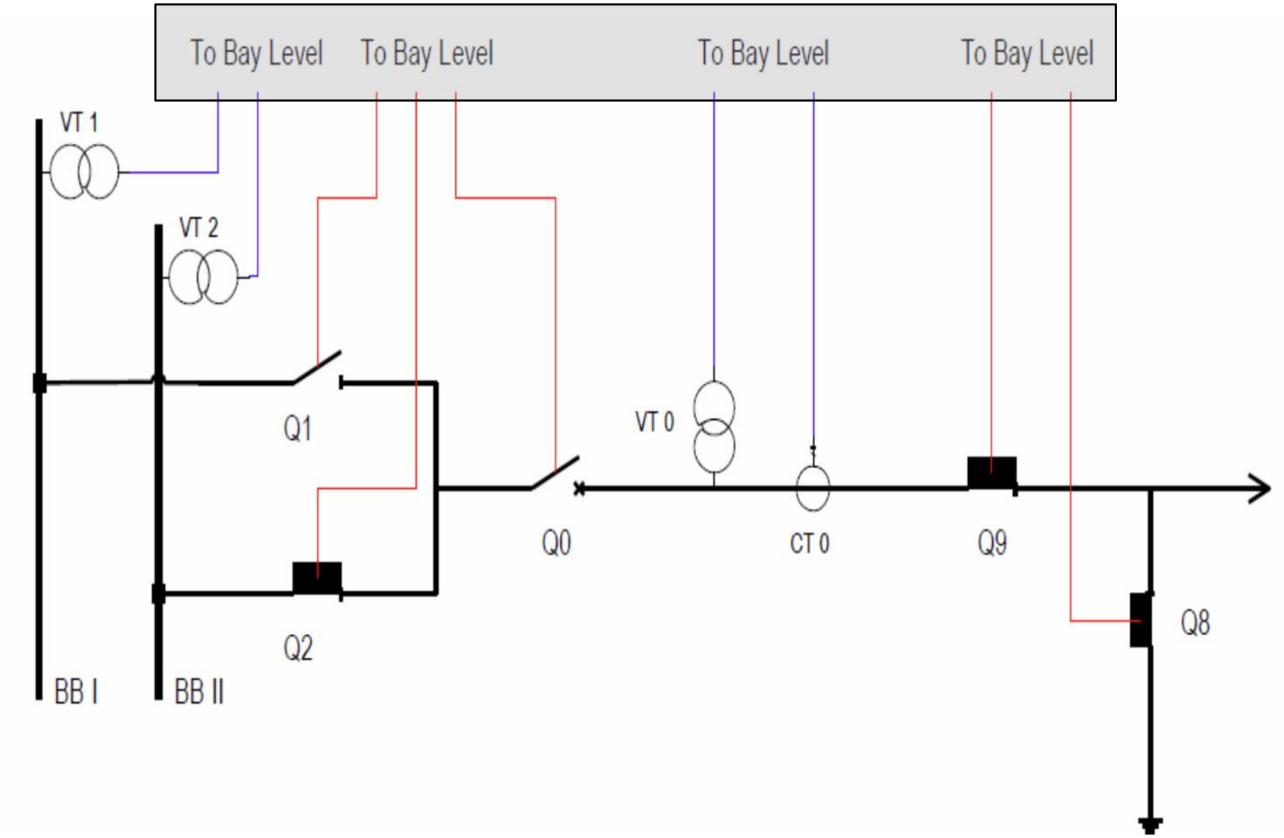
