ČESKÉ VYSOKÉ UČENÍ TECHNICKÉ V PRAZE

Faculty of Electrical Engineering

Power Engineering Department

Zajištění a řízení stability elektrizační soustavy

Power System Stability Maintaining and Control

Bachelor’s Thesis

Study program: Elektrotechnika, energetika a management

Specialisation: Applied Electrical Engineering

Supervisor: Ing. Jan Svec, Ph.D.

Vadim Barba

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Czech Technical University in Prague
Faculty of Electrical Engineering

Department of Electrical Power Engineering

BACHELOR PROJECT ASSIGNMENT

Student: **Vadim Barba**

Study programme: Electrical Engineering, Power Engineering and Management
Specialisation: Applied Electrical Engineering

Title of Bachelor Project: **Power System Stability Maintaining and Control**

Guidelines:

Work up the following items to fulfil the assignment:

1. Describe economic and technical designs of a power system and particular issues.
2. Explain voltage and frequency control mechanisms in power systems including their dynamic aspects.
3. Analyse islanding process and its necessity in power systems as the solutions to prevent from black-outs.
4. Evaluate advantages of WAMS (Wide Area Measurement Systems) and their applying as a solution to detected problems.

Bibliography/Sources:

[1] Prabha Kundur: Power System Stability and Control. ISBN 978-0070359581, McGraw-Hill, 1994

[2] Jan Machowski, Janusz Bialek, Dr Jim Bumby: Power System Dynamics: Stability and Control. ISBN: 978-0-470-72558-0, Wiley 2009

[3] Juergen Schlabbach, Karl-Heinz Rofalski: Power System Engineering: Planning, Design, and Operation of Power Systems and Equipment. ISBN: 978-3-527-40759-0, Wiley 2008

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Valid until the end of the winter semester of academic year 2017/2018

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Prague, April 18, 2016

Declaration

I hereby declare that this thesis is the result of my own work and all the sources I used are in the list of references, in accordance with the Methodological Instructions of Ethical Principle in the Preparation of University Thesis.

In Prague, 26.05.2016 Signature ……………………..

Acknowledgement

I would like to thank everyone that were involved in the development of this thesis, especially my parents for their moral support and the possibilities they have given me in life, Psymetrix for the experience and knowledge they have given me on Power Systems and WAMS, Ing. Jan Svec, Ph.D. and Ing. Jan Kyncl, Ph.D. for their continuous guidance and support.

Abstract

This thesis is about the basics of Power System stability and control, such as basic economic and technical design (constraints, laws, standards and requirements, and topologies), basics of voltage and frequency control, brief explanation of blackouts and islanding, and how WAMS may present a solution to power system problems.

Key Words

Power system, generation, stability, frequency control, voltage control, WAMS, blackout, islanding.

Abstrakt

Tato práce se zabývá základy stability a ovládání napájení systému, jako základní ekonomické a technické provedení (jeho omezení, zákonů, norem a požadavků a topologie), základy napětí a řízení frekvence, stručné vysvětlení výpadků a ostrovnímu a jak WAMS může představovat řešení problémů výkon systému.

Klíčový slova

Napájecí systém, generace, stabilita, regulace frekvence, regulace napětí, WAMS, zatemnění, ostrovnímu.

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1. Introduction

Electricity is one of the most important necessities in the modern day. A long time ago, it was considered a privilege to have a household connected to an electrical network; yet nowadays it is considered a must.

The earliest known electrical transmission systems across large distances were formed in the 19th century. Three transmission systems were widely used: telodynamic (cables in motion), pneumatic (pressurised air) and hydraulic systems (pressurised fluid), which transmitted DC current. At the end of the 19th century, AC systems – which we have today – replaced the DC system.

Electrifying large territories and transmitting electrical power across large distances is one of the greatest achievements. Maintaining and controlling the power flow to varying loads, expanding a power system of an area by connecting new power sources and connecting new loads to it is a different challenge that will never be overcome. There will never be a perfect, flawless power system. Problems and complications such as short circuits, large oscillations, blackouts and brownouts will never be completely solved. Today's engineers are developing and applying new solutions and new products to reduce the occurrence frequency of these problems, by developing new topology arrangements, and/or using WAMS to detect the system's problems.

2. Power System Design [2]

Power system engineering is an integral field when it comes to designing, planning electrical power systems, developing projects and to operation and maintenance of a power system for electrical power supply. It includes the calculation, analysis and design of electrical systems and equipment.

It is important to have a reliable, secure and a profiting electrical energy supply. The electric supply at a reasonable and at a competitive price, of a decent quality and quantity, with a safe and reliable supply through reliable equipment and systems is very crucial to the economic development of industries, countries and regions. It is important to take into account different conditions based on regional and structural forethought that usually have an impact on the technical design. Comparing with other industries, the level of capital investment in electric utilities is placed on the first position. It is so, not only for financial reasons, but for long-term return of assets as well. That is why a thorough investigation and planning is required

The same applies to the reliability supply, and apart the thorough investigation, planning, quality of the equipment in a power system and the knowledge of the power system, the consistent use of norms and standards – especially the IEC (International Electrotechnical Commission) standards, national standards and internal regulations – is of crucial importance. In order to make sure that the system operation is undisturbed and that the electrical power is safely and reliably supplied to the consumers, damage of electrical equipment – being due to technical or human errors – must me maximally reduced, and everything must conform to the set norms and standards, including the system operation mode, planning processes and manufacturing of equipment and devices.

The security of the electrical power supply consists of strict following of the conditions of the norms and standards, and safety regulations concerning accident prevention. In low-voltage systems, the main concern is the individual safety, whereas in higher voltage systems the safety of equipment and installations is also added along to individual safety.

2.1. Legal, Political and Social Restrictions

Power systems operate with certain restrictions, such as legal requirements, financial constraints and socio-political and environmental parameters, which strongly influence the system structure, design of equipment resulting to the influence on the cost of investment, cost of energy, which have no link to economical, reliability and security reasons. Some general areas concerning regulations and laws for electrical power supply are stated below:

- Concession delivery regulations
- Market guidelines for domestic electricity supply
- Electrical power industry laws
- Energy taxation
- Laws supporting or promoting “green energy”
- Environmental aspects
- Safety and security aspects
- Right-of-way for overhead-line and cable routing.

The next type of laws and regulations may have an impact on planning, building and operating power systems and in a similar way on the reliability of the power supply and the cost of electric power, and the economic image of a particular country or region:

- Generating plants will be operated in merit order, that is, the generator with lowest production cost will be operated in preference to operating generation with the highest efficiency.
- Criteria of profitability must be re-evaluated in the light of laws supporting “green energy.”
- Reduced revenues from energy sales will lead to a decrease in the investments, personnel and maintenance costs, with consequences of reduced availability and reliability.

- Increasing the proportion of “green energy” generation plants that have low availability leads to an increase in the running reserve of conventional power stations, with consequences of reduced efficiency of these plants and thus higher costs.
- Reduction of investment for the construction of new power stations leads to a decrease in reserve capabilities and thus to a decrease in the reliability of the power supply.
- Expenditures for coordination during normal operation and during emergency conditions are increased with rising numbers of market participants, with the consequence of an increased risk of failures.
- Today’s power systems are planned for the generation of electrical energy in central locations by large power stations with transmission systems to the load centres. A change of the production structure, for example, by increase of “green energy” production plants and development of small co-generation plants, mainly installed in distribution systems, requires high additional investments for the extension of the power system, resulting in rises in energy prices as well as reduced usage of existing plants.
- The power system structure up to the present day has been determined by connections of the load centres with the locations of power stations, which were selected on the basis of the availability of primary energy, – such as brown coal – the presence of cooling water for nuclear power stations or hydrological conditions for hydro power plants. The construction of offshore wind energy farms requires substantial investment in new transmission lines to transmit the generated energy to the load centres.
- The increase of “green energy” production plants, particularly photovoltaic, wind energy and fuel cells, reduces the power quality due to the increased requirement for power electronics.
- The long periods for planning and investment of power stations and high voltage transmission systems do not allow for fast and radical changes. Decisions on a different development, for example, away from nuclear power generation towards “green energy” production, are to a certain extent irreversible if these decisions are not based on technical and economic background and detailed knowledge but are predominantly politically and ideologically motivated.

In Germany, for example, the structure of public tariffs for electrical energy is characterised by numerous measures conducted by the government. These taxes and expenditures caused by the “green energy” law amounted to approximately €12.43 billion according to the VDEW (the association of public utilities) data, where 6.5% for the support of combined cycle plants, 16.8% for concessionary rates for use of public rights of way, 25.6% for expenditures for the “green energy” laws and 50.4% for energy taxes are part of this amount. Additional 19% VAT is added for private households. For the average consumption of 4600kWh per year of a household, these costs resulting from governmental actions mount to approximately €100 per household per year.

2.2. Power System Planning Requirements

The laws and restrictions mentioned earlier must be taken in consideration when it comes to planning a power system, which means that concepts and structures must be developed in a way that they would be technically and economically plausible. This means that the planning of a power system must be done in such way, that generation and optimisation systems, transmission and distribution networks must be done in such way that flexible and economic operation in long and short terms must be enabled.

Power system engineering must implement specific aspects regarding technical and economic possibility and the ones that are difficult to quantify:

- Load forecast of the power system for a period of multiple years
- Long term energy forecast
- Standardisation, availability, exchangeability and compatibility of equipment
- Standardised parameters of equipment
- Restrictions on system operation
- Feasibility regarding technical, financial and time aspects
- Political acceptance
- Ecological and environmental compatibility

Power system planning concerning installations and equipment is initiated and affected by:

- Customer demand for higher load supply or new production plants connection in an industry
- Demand for higher short circuit power to cover requirements of power quality at the connection point
- Construction of large buildings, such as office buildings or any other large buildings
- Industrial area planning or production process extension in industry with requirement of additional power
- New residential area planning
- General increase in electricity demand.

A reliable load forecast takes into account the developments of a power system mentioned above. The general load increase is affected by the overall economic development of a country. Changes in technical boundary conditions – replacement of old installations and equipment, introduction and implementation of new standards and regulations, construction of new power stations and changes in energy production, for example the connection of renewable energy plants – affect the planning and development of a power system (system topologies, substation schemes and main parameters of equipment), which must be in accordance with economic, security and reliability criteria. The relationships mentioned earlier are graphically represented in *Figure 2.1*.

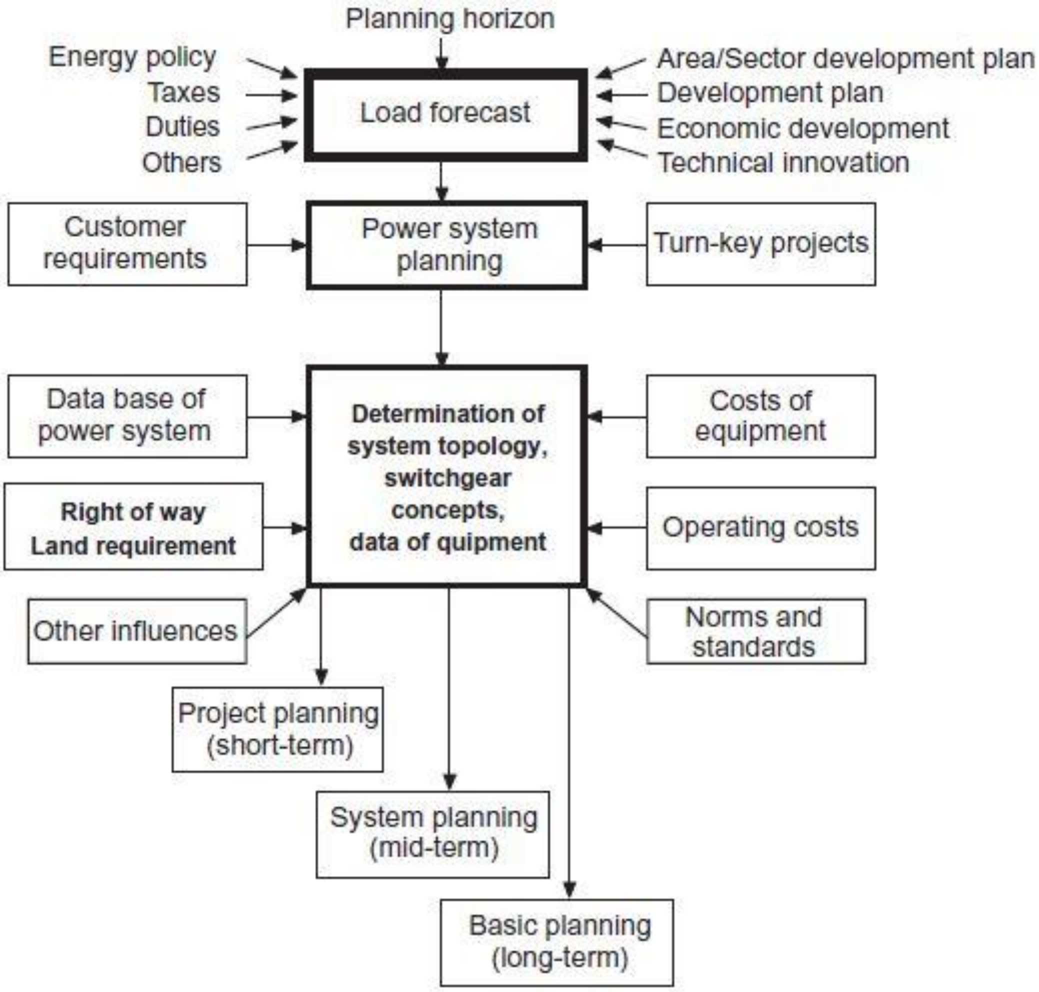


Figure 2.1

2.3. Basic, System Development and Project Planning

As it was mentioned earlier power system planning and project planning have to fulfil specific tasks. When it comes to planning, three of its major parts – basic planning, development planning and project planning – should be covered. All of them take part at different periods of time, as it is shown in *Figure 2.2*.

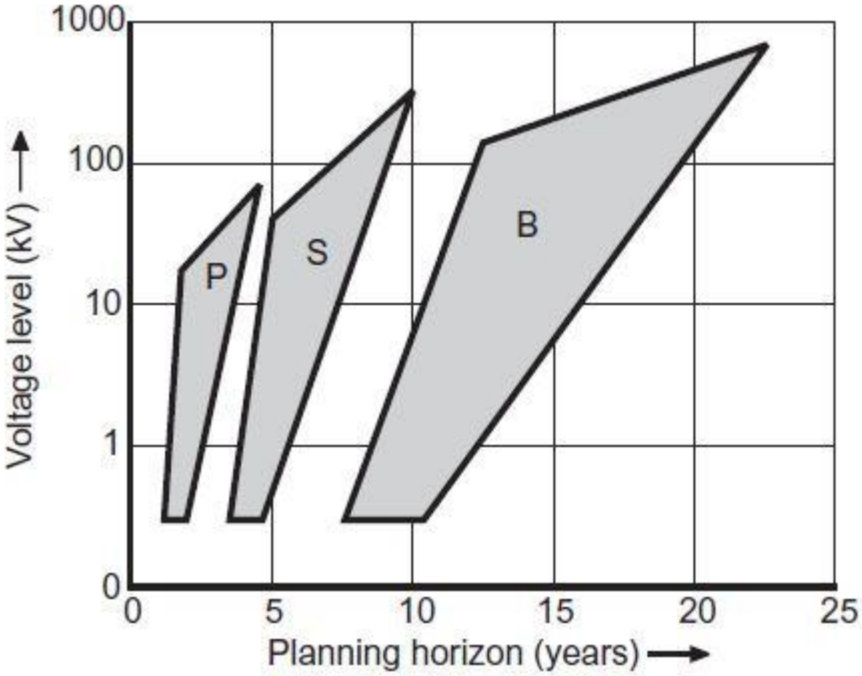


Figure 2.2 – planning stages at varying voltage levels. P – project planning; S – system development planning; B – basic planning.