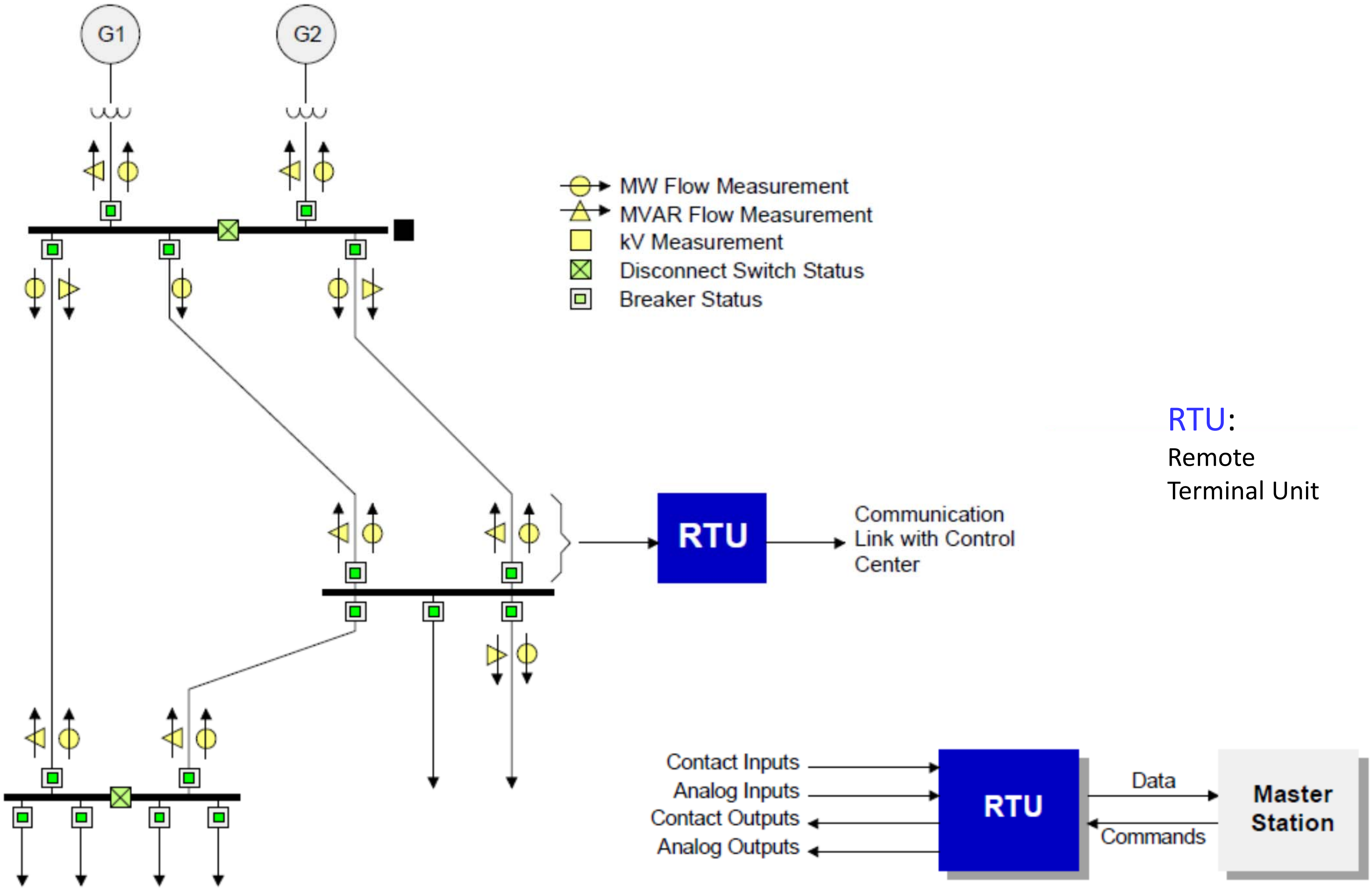


Illustration of the process layer using a double busbar switchyard

RTU:
Remote
Terminal Unit



Process layer

- VT1,VT2, VT0 measure voltages of busbars BBI and BBII, and the line end voltage; CT0 measures the line current
- All switches are equipped with an operation mechanism - a motor, which moves contacts and thus opens / closes the switch when a binary signal is sent from bay level.
- Status of switches is monitored and communicated to the bay level in form of binary signals (on/off).
- Interface between primary and secondary equipment realized by means of:
  - Sensors (VTs, CTs, and switch status sensors)
  - Actuators (switch trip coils and contact movement motors)
- The interface signals between process and the bay levels:
  - Binary Inputs (open or close commands to switches)
  - Binary Outputs (switch status information)
  - Analog Outputs (measurements of current and voltage).

Process layer

- Most common connection between process and bay level is a hard-wired direct connection.
- Some manufacturers use Remote Input / Output Terminals, which are placed in a marshaling kiosk (a small box next to the switchyard) and are hard-wired to sensors and actuators and connected via fiber optics to bay level,
  - to minimize potential electromagnetic compatibility problems.
- Recent trends tend to introduce sensors possessing a transducer and a direct communication interface.

Bay level

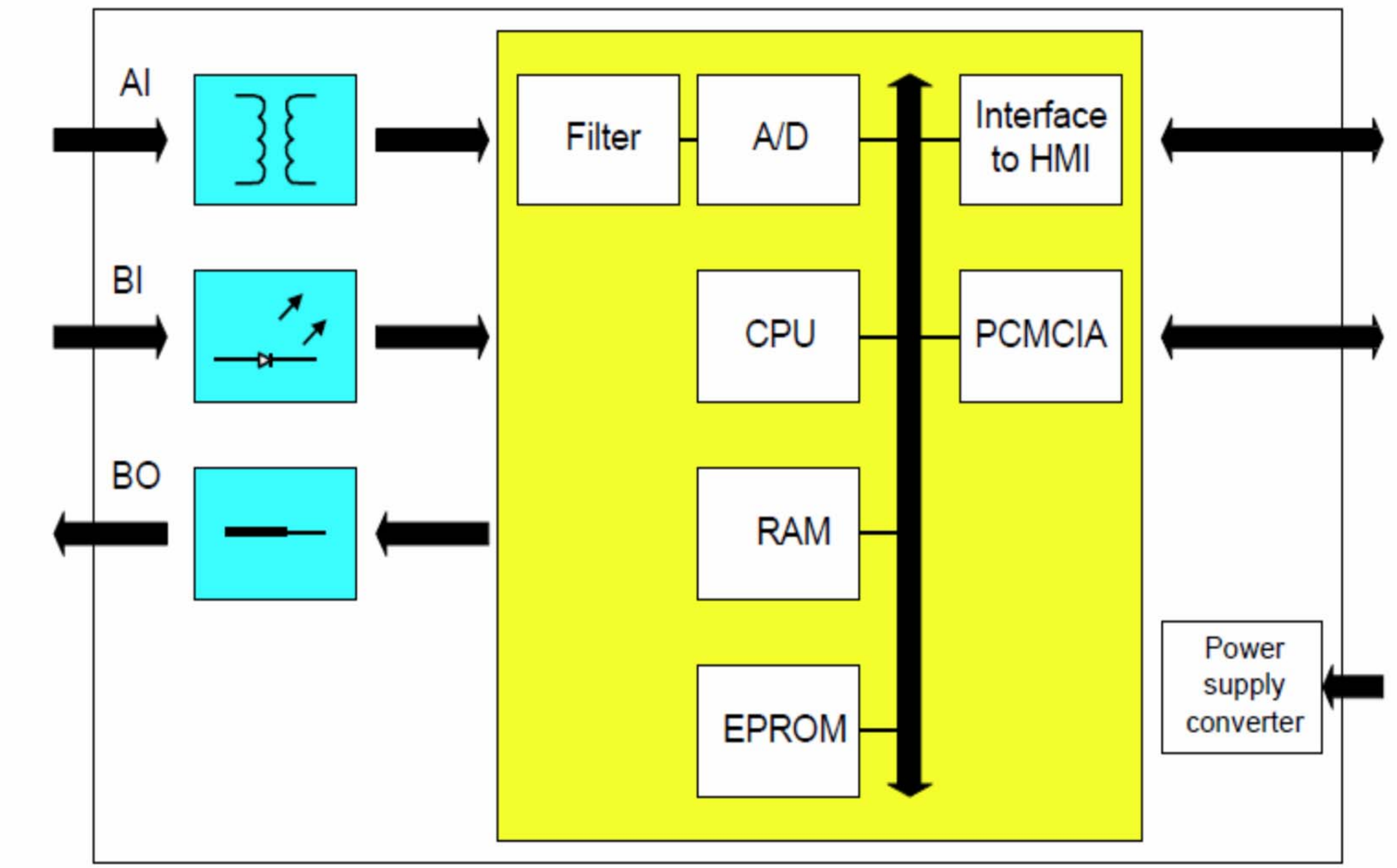
- A bay connects an incoming circuit (power line, transformer, etc) to a busbar assembly.
  - Each bay typically comprises circuit breakers, disconnecters, instrument transformers and surge arresters.
- Bay level devices - IED
  - Devices capable of performing protection and control functions are frequently referred to as IED - Intelligent Electronic Devices.
  - Frequently a manufacturer uses essentially the same hardware platform for both protection and control.
  - The distinction (between protection and control) is then made by the corresponding software and minor hardware modules