2.3.1. Basic Planning

Basic planning covers the defined fundamental system concepts for all voltage levels, such as standardisation of equipment, neutral earthing, nominal voltages and the basics of power system operation. For low-voltage systems, it takes up to 10 years to plan them, and 20 or more years for high-voltage transmission systems.

2.3.2. System Development Planning

System development planning takes less time than for the basic planning, up to 5 years for low-voltage systems and up to 10 years for high-voltage transmission systems. It includes the system topology planning which is based on load forecast, load-flow calculations, short-circuit and stability analysis, and cost estimations. Normally, disturbance and operational statistics are evaluated, locations for installations are determined, and the main equipment parameters – overhead lines and cables' cross-sections; short circuit impedance of transformers – are defined.

2.3.3. Project Planning

The period that it takes to realise the project planning is the smallest compared to the other two stages mentioned above. It is up to one year for low voltage systems, and up to for years for high voltage systems. During the project planning, the defined projects in the development planning stage are implemented. Usually what is covered during that time is the expansion of a power system – connecting new customers, new substations, evaluation of the information of the system loading.

2.4. Power System Load Forecast

Power system load forecast is one of the essential tasks and it is the fundamental part of power system planning. The forecast calculations must be as exact as possible. As it is only natural for any measurement or forecast, there is some uncertainty, the longer the forecast period is, the bigger the uncertainty. Power systems must be planned in such a way so that changing load developments can be implemented in their expansion.

If the three planning stages explained earlier are related with the required details and the accuracy of the load forecast, the planning procedures become more detailed during the short term and less detailed in the long term. Different methods of forecasting are applied in accordance with the voltage levels and with the tasks of the planning. There are many forecasting methods, here are some of them:

- Load forecast with load increase factors
- Load forecast with economic characteristic data
- Load forecast with estimated values
- Load forecast based on specific load values and extent of electrification
- Load forecast with standardised load curves.

2.4.1. Load Forecast with Load Increase Factors

The load forecast with load increase factors method is based on the existing power system load and its increase during the past years, and estimates of the future load increase done by using exponential increase functions. The load of a system in the n^{th} year based on the present system load P_0 is determined by the annual increase factor of $(1+s)$.

$$P_n = P_0(1+s)^n$$

(2.1)

The linear load increase in the n^{th} year is described by the equation below:

$$P_n = P_0(1 + n\frac{\Delta P}{P_0})$$

(2.2)

In order to increase the accuracy of the load forecasting the load forecast must be calculated separately for the individual sectors – households, trade, public supply etc. – since the individual results are summed for every year to get the total system load.

A different method for load forecasting is based on the phenomenological description of the energy consumption growth. The change of the system loads growth P during a period of time t is described by the following equation:

$\frac{dP}{dt} = cP^k(B - P)^l$, where k is the growth exponent; c – the growth rate; B – the saturation level of the growth process as a standardisation value; l – saturation exponent

(2.3)

By using this method, adjustments can be combined with the process of load development of the previous years with different increases and saturation effects for the next years. *Figure 2.3* represents the typical load developments. The load development is standardised at the saturation level *B-1* at the end of the period of the forecast, and the growth rate is set to 1.

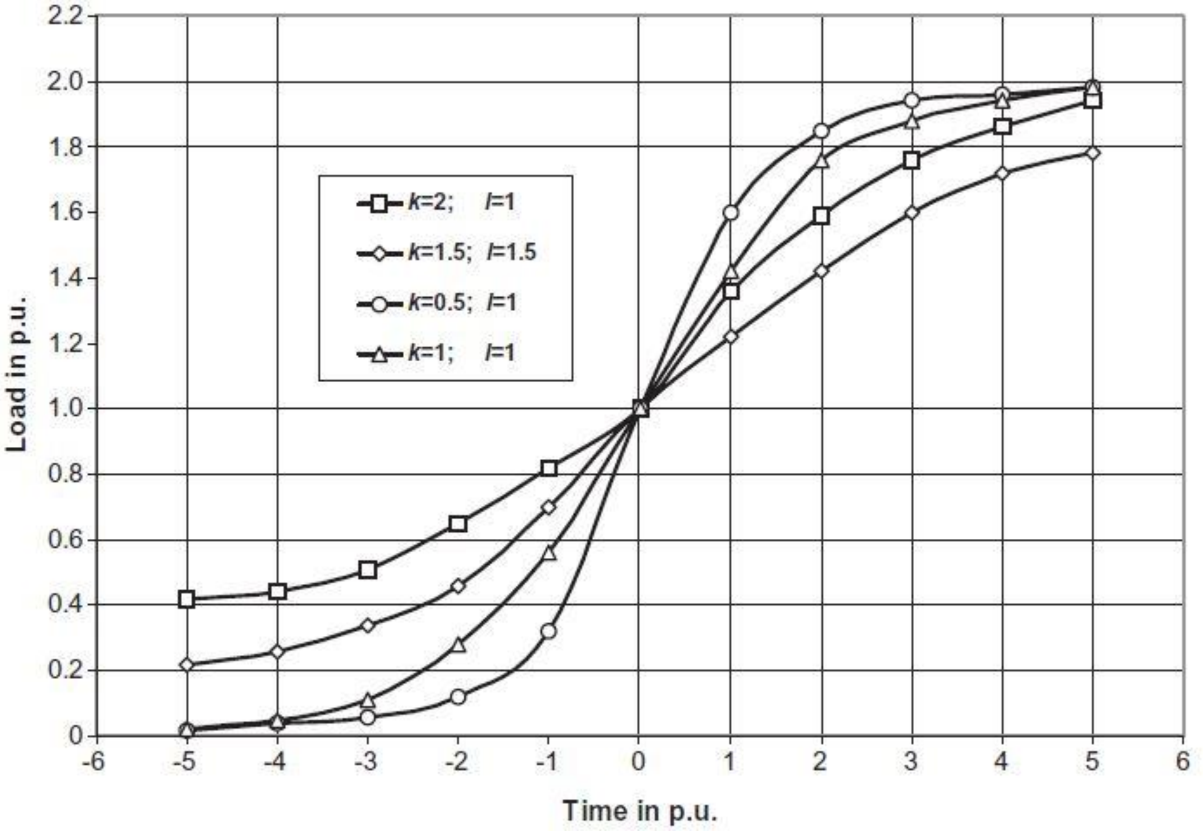


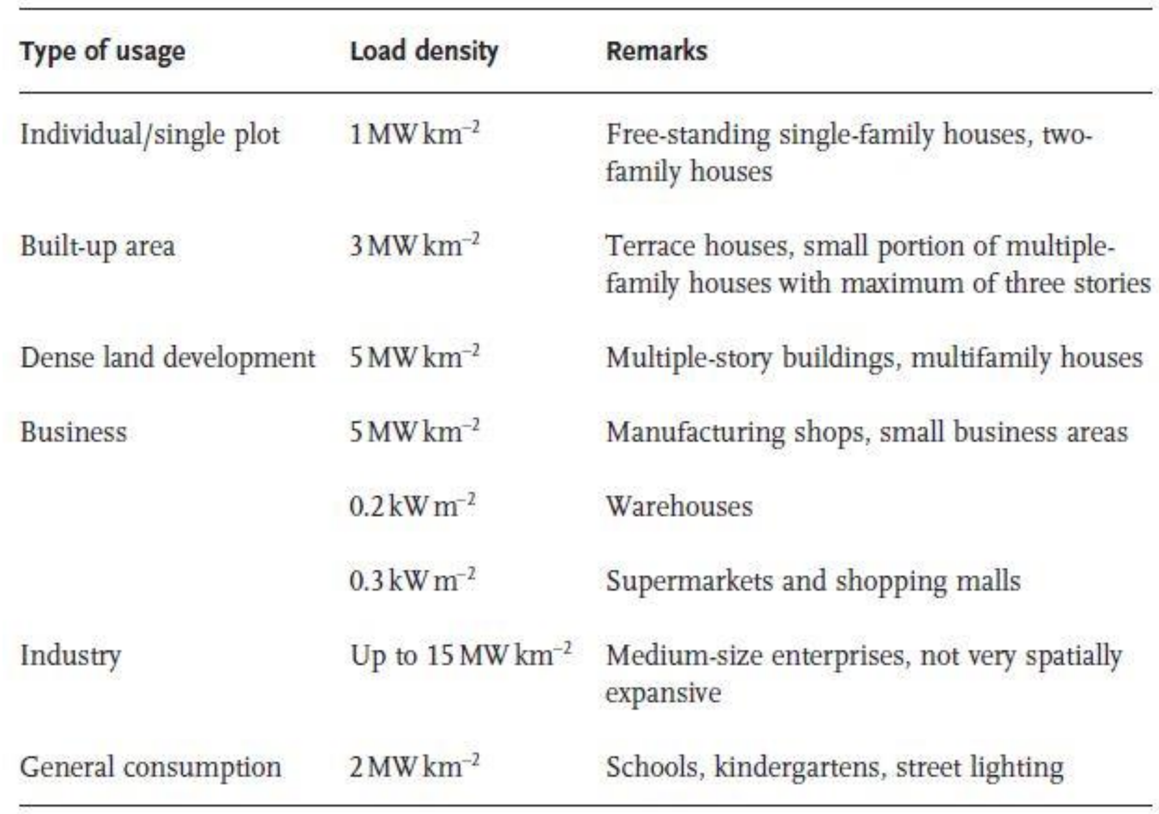
Figure 2.3

2.4.2. Load Forecast with Economic Data

Load forecast with economic characteristic data obtained from electrical energy statistics takes into account different relations between economic growth, availability of energy resources, energy consumption, energy consumption due to population growth and industry energy requirements etc. The degree of industrialisation and the standard of living of a country determines the electrical energy requirement per capita. Nevertheless, high-energy consumption can be an indicator of wasted energy.

When it comes to the connection of bulk loads and industrial customers, the amount of power needed to supply the system load must be determined through the owner of the industrial installation based on the industrial process that they are using, the amount and types of equipment and machinery that they are using.

Land development plans consist of information on the use of a land, its development, and location, types of residential, commercial and industrial areas. These types of plans can help with the estimation of the of the future power system load, for example, the estimation is helpful when it comes to building new substations and transformer stations, such as 110 kV systems that are feeding the distribution system. *Table 2.1* shows the European index of the estimated values of the load densities for different land usage.



Type of usage	Load density	Remarks
Individual/single plot	$1\ \mathrm{MW\,km^{-2}}$	Free-standing single-family houses, two-family houses
Built-up area	$3\ \mathrm{MW\,km^{-2}}$	Terrace houses, small portion of multiple-family houses with maximum of three stories
Dense land development	$5\ \mathrm{MW\,km^{-2}}$	Multiple-story buildings, multifamily houses
Business	$5\ \mathrm{MW\,km^{-2}}$	Manufacturing shops, small business areas
	$0.2\ \mathrm{kW\,m^{-2}}$	Warehouses
	$0.3\ \mathrm{kW\,m^{-2}}$	Supermarkets and shopping malls
Industry	Up to $15\ \mathrm{MW\,km^{-2}}$	Medium-size enterprises, not very spatially expansive
General consumption	$2\ \mathrm{MW\,km^{-2}}$	Schools, kindergartens, street lighting

Table 2.1

2.5. Planning Criteria and Principles

The basic long term planning parameters are the expected active and reactive power of a supply area. Planning principle have to be defined to determine the power system configuration in technical, legal, ecological and economical terms. The supply to the consumers has the highest priority. The supply reliability is defined by system disturbance data, such as faults, scheduled and unscheduled outages, or by quantitative and qualitative criteria.

The reliability of an electrical power system is affected by:

- The fundamental structure of the power system topology
- The selection of equipment
- The operational mode of the power system
- Earthing of the neutral point
- Qualification of the employees

- Regular maintenance
- Operational safety standards

Since it is impossible to achieve a completely secure and reliable power supply, the planning of the system should follow the next idea: ***reliability must be as high as possible, and design and operation must be as economical as possible***.

According to the planning principles, there should be an agreement between an acceptable frequency of outages, their duration until the reset of supply and the power loss due to outages. There are scheduled and unscheduled outages due to system faults. The unscheduled outages are a consequence of:

- The equipment whose insulation strength reduced and led to short circuits and flash overs
- Control and protection equipment malfunction, which can cause switching off of circuit breakers
- External influences such as lightning or earthquakes, which lead to equipment destruction
- Human factors, such as accidents.

2.6. Power System Topologies

Power systems are built and operated as:

- Radial systems
- Ring main systems
- Meshed systems

These system topologies are built and operated at every voltage level.

2.6.1. Radial Systems

The radial system is mostly used in low and medium voltage systems. Individual feeders (outgoing connection of any overhead line or cable from a LV or MV substation) that are connected to the station connect the primaries (switchyard including busbars, transformers and outgoing lines) by radial feeders, as it is shown in *Figure 2.4* (the medium voltage radial system with branch lines is shown in *Figure 2.5*). This type of systems is mainly for low load density areas and for bulk load connections (connection systems).

The characteristics of the radial systems are the following:

- Simple structure
- Low expenditure on planning
- Simple operation under normal conditions
- Line loading up to 100% under normal conditions
- Low investment cost
- Relatively small maintenance cost
- High, unminimizable losses
- Protection given by safety relays – circuit breakers in MV systems, fuses in LV systems

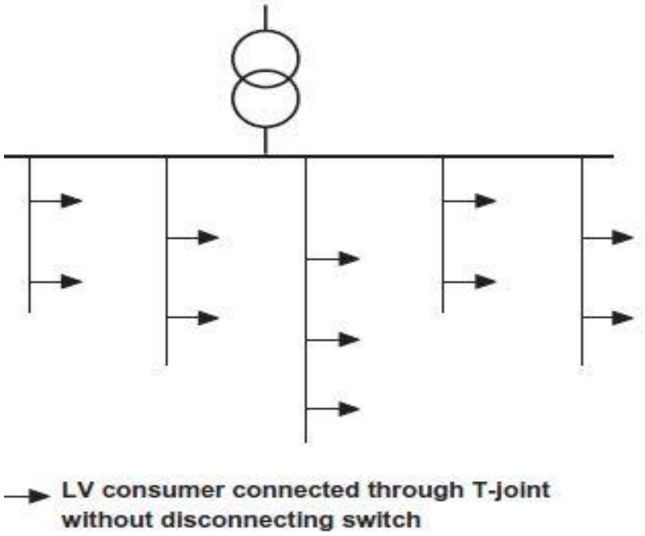


Figure 2.4

Medium voltage radial systems are typical for low load density areas.