IED – Intelligent Electronic Device

IED: a device capable of monitoring processes and communicating directly to the SCADA system

Functional blocks of an IED architecture

AI : analog input
BI : binary input
BO: binary input



IED possesses capabilities to receive and process measurements, issue control commands and communicate with higher level systems (e.g. substation automation).

Functional blocks of an IED architecture

- CPU (Central Processing Unit): interprets instructions and processes data contained in programs incorporating protection, control and communication functionalities.
- PCMCIA (Personal Computer Memory Card International Association): peripherals for additional hardware functions.
- RAM (Random-Access Memory): in IEDs, RAM is used for storing data related to real-time computations - such as measurement samples and instructions computing protection functions.
- EPROM (Erasable Programmable Read-Only Memory): in IEDs, EPROM serves as a storage medium for programs.
- Filter, A/D Converter: A/D converter samples analog signal into a digital form suitable for processing by IED. A usual value of sampling frequency is 600 Hz

Functional blocks of an IED architecture

- Interface to HMI (human machine interface): Most of IEDs can be configured and controlled via both local and remote HMI.
- Interface to Process Level: A galvanic isolation is used between signals coming from process level and an IED. For example, analog measurements are isolated by a transformer before further processing.
- Power supply module: Substations are equipped with a network of secure (i.e. redundant) DC power supply, typically 110 or 220 V. The voltage level is lowered to appropriate level(s) needed by the IED.

Bay level tasks

- Bay level tasks can be divided into Protection and Control
  - Protection is autonomous task dedicated only to bay level (except busbar protection).
- Control oriented functionalities are essentially of two types:
  - **Monitoring**
  - **Switching operations**

(The term control in this context does not directly refer to automatic/supervisory control, rather to data acquisition and control execution tasks.)