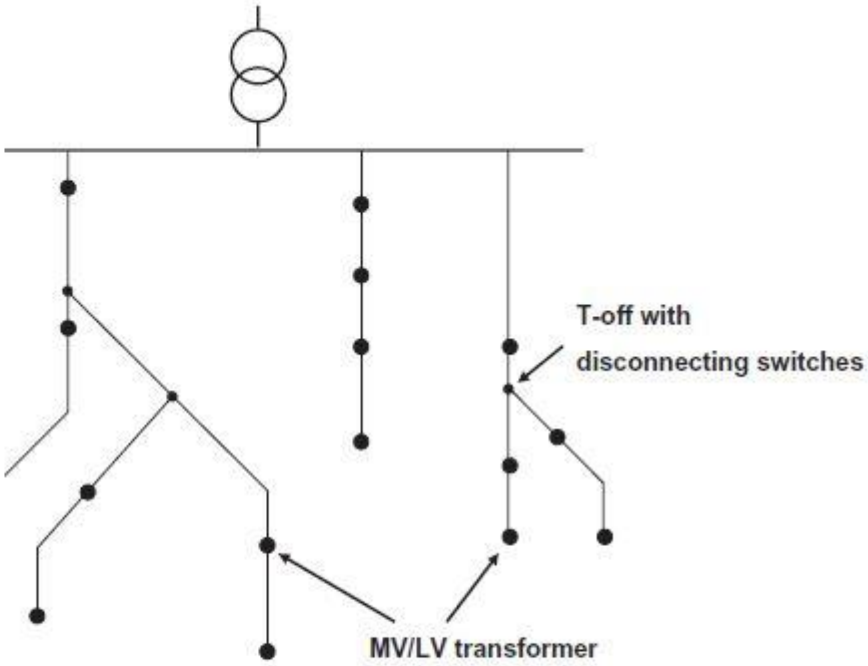


Figure 2.5

In order to improve the reliability of a radial system it is necessary to convert it into a ring main system or to a meshed system.

2.6.2. Ring-main Systems

Ring main systems are usually applied in medium voltage ranges. They are in use in accordance to the permissible load of the lines, reserve capability against outages and to the reliability of the supply. There are several types of ring main systems, such as: ring main systems with and without supply (remote stations), with reserve lines, ring main systems with cross-link connection, and ring main systems with base stations.

2.6.2.1. Ring-main System Basic Topology

Firstly, the basic ring main system will be discussed. The most basic form of a ring main system consists of the connection of the line ends, that start from the radial system, to the supply station as it is shown in *Figure 2.6*. Normally ring main systems are operated with load disconnecting switches at set points of each line.

The loading on the line must be chosen in such a way, so that in case of a fault on the line, the load that the specific line is bearing can be supplied after closing the switch at the disconnection point. In order to keep the normal operating conditions, the thermal admissible load on the line must be kept at half of its value.

The characteristics of ring main systems are the following:

- Simple structure
- Moderate planning expenditures
- Simple operation
- Low investment cost
- Low maintenance cost
- System losses can be reduced by changing the location of the open disconnection point
- Optimisable voltage profiles
- Flexible response to varying load conditions
- Applied in MV system up to 35 kV
- Outgoing connections can be protected by overcurrent protection

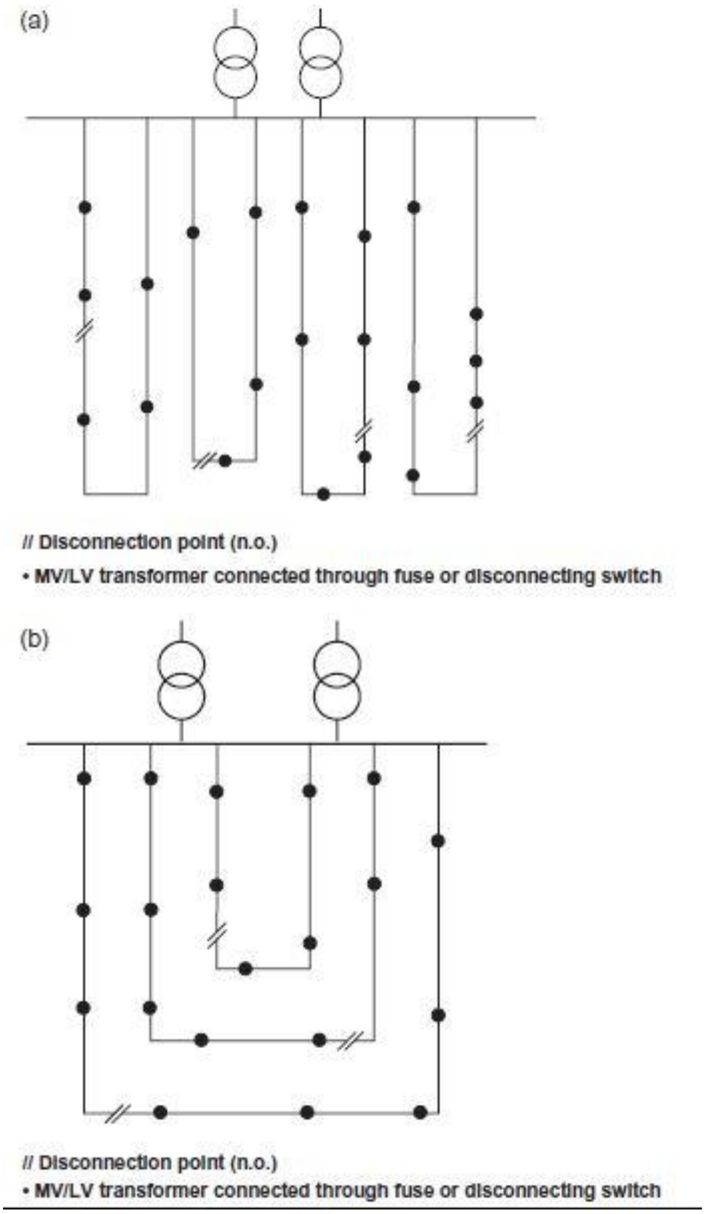


Figure 2.6 – a) Arrangement with limited reserve in the supply; b) Arrangement with reserve to cover outages in the supply

2.6.2.2. Ring-main Systems with Remote Stations

The ring main systems without supply (or with remote stations) have the same technical characteristics as the simple ring main system that is described above. When it comes to connecting individual lines at a receiving point of a station that is not directly supplied by a higher voltage, the topology will take form of a ring main system without supply. As mentioned before, the ring main system has suitable open disconnection points in case of faults and/or outages, in order to keep the load flow and to keep the station energised. The topology of a ring main system without supply is shown in the *Figure 2.7* below.

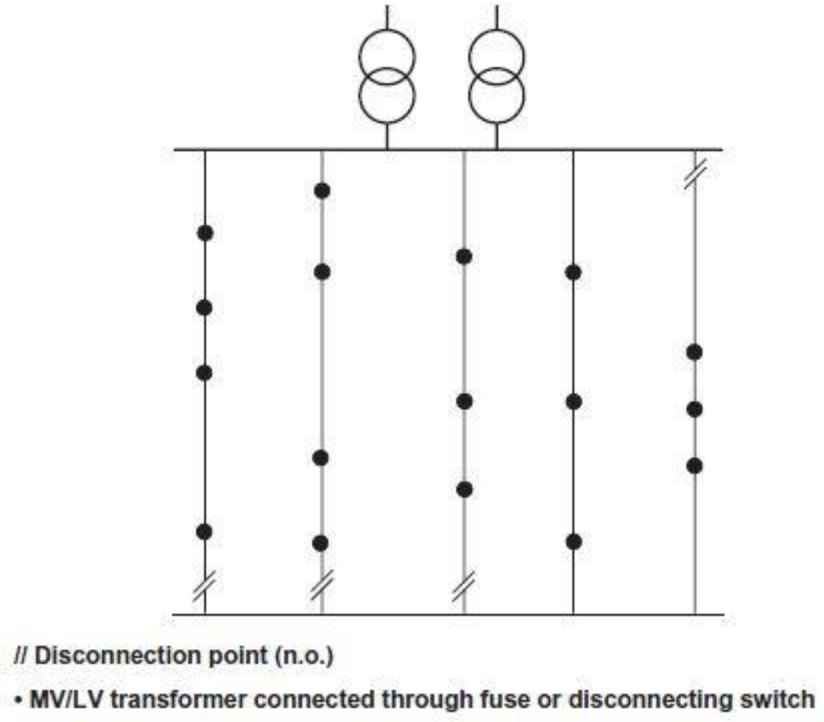


Figure 2.7

A way of improving a ring main system without supply is installing an additional supply from higher voltage levels in the remote station, as it is shown in *Figure 2.8*. The system is able to cover any outages of any lines up to 100% of the maximal thermal loading.

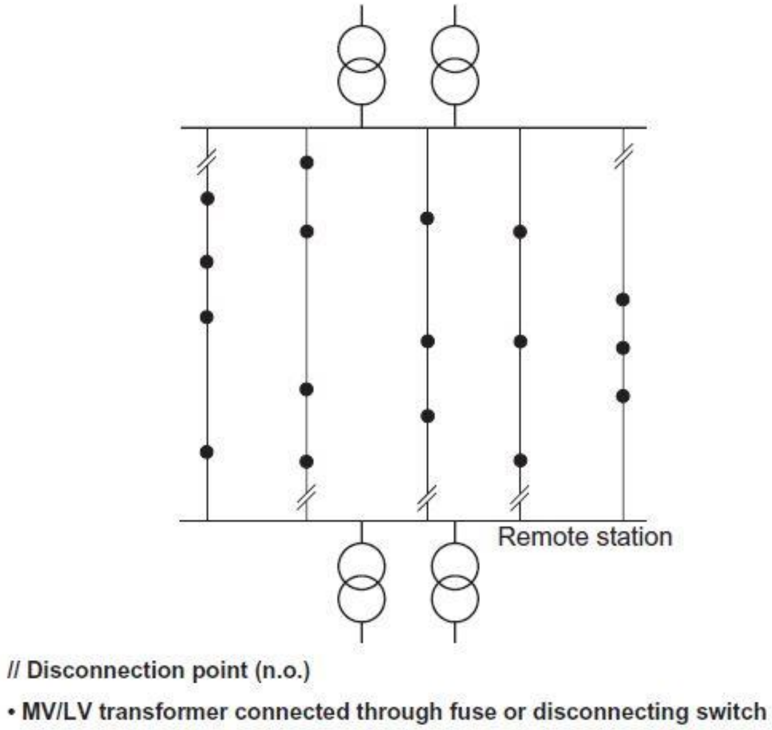


Figure 2.8

2.6.2.3. Ring-main Systems with Reserve Lines

The next discussed ring main system type is the ring main system with reserve lines. The reserve line is a separate line connected between a supplying station and a remote station that does not have a supplying load going through it under normal operating conditions. The role of this reserve line is to improve the system performance and to cover the system performance in case of a line outage. In case of an outage of two lines, it is necessary to have a reserve line with a larger cross section than the main lines, in order to keep the system's performance.

A significant difference between the ring main systems with reserve lines and the ring main system with and without supply is that if the cross section of the reserve line is the same as the other lines (main lines), the loading of the lines can be increased up to 100% (twice as much than for the ring main systems mentioned above). One of the possible topologies for this kind of system is represented by *Figure 2.9*.

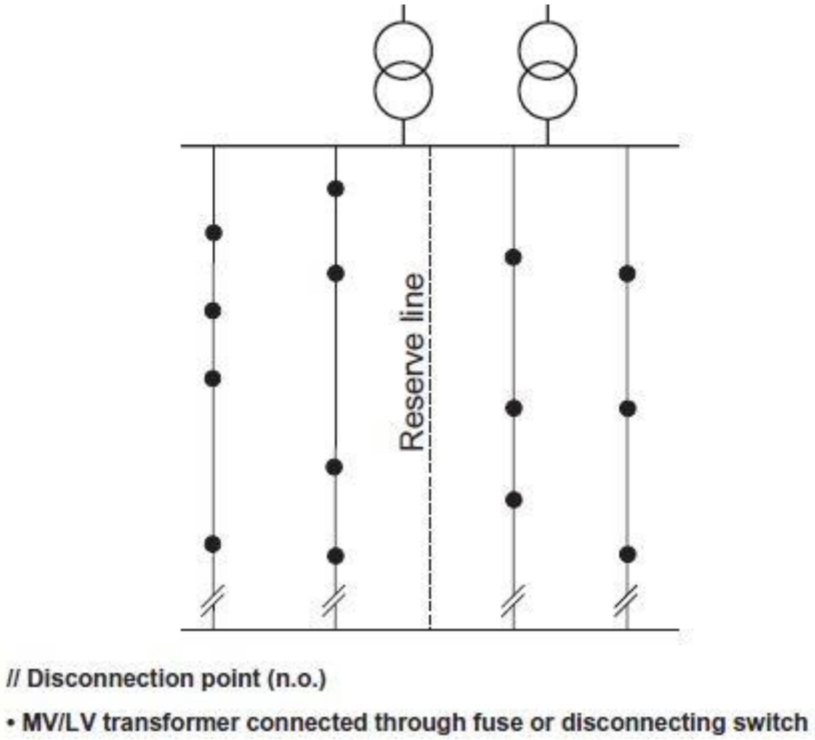


Figure 2.9

However using the reserve line as a substitution of one or two faulty lines, it is only a temporary solution to the problem. The topologies of reserve lines as backups is shown in *Figure 2.10.*

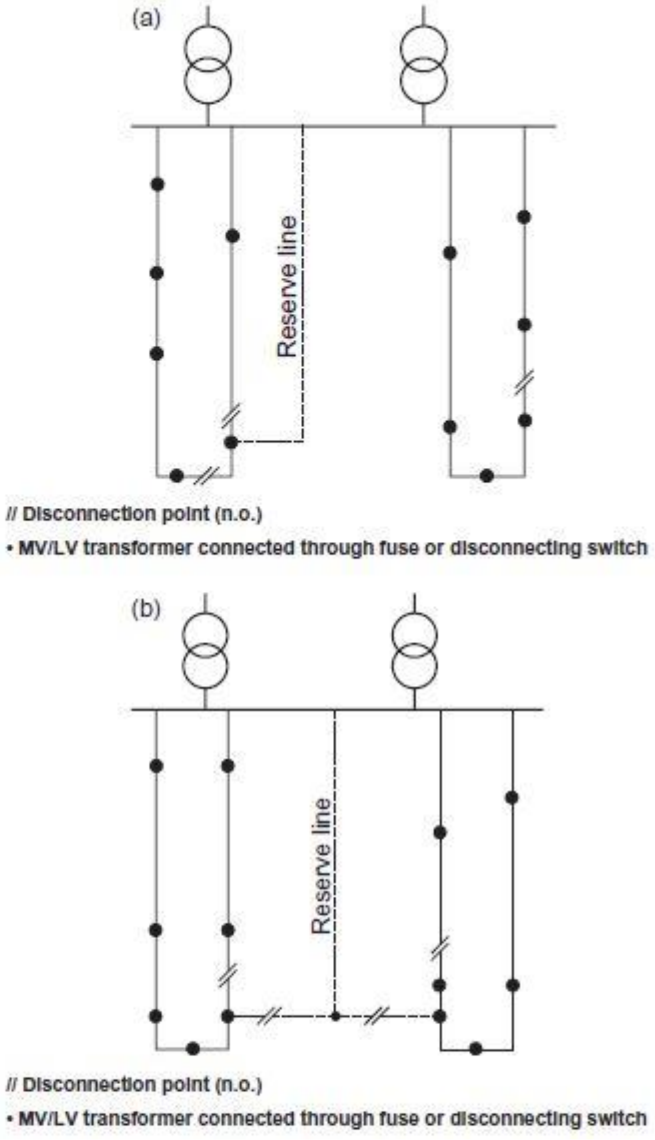


Figure 2.10 – a) Reserve for outages of one or two lines; b) Reserve for outages of several lines

2.6.2.4. Ring-main Systems with Cross-links

Ring main systems with cross-links are also used as temporary solutions to faults and/or outages, just like the ring main systems with reserve lines, and they also give reserve possibilities.

The reserve for outages depends on the preloading of the lines, on the location of the fault and the location of the cross-link itself in the system. As it depends on the location of the fault, with a proper location of the connection of the cross-link, the system can cover up to 100% of preloading of the lines that are connected through the cross-link. Under normal operating conditions the loading of the lines can be up to 60-70% in relation with the acceptable thermal loading. The topology of a ring main system with a cross-link is shown in *Figure 2.11*.

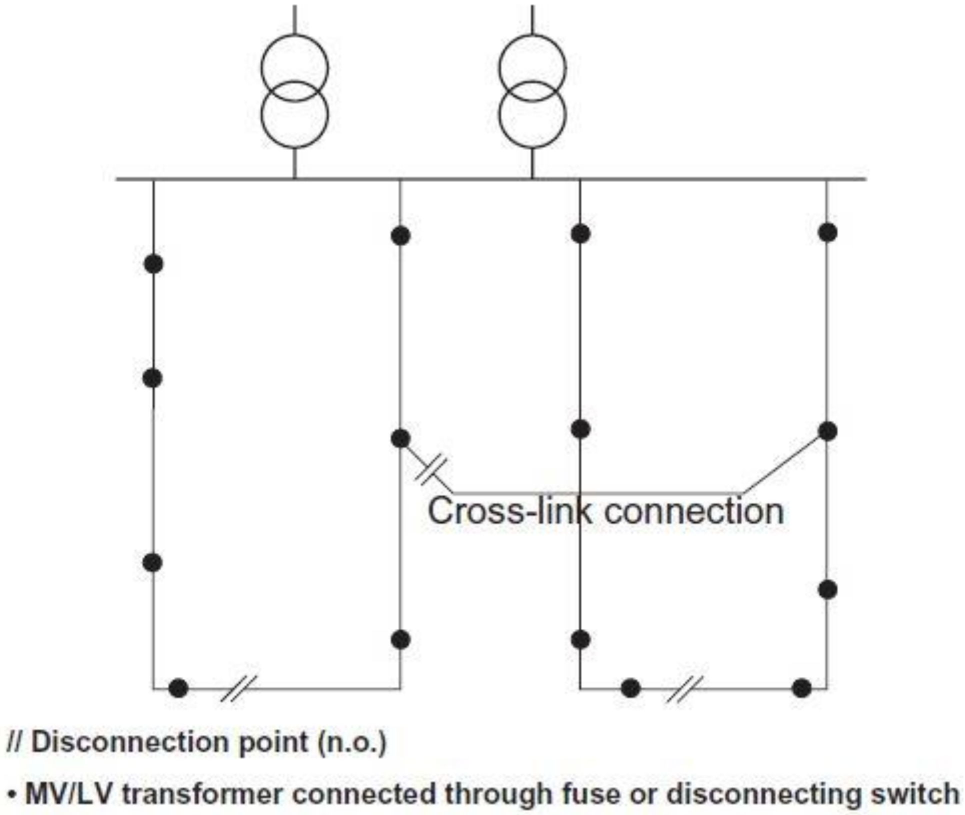


Figure 2.11

The characteristics of this topology are somewhat different compared to the ones mentioned above:

- Relatively unclear system structure
- Comparatively high planning expenditures
- Simple operation under normal operating conditions
- Medium range investment cost; extra cost for the cross-link
- Maintenance cost in the medium range
- Possibility of minimising losses
- Not very flexible for varying load conditions

2.6.2.5. Ring-main Systems with Base Stations

Ring main systems with base stations are usually installed in urban power systems. It is a simple ring main system that was aforementioned that has a base station connected by a double circuit line to the supplying station. In order to have a reserve capability for line outages and/or of the supplying substation, there must be a reserve line that is connected between different base stations and that has a larger cross section than the lines that are connected between the base station and the supplying station. The topology of the ring main system with a base station is shown in *Figure 2.12* below.

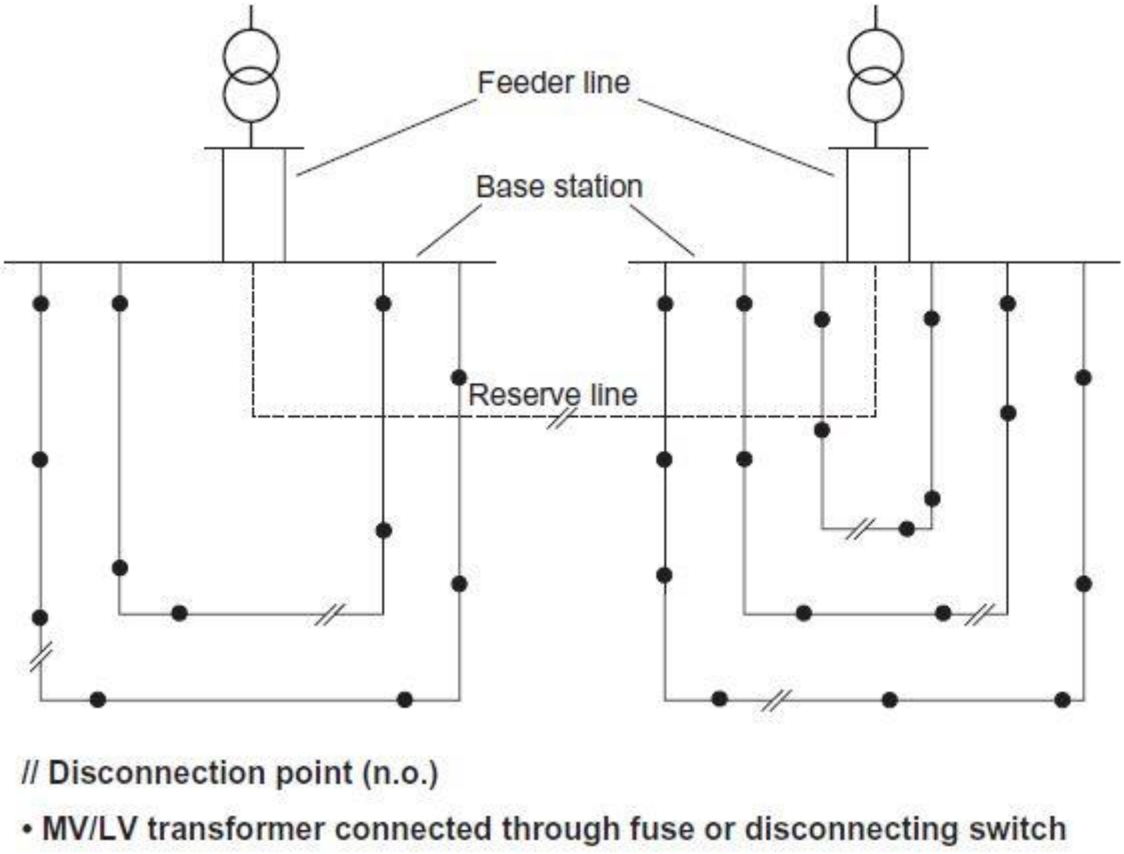


Figure 2.12

The characteristics for ring main systems with base stations are:

- Relatively unclear system structure
- Comparatively high planning expenditure
- High investment cost due to the additional base station
- High maintenance cost

2.6.3. Meshed Systems

2.6.3.1. Meshed Systems in HV Transmission Systems

Meshed systems are planned and operated in a way to maintain the supply to the load, meaning that at medium and high voltage, they are restricting any losses caused by outages of equipment. However, the voltage profile will become worse during the outage, that is why in order to improve the voltage profile it is necessary to reduce the load on the equipment by rearranging the system. There are two criteria that are allowed without loss of supply, which depend how the system is planned, which are single outage criterion $(n-1)$; and the multiple outage criterion $(n-k)$. The single outage criterion is applied for the meshed systems which voltage level is above 110kV. An example of this kind of system is shown in *Figure 2.13*, which represents a high voltage transmission system with different voltage levels.

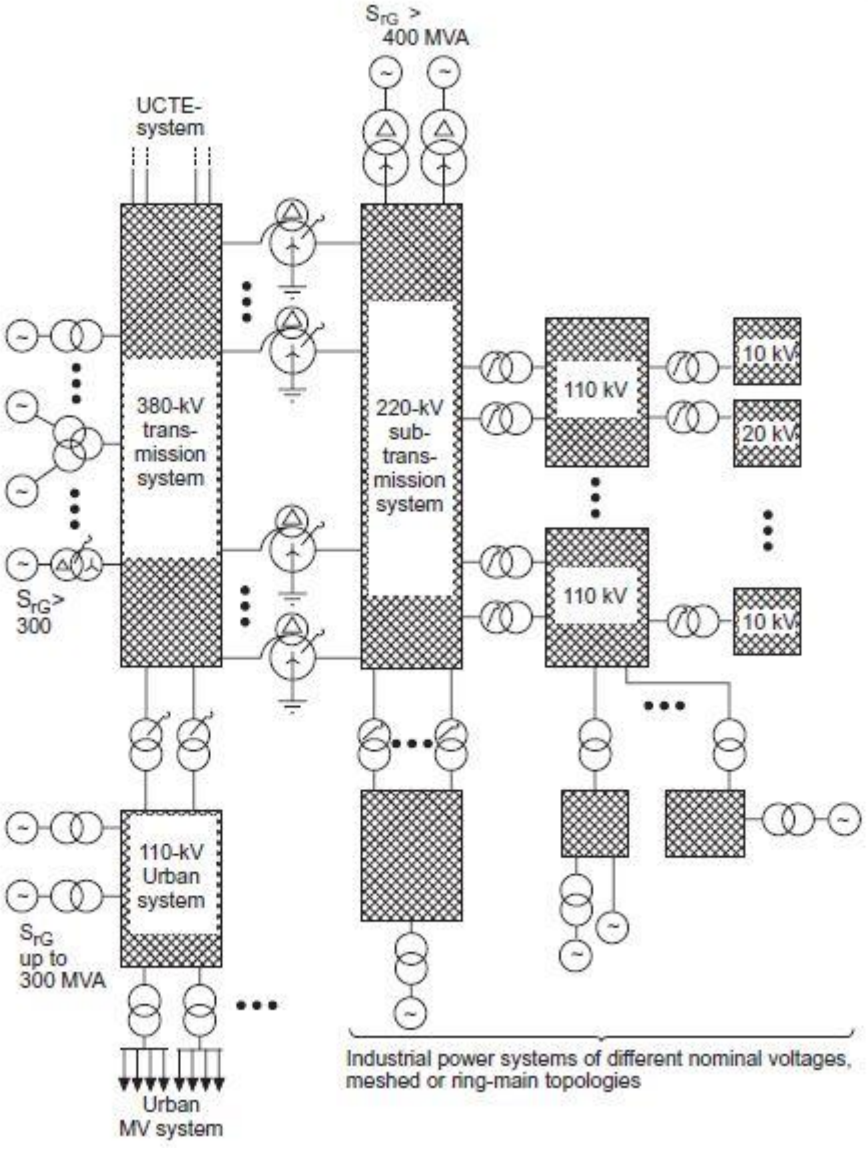


Figure 2.13

The meshed system in high voltage transmission system is characterised by:

- Complicated system structure
- High expenditure for system planning

- High investment cost
- High maintenance cost
- Under normal operating conditions, it’s operated with all breakers closed
- The lines are loaded according to the planning criteria
- Minimal system losses, however the topology must be changed in some cases
- Voltage profile depends on the planning criteria
- No interruption of supply
- High flexibility for varying loads
- Distance protection relays or differential protection are used
- Applicable for high voltage and extra high voltage systems for high load densities

2.6.3.2. MV Meshed Systems

Typically, the medium voltage meshed systems are ring-main systems. Just as the high voltage meshed systems, the medium voltage meshed systems are operated with all closed switches. They can usually be found in industrial power systems. As an example, a ring-main system with a feeding remote station is shown in *Figure 14*, where all breakers and switches are closed and the load on the lines depends on the actual load, impedance of the line, the r.m.s. value and the voltage phase angle in the supplying substations. Medium voltage systems can be found in public medium voltage systems only if the low voltage load has an uninterruptable supply, which can only happen if the low voltage transformers are connected with circuit breakers.

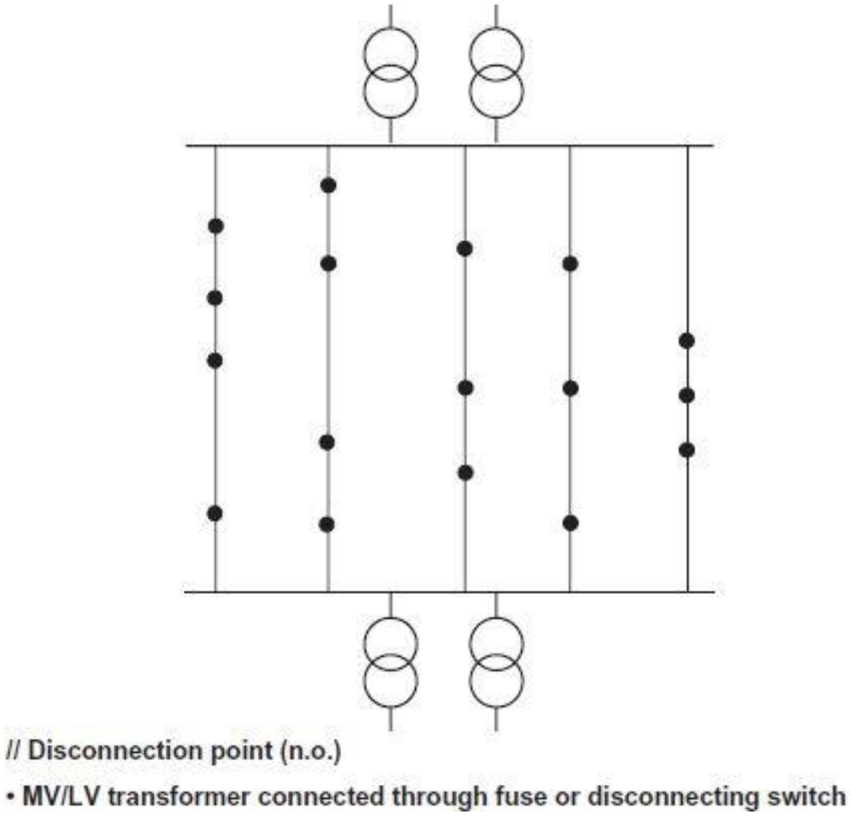


Figure 2.14

Medium voltage meshed systems are characterised by:

- Clear and simple structure
- Ranges between moderate and high planning expenditure
- Simple operation under normal operating conditions
- 70% line loading under normal operating conditions
- Outage reserve for more than one line
- High investment cost, even higher whether circuit breakers are installed or not
- High maintenance costs
- Minimal system losses
- High flexibility for varying loads
- Supply protection with distance or differential protective relays

2.6.3.3. LV Meshed Systems

Low voltage meshed systems are found in industrial power supply systems. They are very reliable, have a flat voltage profile and the have minimal system losses. There are three different types of systems that depend on the connection of the supplying primaries:

- Station-by-station supply
- Single-line supply
- Multiple-line supply

The low voltage meshed system is characterised by:

- Complex topology
- High planning expenditure
- High maintenance cost
- Easy operation under normal operating conditions
- 70%> line loading under normal operating conditions
- Minimal system losses
- Flat voltage profile
- High flexibility for varying loads
- Overcurrent protection and back-power relays are necessary
- Application in low voltage systems with high load densities and with high reliability requirements

2.6.3.3.1. LV Meshed System with Station-by-station Supply

A general structure of a meshed system that is supplied station-by-station is represented in *Figure 2.15*. Each low voltage system is supplied by a low voltage transformer. In urban areas, the medium voltage system can be designed as a ring-main system and in rural areas as a radial system. As mentioned above, at low voltage levels the system has minimal supply losses. Large supply losses are a result of low voltage transformer and/or medium voltage line outages.