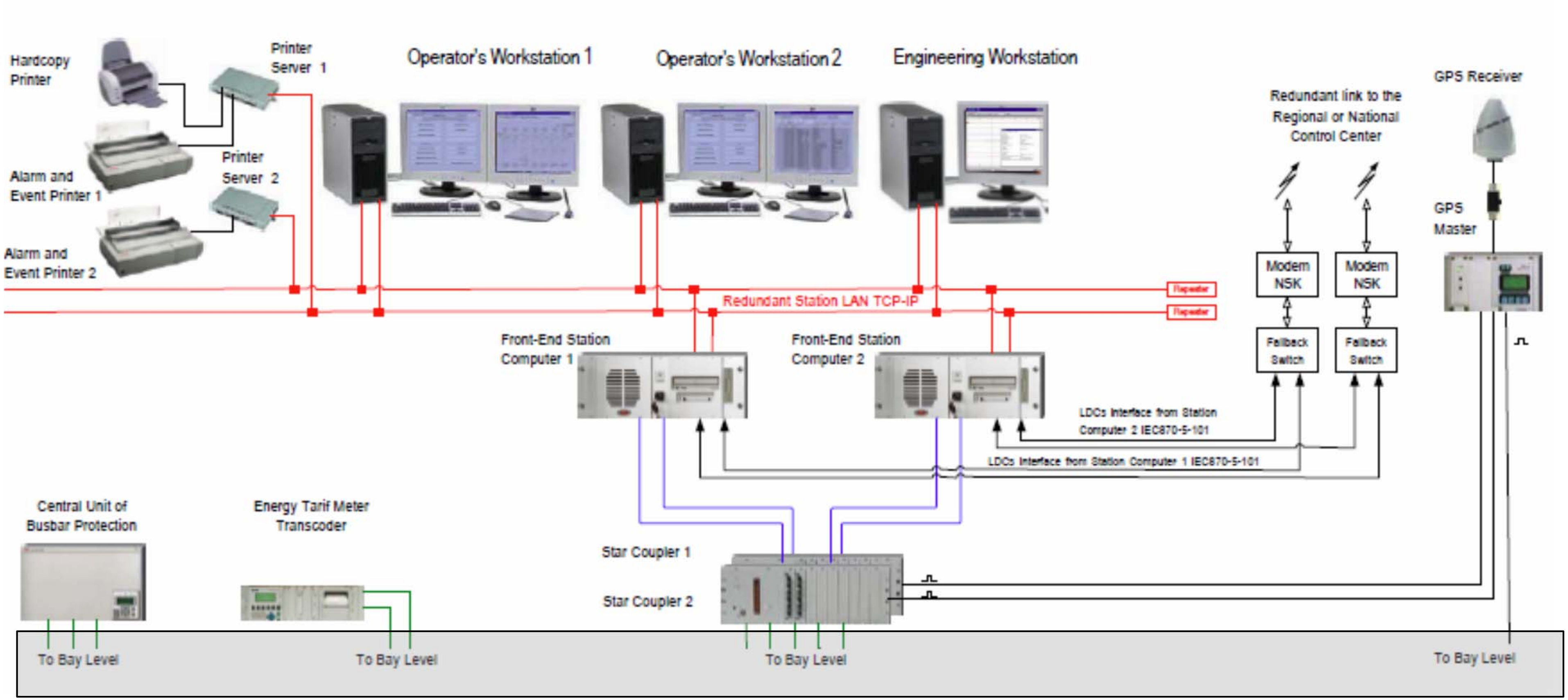
Monitoring

- Monitoring represents supervision of data coming from the process level and sending them to substation level as soon as certain criteria are met.
- For binary inputs it is a change of their value - state.
  - When such a situation is detected, a GPS time stamp is added to the signal. The purpose is, for example, to determine the exact time of a line trip.
- Analog inputs are continuously scanned and values are compared to the last value sent to the station level.
  - As soon as a value of analog input deviates by a defined dead-band either directly from the last value, or accumulated/integrated deviation from the last value.
- This implies that most of the time in vast majority of systems, measurements (voltage magnitude, active and reactive power) are collected in irregular time intervals.

Switching operations

- Switching operations can be initiated either locally (via a local bay level mimic) or remotely (from any other hierarchically higher level).
  - Switching means sending a binary signal to the process level, which opens/closes a switch (circuit breaker, disconnecter or earth switch).
  - A feature called inter-locking is implemented, which blocks closing or opening a switch in a way that could lead to the equipment damage or endangering human health.
  - A typical example is an attempt to open a disconnecter in which both sides are energized. That would lead to an arc - a current flowing in the air, which would heat up contacts and eventually destroy them.

Architecture of a modern large substation secondary equipment



Substation automation

- Substation Automation is a system, which provides a set of substation-wide functionalities, such as components condition monitoring (a typical example is number of switching operations of a circuit breaker, which has a strong impact on the circuit breaker lifetime), data archiving and switching operations between bays.
- Facilities consist of station computer, operators' workplaces (i.e. HMI), peripheral devices (e.g. event printers) and communication among all listed components.
  - Switching operations can be done using a sequencer functionality obeying inter-bay interlocking rules, which are similar to the ones on the bay level, but here relations between different bays are considered.