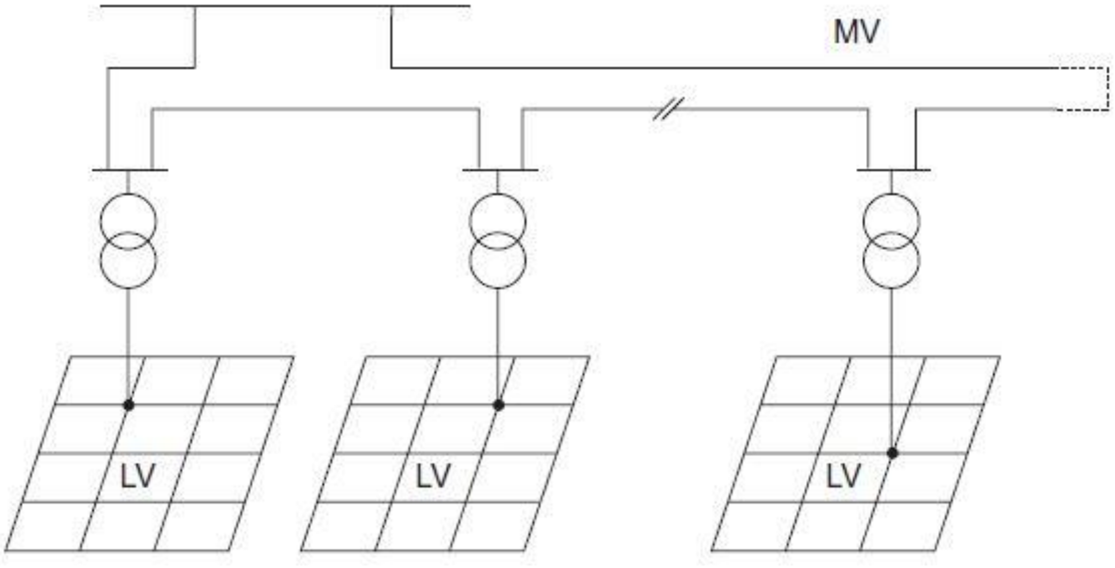


Figure 2.15

2.6.3.3.2. LV Meshed Systems with Single-line Supply

An example of a single-line supply of a low voltage system is shown in *Figure 2.16*. This type of systems is supplied by more than one low voltage transformer, nonetheless, at medium voltage level all the transformers are connected to one line. The system covers low voltage system and low voltage transformer outages. As for the station-by-station supply, the medium voltage line outages will result in supply losses.

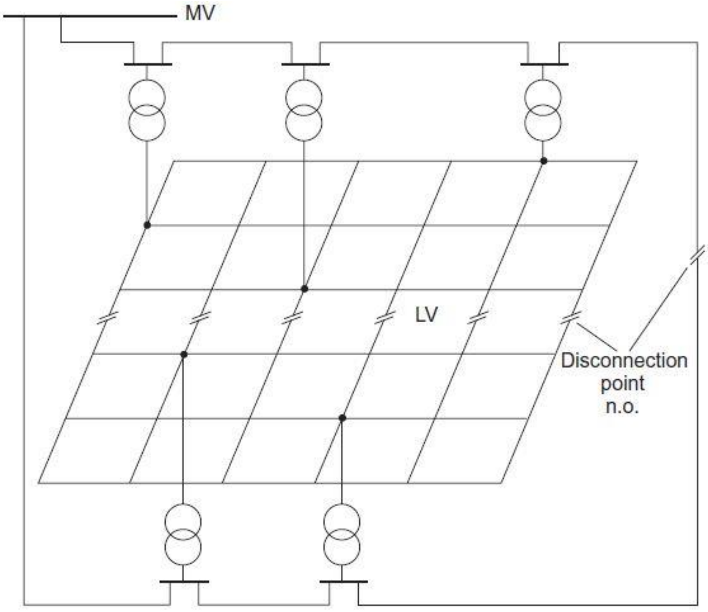


Figure 2.16

2.6.3.3.3. LV Meshed Systems with Multiple-line Supply

The typical structure of multiple-line supplied system is shown in *Figure 2.17*. In contrast to the single-line supplied systems, the multiple-line supplied systems have several low voltage transformers, where at the medium voltage level the transformers are connected to different lines. Just as the single-line supplied system, this kind of system covers the low voltage system and low voltage transformer outages, and additionally it covers the medium voltage system outages, depending whether the system is designed accordingly.

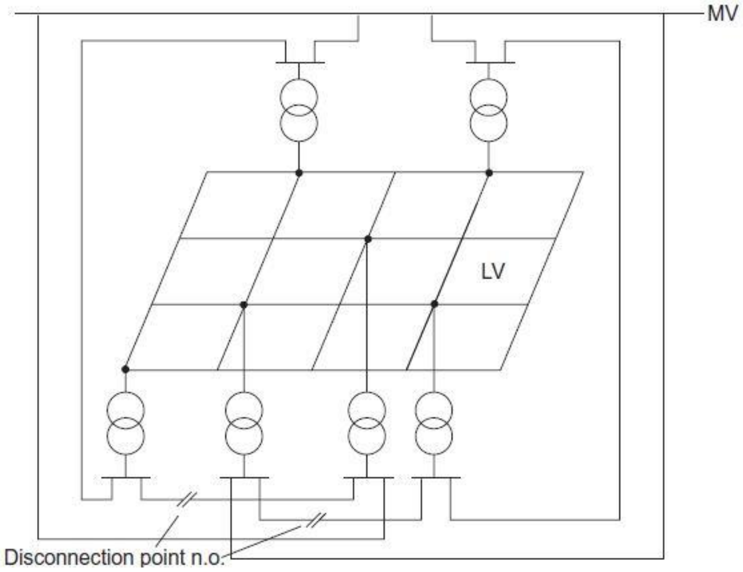


Figure 2.17

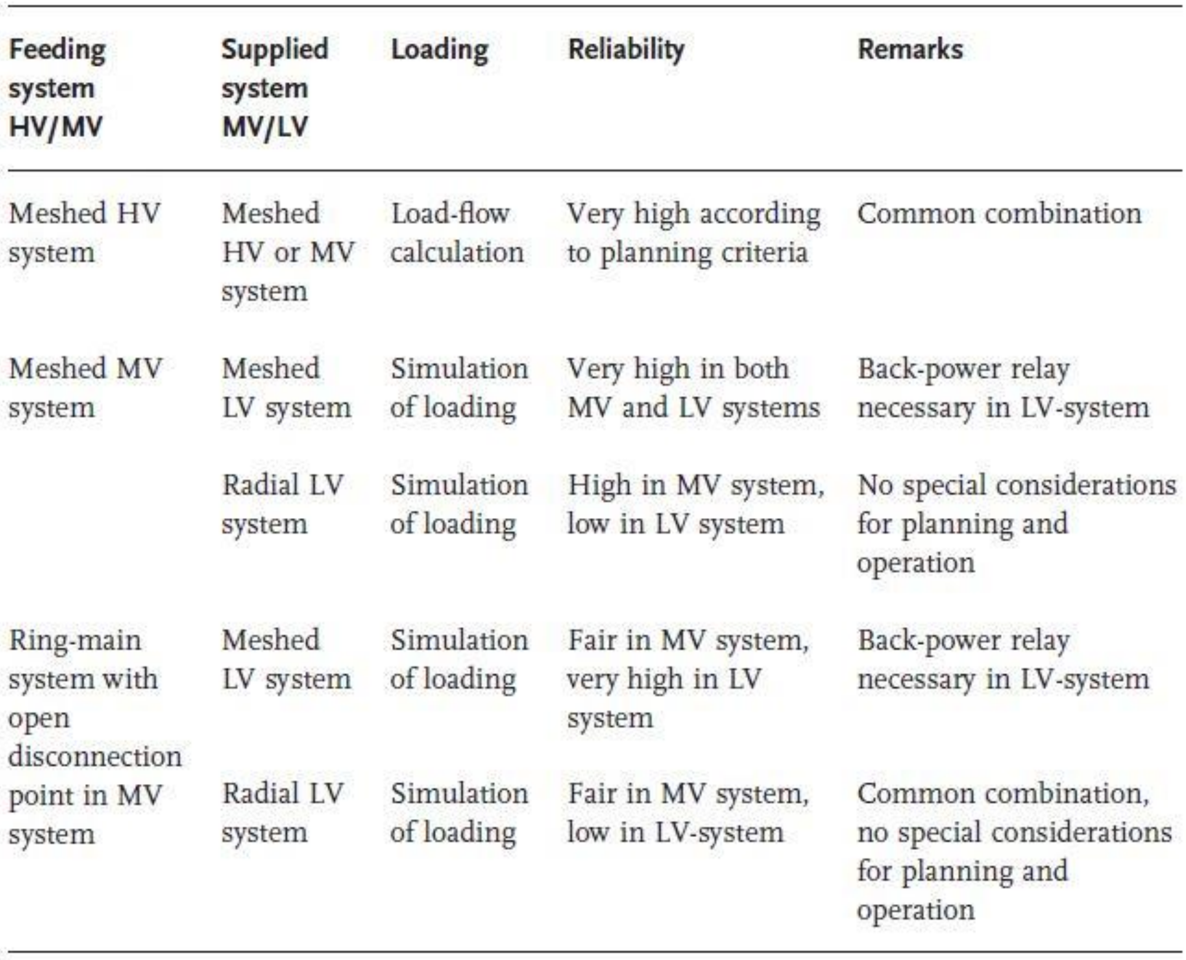
2.6.4. Operating Conditions between Topologies

Of course, some operating considerations must be taken into account when applying and/or planning and designing the aforementioned types of systems. Power system planning must always take into account operational constraints and a long-term consideration of load development. A general change of any system topology, planning, and operating criteria can be done only over a long period of time, which allows gradual restructuring of existing systems.

When it comes to the interaction between different voltage levels, medium and low-voltage systems must be planned and operated in such a way that a corresponding structure is maintained on both voltage levels, for example, if a 10 kV system is operated as a meshed system, the 0.4 kV system can be operated as a meshed or as a radial system.

With a few exceptions, high-voltage transmission systems are operated as meshed systems. Load-flow calculations determine the equipment load, losses and the voltage profile under normal and emergency conditions. Since medium voltage and low voltage systems are operated as meshed system, their impedances usually do not allow any load to flow through the low voltage system. The low voltage transformer load is only determined by the low voltage system's load, and can only be changed by changing the system topology.

If the medium voltage system is operated as a ring-main system with open disconnection points, the low voltage system should be operated analogically. This is important considering short circuits in the medium voltage system in case if the short circuit current of a branch is flowing through the low voltage system. To prevent this situation it is necessary to install back-power relays. If only one low voltage transformer supplies the low voltage system, then it can be connected to any type of medium voltage system. *Table 2.2* shows different aspects for combining different system topologies at different voltage levels.



Feeding system HV/MV	**Supplied system MV/LV**	**Loading**	**Reliability**	**Remarks**
Meshed HV system	Meshed HV or MV system	Load-flow calculation	Very high according to planning criteria	Common combination
Meshed MV system	Meshed LV system	Simulation of loading	Very high in both MV and LV systems	Back-power relay necessary in LV-system
	Radial LV system	Simulation of loading	High in MV system, low in LV system	No special considerations for planning and operation
Ring-main system with open disconnection point in MV system	Meshed LV system	Simulation of loading	Fair in MV system, very high in LV system	Back-power relay necessary in LV-system
	Radial LV system	Simulation of loading	Fair in MV system, low in LV-system	Common combination, no special considerations for planning and operation

Table 2.2

3. Voltage and Frequency Control [1], [2], [4], [5]

As it was mentioned before, a power system must deliver power to the load in an adequately reliable and economical way.

Accidents that are linked to the disruption of stability of big scale electrical power systems have a disruption of the supply to the load as consequence. Taking care of such problems and regaining the normal conditions for the electrical systems to work are very difficult to achieve since it takes a lot of time, attention from the transmission system operator (TSO), and of the other staff responsible for the operation of the system. In contrast to any other types of accidents, the biggest loss of supply is a consequence of this case specifically. It can be said that the system stability is one of the basic factors for maintaining the electrical system to work properly.

Generally speaking, power systems are one of the most complex dynamic systems ever made. Power systems are subjected to instabilities when it comes to changing states, which are in form of oscillations. It is very important to keep the oscillations damped in order to maintain the stability of the system. Voltage and frequency control play a significant role after the planning stage of a power system is complete and during its operation. The two control types are one of the keys to maintaining the stability of a power system, not for just a country, but for a region as well. The failure of keeping the voltage or frequency stability may bring to blackouts, brownouts, equipment and installation damage etc.

To have it in general terms, power system control is all about keeping the balance between the produced power by the generators and the power used by the consumers (the load) at all costs. If the balance fails to be kept, it results in frequency deviations that may affect the system operation depending on the size of the deviations. In addition to keeping the balance, it is necessary to conform to the criteria listed in the previous chapter, the voltage magnitude and the frequency must be controlled and maintained within specific thresholds.

As it was mentioned in the planning part, the generated energy must comply with the size of the load. Any load change that occurs reflects on the generation – specifically on the kinetic energy of the rotors and turbines – which results in a frequency change. If the frequency is too high after the load has changed, then the power supplied by the generating part of the power system must be changed in order to stabilise the system. Unbalances in the generated and consumed power can be caused by the consequences due to some faults that trip the generating units. All of this is done through frequency control of the operating generators. The aim of the frequency control is to keep any frequency deviations within the acceptable thresholds.

Before going into more depth about frequency and voltage control, it is necessary to have the basic understanding of both static and dynamic stability.

3.1. Power Characteristic

Figure 3.1 shows a basic diagram of electric transmission in which the generator is connected to a transformer and a transmission line that goes to the receiving system, whose power is so large in comparison with the power of the transmission the figure represents, that the voltage of the receiver $\hat{U}$ can be considered unchangeable if take it as an absolute value. *Figure 3.2* represents the diagram of the equivalent circuit of the transmission system shown in *Figure 3.1*, in which the resistances and the capacitances are removed and inductive resistances (reactance) represent all the elements. The sum of the inductive resistances of the generators, transformers and transmission lines gives the total reactance of the system: $X_C = X_G + X_{T1} + 0.5X_L + X_{T2}$.

Figure 3.1 – Electric transmission schematic diagram

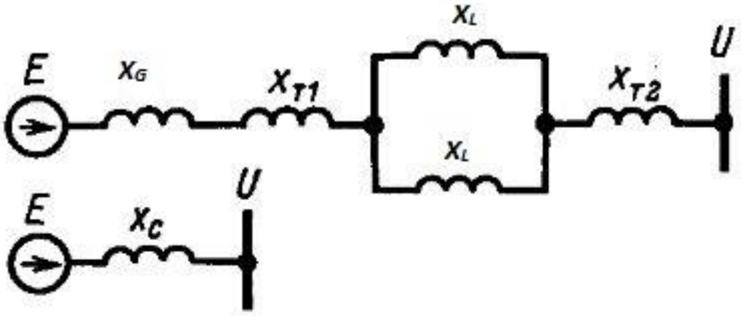


Figure 3.2 – Equivalent circuit of electrical transmission

Figure 3.3 represents the vector diagram of the working state of the transmission system under normal conditions, where $OA = E\sin\delta$ and $BC = I_a X_c$, which give us the relation:$I_a X_c = E\sin\delta$, where I_a

is the current; δ – the changing angle of the electromotive force $\hat{E}$ relative to the vector of the voltage of the receiver $\hat{U}$. By multiplying both sides with U/X_c, we get $UI_a = \frac{EU}{X_c}\sin\delta$ which gives us (3.1),

$$P = \frac{EU}{X_c}\sin\delta$$

(3.1)

where P is the active power given by the generator.

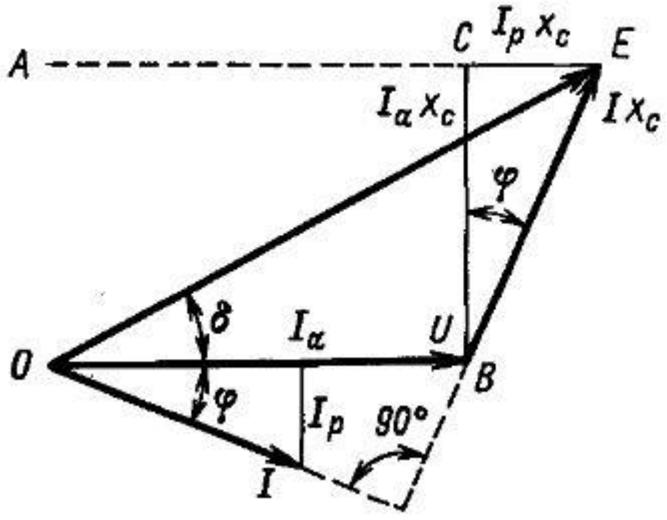


Figure 3.3 – vector diagram of the working state of the transmission system

By having constant e.m.f. *E* and voltage *U*, the change in the transmitted power can be achieved only by the change of angle *δ*. As it is known, the change in power affects the control of the turbines. Under normal conditions, the power of the turbine is the same as the power of the generator, which is rotating with a constant frequency. Depending on the opening of the regulating valves, the power of the turbine is increasing and the equilibrium between the torque and the breaking momentum of the turbine and the generator is lost, which results in the acceleration of the generator’s rotation.

By accelerating the generator, the vector of the e.m.f. *E* (shown in *Figure 3.4*) is being displaced relative to the rotating vector of the voltage of the receiver *U*, which is not affected by the angular speed *ω*. According to this and to (3.1), the increasing angle *δ* affects the power of the generator *P*, which is increasing until it will stabilise the increasing power of the turbine. This way, the magnitude of the active power of the generator of the receiving is determined by angle *δ*.

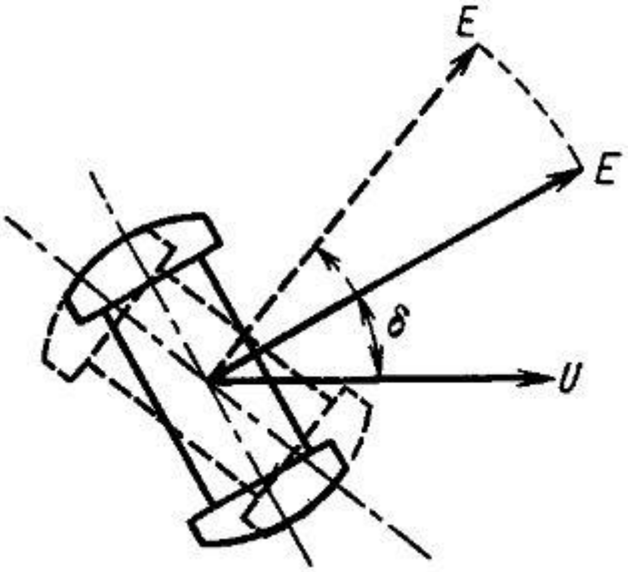


Figure 3.4 – the displacement of vector E of the generator due to the generator's acceleration

As it is shown in (3.1) the active power has a sinusoidal dependence on angle δ (*Figure 3.5*), therefore as δ is increasing, active power P is increasing and after reaching its maximum it starts to decrease.

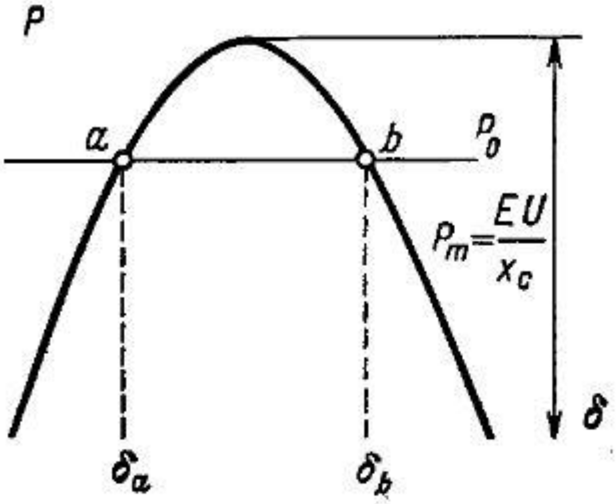


Figure 3.5 – Power dependence on angle δ

According to the relation described above, the maximum transmitted power P_m is shown in (3.2),

$$P_m = \frac{EU}{X_c}$$

(3.2)

which can be named as the *ideal working point* in the simplest electrical system. The equilibrium between the power of the turbine and the power of the generator is only achieved when the power (let it be P_0) is lower than P_m. Generally speaking, P_0 has two possible equilibrium points on the power characteristic, and two magnitudes of the angle δ_a and δ_b, respectively (as represented in *Figure 3.5*). However, the actual stable point can only be at angle δ_a, since δ_b is on the decreasing side, which is unstable and cannot be kept for a long time.

3.1.1. Understanding Static Stability

In the most basic conditions, the change characteristic of power and moments by small deviations from the stable or equilibrium state, which makes the system return itself back to its initial state, describes the stability of a system. As mentioned above at point *a* (*Figure 3.6*) the power of the generator and the turbine are in an equilibrium state (are balancing each other). If assumed that angle δ_a is increased by $\Delta\delta$, then the power of the generator, following the sinusoidal dependence of the angle, is also changed by ΔP, though as it shown in *Figure 3.6*, at point *a* on the increasing side, where $\Delta\delta$ is also increasing, the change in power ΔP is also changing positively. As for the power of the turbine, it does not depend on the angle δ, and under any changes, it will always be equal to P_0. As a result of the change in power of the generator, the balance of the moments of the turbine and the generator is being disturbed, because of the excessive breaking moment, since the breaking moment of the generator in the positive direction of ΔP is greater than the torque of the turbine.

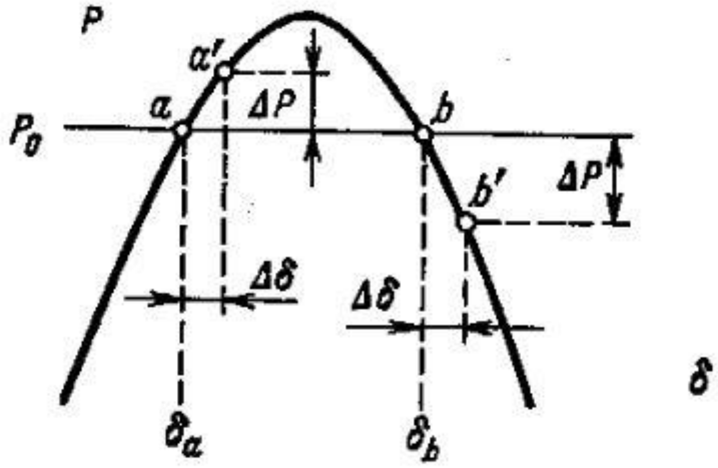


Figure 3.6 – the change in power due to the increasing angle

Under the effect of the breaking moment, the rotor of the generator starts to slow down, which explains the displacement of the e.m.f. vector of the generator *E* in the direction of the reduction of angle δ. As a result of the decrease of the angle restores the system to its initial state, this behaviour is said to be stable. It is possible to come to the same conclusion if the change in the angle is decreasing at point *a*.

At point *b* there is a completely different picture. In this case, if $\Delta\delta$ is positively increased, the effect will be negative instead of a positive change of ΔP like at point a. The change of power of the generator causes an excessive moment of an accelerating characteristic, under which angle δ is not decreasing, but oppositely, it is increasing. With the increase of the angle, the power of the generator continues to decrease, which makes the angle to increase even further, and so on. This process is accompanied by the uninterrupted displacement of the e.m.f. vector E relative to the vector of the voltage of the receiver U (*Figure 3.7*) and the system loses its state of synchronism. This way, the working state at point *b* is statically unstable and cannot be achieved in practice

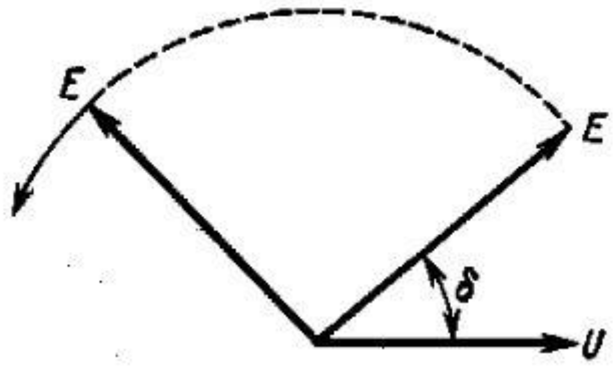


Figure 3.7 – synchronism loss

By static stability it is understood as the capability of the system to return to its initial state under any small deviations. Static stability is a required condition of any existing working state of the system, even though it does not allow the system to work in case of large deviations, such as short circuits. This side of the problem will be described later under dynamic stability.

So at point a and at any point on the increasing side of the sinusoidal power characteristic are responsible for the static stabilisation, and the other way round, all the points on the decreasing side of the characteristic are statically unstable. From all the statements mentioned above, that characterised the conditions of the working states of the system, the next characteristic of static stability seen from the simplest system: the increase of angle δ and power P must have the same sign, in other words, $\Delta P/\Delta\delta > 0$, or it is going to this limit shown in (3.3).

$$\frac{dP}{d\delta} > 0$$

(3.3)

The differential $\frac{dP}{d\delta}$, as it is known, is holding the name of synchronising power, respectively, the criterion of the static stability of the system of the conditions discussed above is the positive sign of the synchronising power. The derivative of the power according to the angle, according to (3.1), is equal to (3.4).

$$\frac{dP}{d\delta} = \frac{EU}{X_c}\cos\delta$$

(3.4)

Of course it is positive when $\delta < 90°$, (*Figure 3.8*). When $\delta = 90°$, the characteristic of the power reaches the maximum, and it is critical, from the stability point of view (of the discussed cases above, meaning only completely inductive link of the generator to the receiving station).

3.1.2. Understanding Dynamic Stability

The fact that the system is keeping the static stability in the set working condition cannot say that the system may be stable even if short circuits, disconnecting generators or lines etc., interrupt the working state. This side of the problem must be investigated individually and it raises many other questions concerning the so-called dynamic stability of electric power systems.

This way, if during the investigation/analysis of the static stability it is necessary to deal with infinitely small system disturbances, such as losing synchronism due to an unstable system, then the dynamic stability of a system is for the analysis of major system disturbances, and the characteristic and the magnitude of the disturbance represent the essential meaning of the problem.

In order to find the main conditions of dynamic system stability, the consequence of an unexpected interruption of one of the two parallel connection of transmission lines (shown in *Figure 3.9*), that connects the remote station with constant voltage buses. The circuit diagrams of the system before and after disconnection is shown in *Figure 3.10.* The reactance of the system that is equal to $X_C = X_G + X_{T1} + 0.5X_L + X_{T2}$, represents the amplitude of the power characteristic under the condition shown in (3.2).

Leaving the effect of the electromagnetic processes of the generators aside, it can be stated that due to the disconnection of one of the two transmission lines (*Figure 3.10.b.*), the reactance of the system is: $X_{C1} = X_G + X_{T1} + X_L + X_{T2}$ – larger than the reactance under the normal conditions shown in *Figure 3.10.a*, since the reactance of the system is increasing by half due to the disconnection. The amplitude of the power characteristic when the line is disconnected is EU/X_{c1} respectively. The power characteristics under normal conditions and during the disconnection are shown in *Figure 3.11.* If the working conditions before disconnecting the transmission line were shown at point *a* of the normal working conditions with the transmitted power P_0 under the angle δ_0 (*Figure 3.11 – I*), then after the disconnection, then there should be a new power characteristic (*Figure 3.11 – II*), with b as a stable point under the same angle $\delta = \delta_0$ as under the normal working conditions.

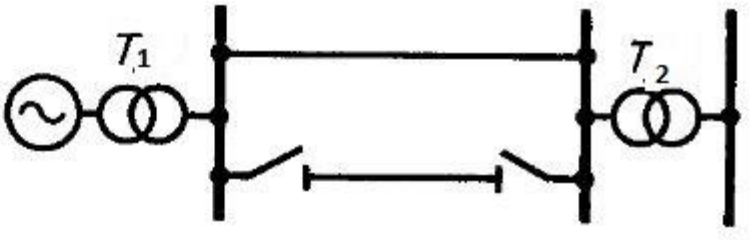


Figure 3.9

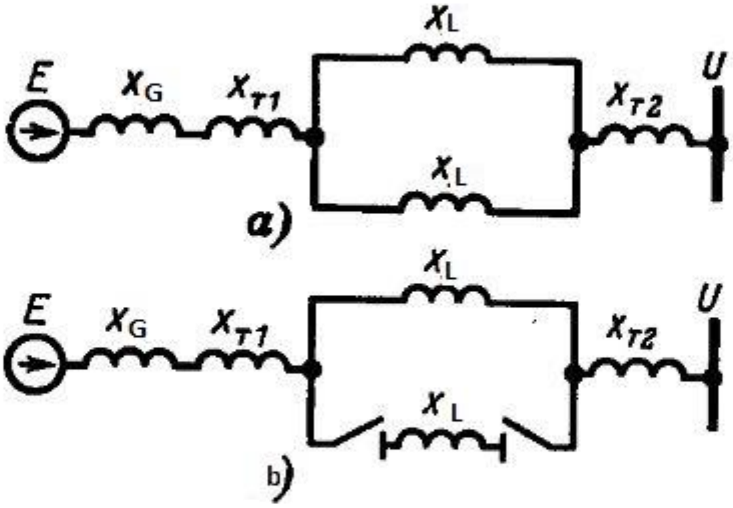


Figure 3.10

Angle δ keeps that magnitude at the moment of disconnection, since the e.m.f. vector $\hat{E}$ of the generator can be displaced relatively to the vector of the voltage of the receiving system $\hat{U}$ only due to the change of the rotation frequency of the generator's rotor. The rotor cannot withstand jumping changes due to its mechanical inertia.

This way, at the moment of disconnection of the circuit, the working condition changes and is not characterised by point a, but by point b on the new characteristic, which determines the sudden decrease of the generator's power. However, the power of the turbine stays the same (P_0), since the turbine regulators react to the change of the frequency of the generator.

Subsequently, the speed of the generator will be changing, though at this stage of the process as well, it can be considered that the regulators are not able to noticeable influence the power given by the turbine.

The power unbalance and of the moments of the turbine and the generator respectively, causes excessive moment under which the generator and turbine start to accelerate. The e.m.f. vector $\hat{E}$, which is related to the generator, starts to rotate faster than the rotating vector of the voltage of the receiving system $\hat{U}$ under the unchanging angular speed ω_0. The change of the speed v of the displacing vector $\hat{E}$ of the generator relative to the bus voltage of the receiving system $\hat{U}$, representing the differences in the angular speed between $\hat{E}$ and $\hat{U}$, is shown in *Figure 3.11*.

The origin of the relative rotating speed v leads to the increase of angle δ, and on the power characteristic graph of the generator at the moment of disconnection of the transmission line, the working point is moving from point *b* to point *c*. Hereby, the power of the generator is starts to increase. However, the all the way to point *c*, the power of the turbine still has a greater power than of the generator's, and the excessive moment, though decreasing, but is still keeping its sign, thanks to what the relative rotating speed is constantly increasing. At point *c* the powers of the turbine and of the generator, again, stabilise one another and the excessive moment is equal to zero. However, the process is not ending at this point, since the relative rotating speed of the rotor reaches the highest magnitude and the rotor passes point *c* due to its inertia.