Substation level elements

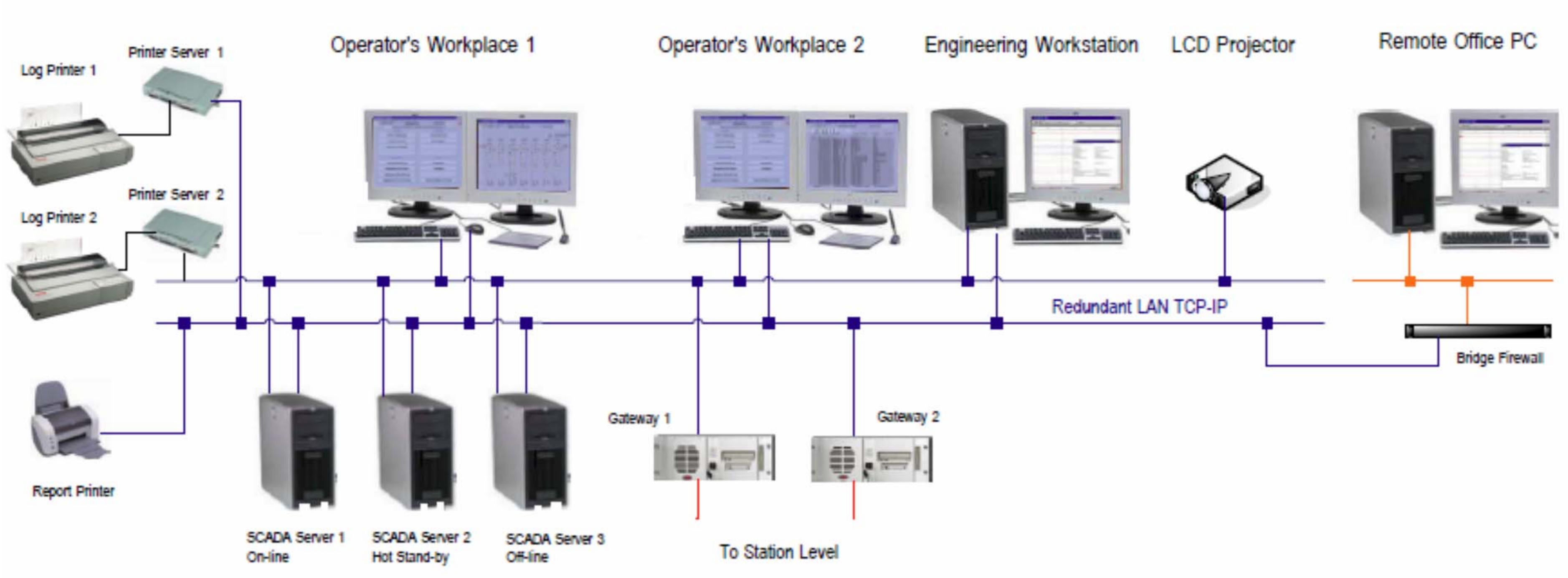
Common elements at the substation level:

- Gateway is a bidirectional communication interface to higher level systems
  - to allow remotely triggered (e.g. by network operator) execution of control commands in the substation as well as remote collection of measurements taken in the substation.
- Time synchronization is achieved either by a time server and mutual communication or by a GPS receiver and master clock, which serve as a source of the time reference signal, which is used both at station as well as bay level.
- Busbar and breaker failure protection cover the whole substation and collect measurements coming from all bays.

Regional and Network Control Center

- The major task of the control center is to provide information to an operator, based on which he/she makes decisions whether some control actions are needed or not.
- It receives data from substations and depending on system architecture, also from other control centers (from regional control centers and/or national control centers of surrounding countries).
- Data are then either directly displayed, or further processed by Energy Management System (EMS) applications together with signal acquisition data chain and components in a control center.

Regional and Network Control Center



Example of a typical control center

Regional and Network Control Center

SCADA

- SCADA stands for Supervisory Control and Data Acquisition.
- SCADA is a technology for collection of data (typically to a central location) from remote (often distributed over large geographical area) facilities and sending control commands to those facilities.
  - SCADA represents a tool, which an operator uses for a supervision of a large process/system.
  - When talking about a particular process/system supervised by SCADA, expression ’SCADA System’ is used.
- A basic structure of a modern SCADA system consists of three groups of components:
  - Distributed Data Acquisition and Control Execution – RTUs, Actuators and Sensors
  - Communication
  - Central Processing

RTU = Remote Terminal Unit

SCADA – Master station

- Central Processing takes place in a so called Master Station (Master Terminal Unit) and provides a direct access point for an operator – HMI.
  - In small SCADA installations, hardware may be a single PC.
  - In larger SCADA installations, hardware may include several servers, operator and maintenance working places.
  - The HMI is usually implemented in a form of a mimic representing the supervised plant.
- Operator working place is usually represented by a keyboard and one or several screens.
  - Sometimes an additional mimic is provided, either as a large dimensioned on-wall projection, a large LCD panel, or a special wall representing the supervised system.
  - Frequently a set of printers is provided in order to produce a hard-copy list of events. Operating systems are usually Unix or similar. Windows is sometimes used for graphical interface part. Software modules implement functions such as communication, data storage and archiving, HMI etc.

SCADA – Communication system

- In terms of hardware, SCADA communication systems employ all types of media, e.g. radio and direct serial or modem connections, frequently combinations of them within one SCADA system installation.
- Standard SCADA communication protocols are IEC 60870-5-101 or 104, Profibus and DNP3. However, a large number of legacy protocols exist, e.g. Modbus, RP-570 etc.
- Many protocols feature extensions, enabling them to operate via TCP/IP. However, a usual practice is to keep SCADA communication system free of connection to internet in order to avoid possible security problems.

SCADA – Remote terminal unit RTU

- A major component in data acquisition and control execution is RTU (Remote Terminal Unit).
- Typically, there is one RTU per geographical location of a remote facility; RTU is a communication interface to the process level, i.e.
    - measurements (analog inputs),
    - switches (e.g. circuit breakers, disconnecters, etc.),
    - statuses (binary inputs) and opening or closing switches (binary outputs).