Under the continuing increase of angle δ, the power of the generator is already exceeding the power of the turbine and the excess moment changes its sign, meaning that it start to slow it down. The relative rotating speed v is now decreasing and at point *d* is equal to zero. This means that, at point *d* the e.m.f. vector $\hat{E}$ is rotating with the same angular speed, as the voltage vector $\hat{U}$, and consequently, angle δ between them stops increasing. Angle δ at this point reaches its maximum magnitude δ_m. However, the process is still not ending, since the consequence of the unbalance of the powers gives an excess moment with a breaking characteristic, under which influence the rotating frequency keeps decreasing and the relative speed v becomes negative. Angle δ starts to become smaller, and the working point that characterises the process on the power characteristic is moving in the opposite direction, to point *c*. Again, the rotor is passing this point by inertia, and around point *b*, it starts to increase. After a number of gradually fading oscillations at point *c*, a new condition is set with the initial magnitude of the power P_0 and with a new magnitude of the angle δ_{stable}. The graphical representation of the oscillations of angle δ during time is shown in *Figure 3.12*. The gradual decrease of the amplitude explains the energy losses due to oscillations of the frequency of the rotation of the generator.

This type of change characteristic to a new working condition will not bring any complications. In any case, instability did not happen in the picture. It is only possible to state that in the transitioning electromechanical process, angle δ reached the magnitude of δ_m, which surpassed the value of δ_{stable} of the new working condition.

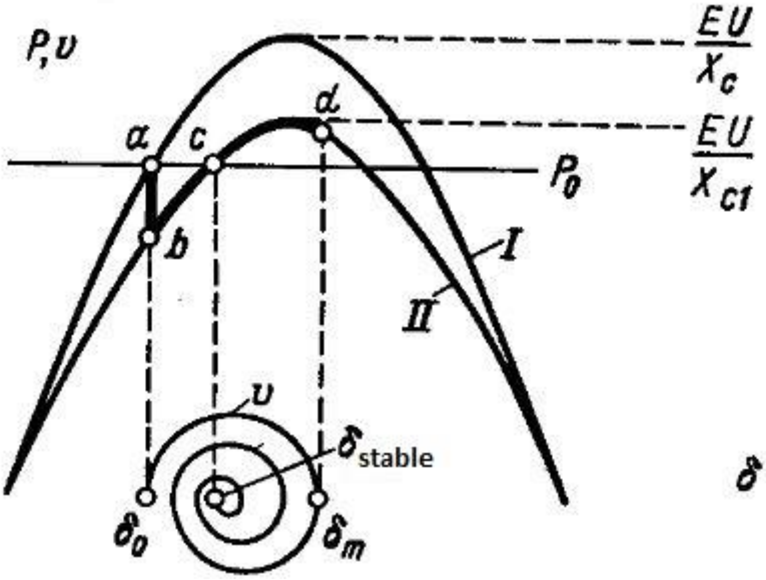


Figure 3.11 – power oscillations and of the relative angular speed of the generator during disconnection. I – power characteristic during normal working conditions; II – power characteristic during disconnection of the circuit.

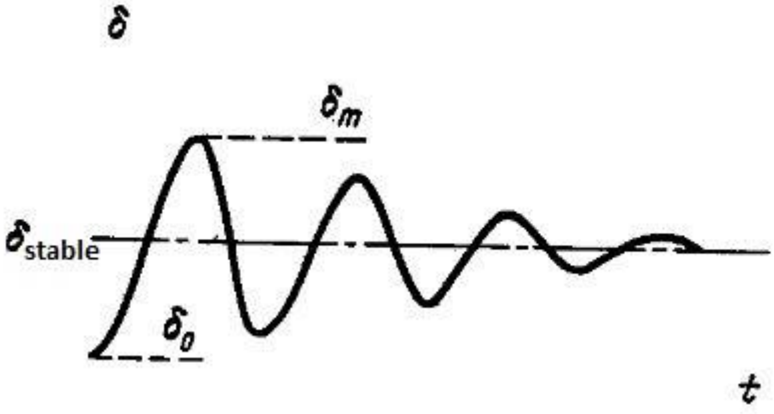


Figure 3.12 – angle oscillations due to diconnection of one of the parallel lines

There is a possibility of a different outcome, represented in *Figure 3.13*. The breaking of the rotor, starting from point *c*, decreases the relative rotation speed *v*. However, the angle at this stage of the process is still increasing, and if it manages to reach the critical value δ_{crit} at point *c* at the intersection with the decreasing part of the sinusoidal of the generator's power with the horizontal of the power of the turbine P_0 before the relative speed *v* falls to zero, the next excessive moment will be, again, an accelerating one. The speed *v* will start to increase quickly and the generator will lose its synchronism (*Figure 3.14*).

This way, if during the oscillation process point *c'* will be passed, then the returning back to a stable condition would be impossible.

It can be stated that despite the theoretical possibility of a new set condition, which is also statically stable, at point *c*, the process of the generator's oscillations due to the transition to this working condition can lead to the loss of synchronism. This type of behaviour of the disturbance can be considered as dynamic.

It can be concluded that the main reasons for dynamic stability disturbances are usually short circuits, and/or sudden decrease of the amplitude of the power characteristic.

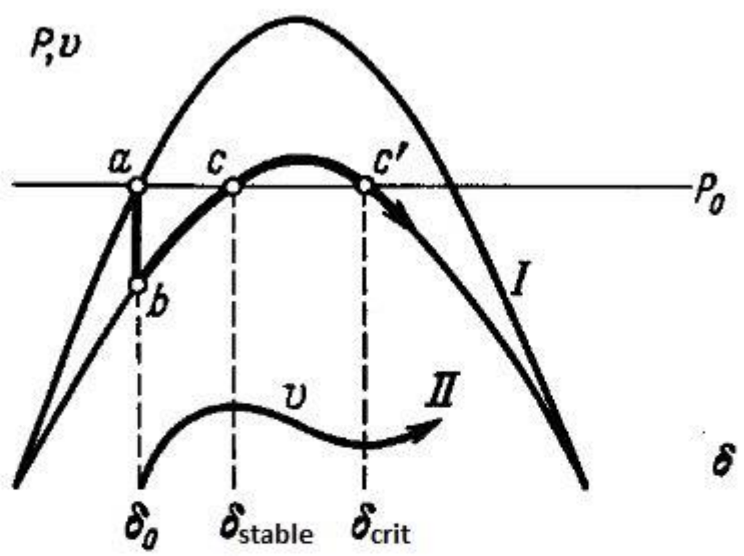


Figure 3.13

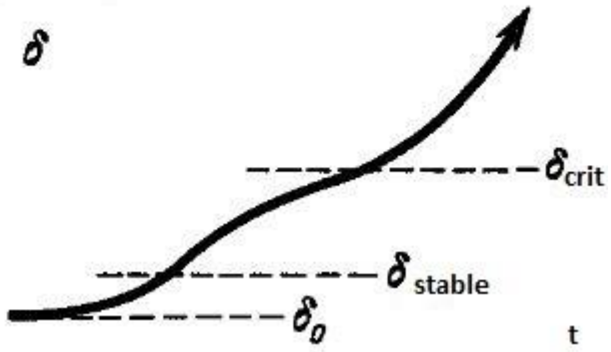


Figure 3.14

3.2. Active Power and Frequency Control

In the European power system (ENTSO-E), load frequency control is described as "the continuous balance between supply and demand that must be maintained for reliability and economic operational reasons[1]" in the "UCTE Operation Handbook". The general aim of the Operational Handbook is to make sure that all the transmission system operators (TSOs) of the synchronous areas are interoperable. The system frequency derives the quality of the overall balance of the system, which should not have a high deviation from the set nominal frequency of 50 Hz. Generally speaking, load frequency control has five different types of control, which depend on one another:

- Primary control – starts within seconds
- Secondary control – replaces primary control after some minutes
- Tertiary control – restores secondary control reserve by rescheduling generation
- Time control – corrects the total time deviations of the synchronous time in the long term
- Measures for emergency conditions

Aforementioned above, generation is connected to frequency. Active power is related to frequency, where reactive power is related to voltage. It is necessary to first discuss the relation between active power and frequency.

3.2.1. Primary Control

As it was mentioned before, in order to have a stable operation of a power system, it is necessary to keep the frequency as nearly constant as possible. In order to ensure synchronous motors and induction speeds constancy, relatively close frequency control is required. As aforementioned, the frequency of a power system is dependent on the power balance. As there is a change in demand power grows, it will act on the frequency as well, meaning that if more power is needed, the frequency will increase accordingly. The speed governor of a generator provides the primary speed control.

In an interconnected system, where are more than two independently controlled areas, in order to keep the schedule of the power interchange, generation is controlled beside the frequency being controlled. The control of both generation and frequency is called *load-frequency control*.

3.2.1.1. Speed Governing

A generator that is supplying an isolated load is shown in *Figure (3.15).* The diagram illustrates the basic concept of speed governing.

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[1] [4]

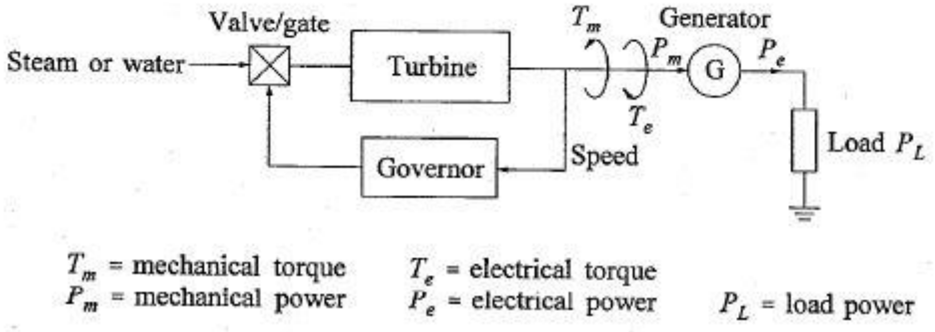

Figure 3.15

Load change is instantaneously reflected a change in electrical torque of the generator T_e. Consequently, there is a mismatch between the mechanical (T_m) and the electrical one, which causes variations in speed.

The relation between power and torque can be given by (3.5) below, where P is power, ω_r – rotor's speed and T is torque.

$$P = \omega_r T$$

(3.5)

Let some deviations of the initial values be considered:

$$P = P_0 + \Delta P$$
$$T = T_0 + \Delta T$$
$$\omega_r = \omega_0 + \Delta\omega_r$$

(3.6)

If the (3.5) and (3.6) are combined the power-torque relation will be

$$P_0 + \Delta P = (\omega_0 + \Delta\omega_r)(T_0 + \Delta T)$$

By neglecting the high order factors after expanding the brackets of the expression above, the power-torque relationship will be given by (3.7).

$$\Delta P = \omega_0 \Delta T + T_0 \Delta\omega_r$$

(3.7)

Therefore, if the power-torque relation is used to describe how the generator behaves when there is a change of load, then (3.8) will give the relation below, where P_m and P_e are mechanical and electrical power respectively.

$$\Delta P_m - \Delta P_e = \omega_0(\Delta T_m - \Delta T_e) + (T_{m0} - T_{e0})\Delta\omega_r$$

(3.8)

3.2.1.2.Governors with Speed-droop Characteristic

Governors with constant speed (also known as isochronous governors) adjust the turbine valve/gate to bring the frequency back to the nominal value.[2] A schematic diagram of an isochronous governor is shown in *Figure 3.16*. The measured speed of the rotor ω_r is compared to the reference speed ω_0. The speed deviation, which is equivalent to the error signal, is amplified and integrated to produce the control signal ΔY, which activates the main steam supply (in case of steam turbines), or gates in the case of a hydraulic turbine. A new steady state will be reached only when the rotors speed will be equal to zero.

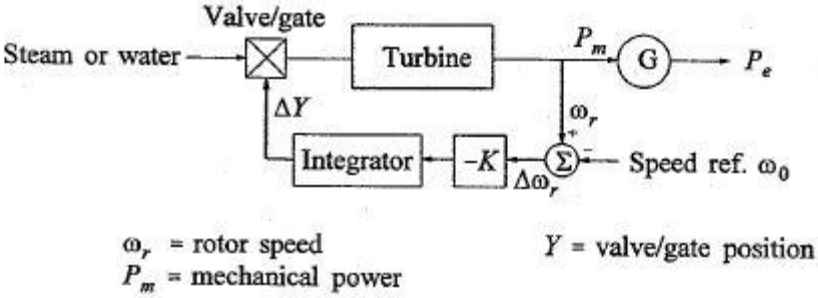

Figure 3.16

Even though isochronous governors are used for adjusting, they cannot be used in a system with two or more generators, because, in that case, each of the generators should have a precisely set speed setting. The reason behind that is each generator is trying to control the system frequency according to their own speed setting. So in order to keep the division of the load stable between generators that are operating in parallel the governors are given the characteristic of reducing the speed when there is a load increase in the system.

Speed-droop *R* may be obtained by adding a steady state feedback loop to the integrator of the isochronous governor (*Figure 3.16*) as shown in *Figure 3.17*.

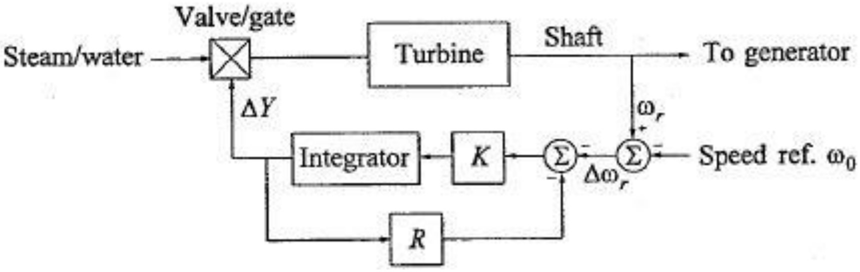

Figure 3.17

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[2] [1]

The droop determines the steady state speed against the load characteristic of the generator, which is the ratio of the speed or frequency deviation and the power output (3.9). *Figure 3.18* depicts the ideal steady state characteristics of a governor with speed droop.

$$R = \frac{\Delta f}{\Delta P}$$

(3.9)

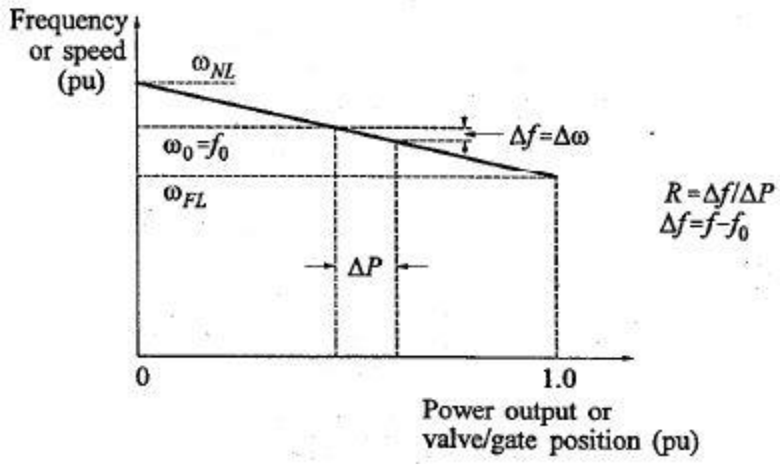

Figure 3.18

When two or more generators that have drooping characteristics are connected to the same power system, they have to operate at the same frequency at which they share the same change in load. *Figure 3.19* depicts an example of two generators with drooping characteristics. Both of them start with the nominal frequency f_0, and have P_1 and P_2 respectively as their output. In the case of power change ΔP_L, for example an increase that causes the generators to slow down, their governors would increase their output until both generators reach a new common frequency f'. The amount of power they generated depends on the drooping characteristic:

$$\Delta P_1 = P'_1 - P_1 = \frac{\Delta f}{R_1}$$

$$\Delta P_2 = P'_2 - P_2 = \frac{\Delta f}{R_2}$$

The equations above can be combined into the next relation:

$$\frac{\Delta P_1}{\Delta P_2} = \frac{R_2}{R_1}$$

If the droop of the generators are almost equal, the change in output of each generator will be nearly proportional.