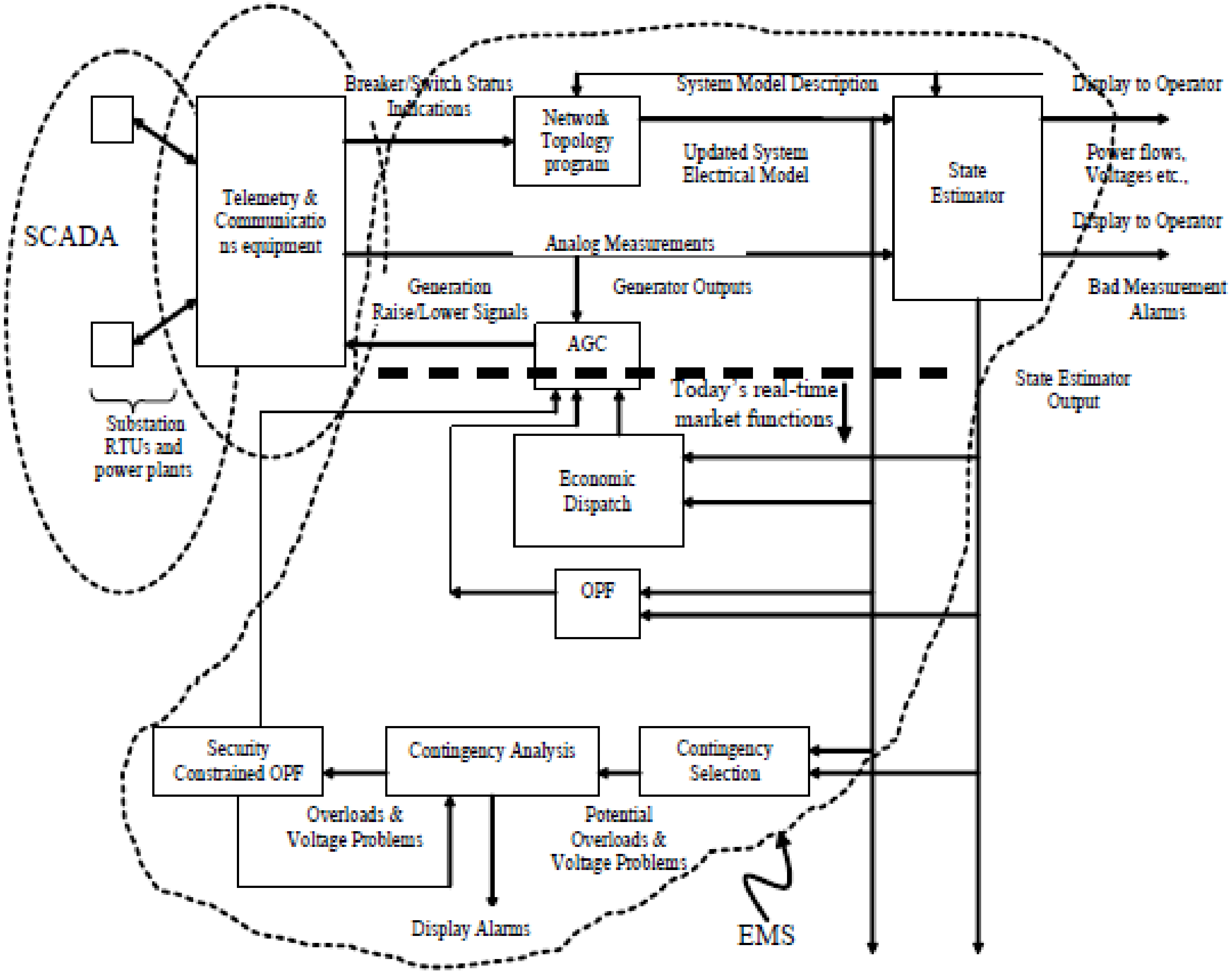
SCADA – Remote terminal unit RTU

- Thus, the measurement itself is taken by a sensor converting it to a form suitable for RTU input.
- In power systems this is done usually in two separate stages, i.e.
  - first the measured quantity is converted to the safe level (e.g. voltage is measured by the voltage transformer and converted to the value around 100 V) and then
  - rectified by a transducer to a RMS (Root Mean Square) value.
- Similarly, RTU output goes to an actuator, which executes the desired control command.
- The entire processing takes place in a control center
- Frequently, a back-up control center is established, which should take over all vital functions in a case of the main control center failure (e.g. a physical damage in war conditions). In some systems, one or several regional control centers may serve as a back-up of national control center.

Energy Management System EMS

- SCADA usually delivers only ’raw’ data, which are further processed by **Energy Management System (EMS)**.
- EMS is a set of programs/tools, which adds an interpretation to measurements, allowing an operator to assess the system security better and even to compute suitable control actions.

Energy Management System EMS



Load Dispatch Center /Energy Management System

- An **energy management system (EMS)** is a system of computer-aided tools used by operators of electric utility grids to monitor, control, and optimize the performance of the generation and/or transmission system.
- The computer technology is also referred to as SCADA/EMS or EMS/SCADA. In these respects, the terminology EMS then excludes the monitoring and control functions, but more specifically refers to the collective suite of power network applications and to the generation control and scheduling applications.
- Load Dispatch Center:
  - Real time grid operation
  - optimum scheduling and dispatch of electricity
  - monitor grid operation

Source : Wikipedia

EMS functions objective

- Power system monitoring
- Power system control
- Power system economics
- Security assessment

EMS : Classification by function

1. State Estimation
2. Power Flow Analysis
3. Contingency Analysis
4. Security enhancement

EMS : Classification by Time Domain

- Pre Dispatch Functions
  - Load Forecasting/Inflow forecasting
  - Resource Scheduling And Commitment
  - Network Outage Planning
- Real Time Operation
  - State Estimator (RTNET)
  - Real Time contingency analysis (RTCA)
  - Real Time Security Enhancement (RTSENH)
  - Real Time Generation Control (RTGEN)
  - Voltage Var Dispatch

- Post Dispatch / off line activities
  - Dispatcher training Simulator
  - Other features like
  - Historical Data Recording,
  - Historical Information Management,
  - Sequence Of Events,
  - Load Flow Studies (STNET)
  - ….