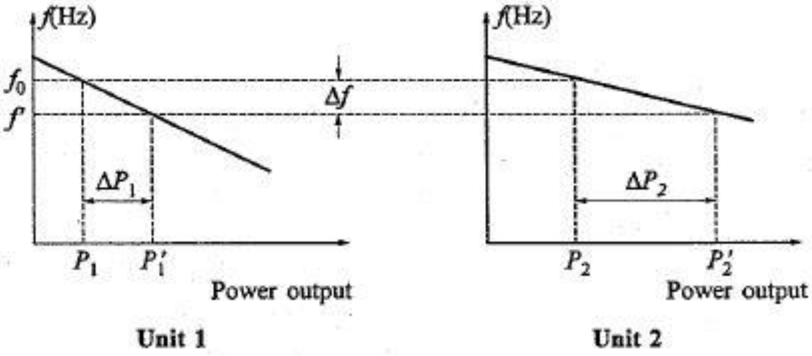

Figure 3.19

Since all the generators are synchronised and operate at the same frequency in steady state when the overall change of the total generated power of the system *ΔP_T* can be calculated as the sum of all the power changes of all generators ((3.10), where *N* is the number of generators).

$$\Delta P_T = \sum_{i=1}^{N} \Delta P_{m_i}$$

(3.10)

Figure 3.20 is a graphical representation of (3.10), and shows how individual characteristics of generators can be added in order to get the general characteristic of the system.

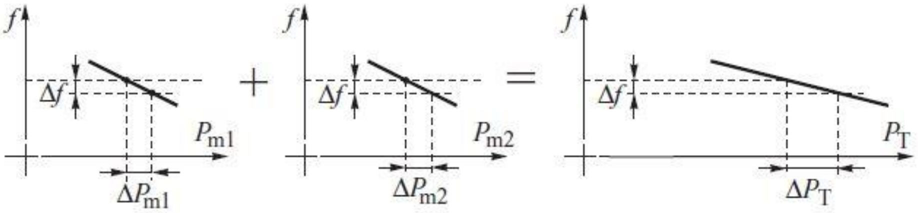

Figure 3.20

The generation characteristic of a system depends on the number of generators it has that operate above or below their part load limit. So it will depend on the spinning reserve as well, which is the difference between the sum of the power ratings of all the generators and their actual load.[3] *Figure 3.21* (where (a) – the spinning reserve is placed proportionally to both generators, in order they both get the upper limit at the same frequency f_1; (b) – the spinning reserve is placed on the second generator, and the first generator operates at full load) depicts the influence of the upper power limit of the generator and the spinning reserve on the generation characteristics.

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[3] [2]

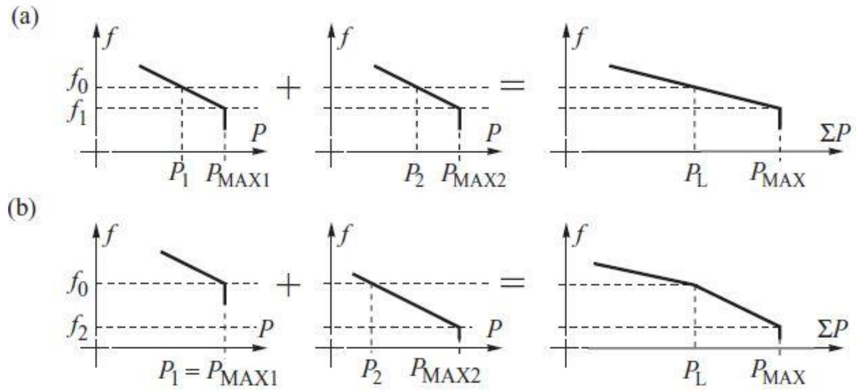
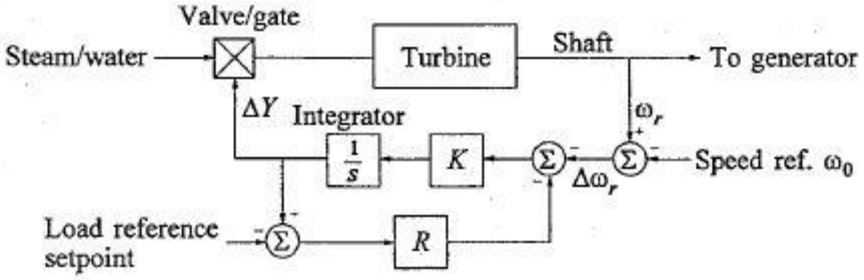


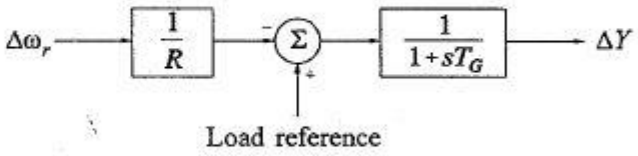
Figure 3.21

3.2.2. Secondary Control

The speed-load relationship can be regulated by changing the input ("load reference setpoint" *Figure 3.22*). The regulation of the load reference setpoint is done by operating the "speed-changer motor". *Figure 3.23* shows the effect of the regulation. There is a set of load reference setting characteristics for different speed settings in a 60 Hz system. At 60 Hz, characteristic A has zero output, characteristic B – 50% output, and respectively C has 100% output. The output of the generator at a certain speed can be adjusted to any value by regulating the load with the speed-changer motor. For every characteristic, there is a 5% droop that causes a 100% change in output.



(a) Schematic diagram of governor and turbine



(b) Reduced block diagram of governor

Figure 3.22

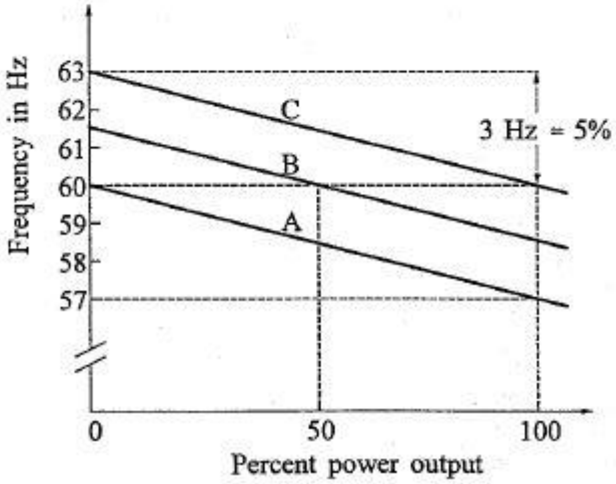


Figure 3.23

When a sudden change in load of the system occurs in a system where two or more generators operate in parallel, the droop characteristic of each generator creates the load proportion of the load. The speed-droop characteristic is moved depending on the change of the load reference.

3.2.2.1. Automatic Generation Control (AGC)

Depending on the droop characteristic of the governor and the frequency sensitivity of the load, any change of the system load will lead to steady-state frequency deviation. All the generators on speed governing in the system will have a role in contribution to the total change in generation. Through the speed-changer motor, the restoration of the system frequency back to the nominal value requires additional control action. It is necessary to change the power output of the generators when the system load is changing.

The main point of AGC is to maintain the frequency at scheduled values, the total power interchanges with neighbouring control areas at scheduled values, maintain power allocation between the generators according to the area needs. Another objective of AGC is the distribution of the required changes in generation in order to minimise the costs.

3.2.2.1.1. AGC in an interconnected System

Let there be an interconnected system that is depicted in *Figure 3.24(a)*. The system has two areas that are connected through a tie line with its reactance being X_{tie}. *Figure 3.24(b)* shows the equivalent circuit of that two-area system. The power flow between the two areas is

$$P_{12} = \frac{E_1 E_2}{X_T}\sin(\delta_1 - \delta_2)$$

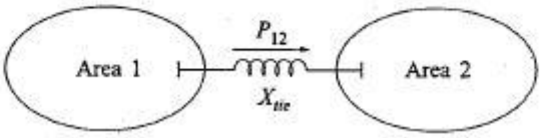
If linearizing the system at an initial working point by $\delta_1=\delta_{10}$ and $\delta_2=\delta_{20}$ there will be the next relation:

$\Delta P_{12} = T\Delta\delta_{12}$, where $\Delta\delta_{12} = \delta_1 - \delta_2$ and T is the synchronising torque coefficient.

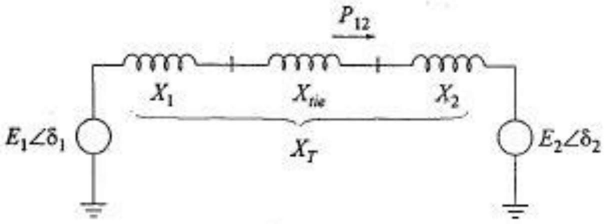
T is given by:

$$T = \frac{E_1 E_2}{X_T}\cos(\delta_{10} - \delta_{20})$$

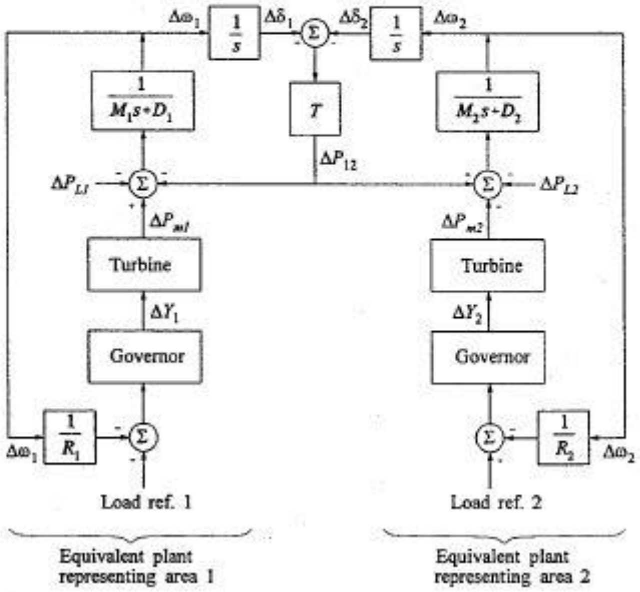
(3.11)



(a) Two-area system



(b) Electrical equivalent



(c) Block diagram

Figure 3.24

The block representation of the system, shown in *Figure 3.24(c)*, has each area represented by an equal inertia *M*, load constant *D*, and the speed droop of the turbines and generators *R*. The tie line is represented by *T*. If ΔP_{12} is positive, then there is a power flow increase from area 1 to area 2, which means that area 1 is increasing its load when are 2 is decreasing, therefore the feedback would be negative for area 1 and positive for area 2.

Let the frequency in steady state be the same in both areas, so for a total load change of ΔP_L,

$$\Delta f = \Delta\omega_1 = \Delta\omega_1 = \frac{-\Delta P_L}{\left(\frac{1}{R_1} + \frac{1}{R_2}\right) + (D_1 + D_2)}$$

(3.12)

If there is an increase in area 1 by ΔP_{L1} there will be

$$\Delta P_{m1} - \Delta P_{12} - \Delta P_{L1} = \Delta f D_1$$

(3.13)

And for area 2

$$\Delta P_{m2} + \Delta P_{12} = \Delta f D_2$$

(3.14)

The change in mechanical power depends on the regulation:

$$\Delta P_{m1} = -\frac{\Delta f}{R_1}$$

(3.15)

$$\Delta P_{m2} = -\frac{\Delta f}{R_2}$$

(3.16)

If substituting (3.15) in (3.13) and (3.16) in (3.14) we get

$$\Delta f\left(\frac{1}{R_1} + D_1\right) = -\Delta P_{12} - \Delta P_{L1}$$

(3.17)

$$\Delta f\left(\frac{1}{R_2} + D_2\right) = \Delta P_{12}$$

(3.18)

If (3.17) and (3.18) are solved, we get

$$\Delta f = \frac{-\Delta P_{L1}}{\left(\frac{1}{R_1} + D_1\right) + (\frac{1}{R_2} + D_2)} = \frac{-\Delta P_{L1}}{\beta_1 + \beta_2}$$

(3.19)

$$\Delta P_{12} = \frac{-\Delta P_{L1}(\frac{1}{R_2} + D_2)}{\left(\frac{1}{R_1} + D_1\right) + (\frac{1}{R_2} + D_2)} = \frac{-\Delta P_{L1}\beta_2}{\beta_1 + \beta_2}$$

(3.20)

Where β_1 and β_2 are the composite frequency response characteristics of areas 1 and 2, these relations are shown in *figure 3.25*

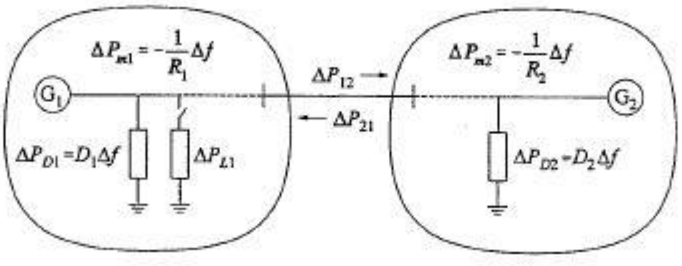


Figure 3.25

The same applies for the opposite direction of the power flow, from area 2 to area 1. If ΔP_{12} is negative, then it shows that there is a flow from area 2 to area 1, so when there is a change in area 2 by ΔP_{L2} we get

$$\Delta f = \frac{-\Delta P_{L2}}{\beta_1 + \beta_2}$$

(3.21)

$$\Delta P_{12} = -\Delta P_{21} = \frac{\Delta P_{L2}\beta_2}{\beta_1 + \beta_2}$$

(3.22)

All the relations above from the basis of LFC of interconnected systems.

3.2.2.1.2. Area Control Error (ACE)

The main point of secondary control is to restore balance between the load and generation of two or more areas of a system, and it can only be achieved when the control maintains the frequency at the scheduled value and the net interchange power with neighbouring areas at scheduled values.

For example, if there is a change in the load of area 1, there should be a secondary control only in that area and not in the other ones.

Equations (3.19) to (3.22) show that the control signal should made up of tie line flow deviation added to the frequency deviation that have an additional bias factor would reach the desired objective. The control signal is the so-called area control error (ACE). From (3.17) and (3.18), it can be deduced that the suitable bias could be β, the frequency-response characteristic. So the ACE for areas 1 and 2 would be:

$$ACE_1 = \Delta P_{12} + B_1 \Delta f$$

(3.23)

where

$$B_1 = \beta_1 = \frac{1}{R_1} + D_1$$

(3.24)

and for area 2:

$$ACE_2 = \Delta P_{21} + B_2 \Delta f$$

(3.25)

and

$$B_2 = \beta_2 = \frac{1}{R_2} + D_2$$

(3.26)

The ACE represents the required change in the generation of an area in MW.

3.2.3. Tertiary Control

Tertiary control is an additional type of control to primary and secondary frequency control, which is slower than both of them are. The objective of the tertiary control depends on the organisational structure of a power system and the role of each power station or area in this power system.

The TSO sets the working point of each station that are based on their optimal power flow (OPF). The OPF minimises the overall cost of generation. Therefore, the tertiary control sets the power values of individual generators to the calculated values by the optimal dispatch in a way that the overall demand is in accordance with the power interchange schedule.

The required values schedule of power interchange $P_{tie\ ref}$ is sent to the central regulator depending on the schedule of the entire interconnection of the system. Changes in $P_{tie\ ref}$ values are done as it is shown in *Figure 3.26*. These changes are made for the prevention of power swings between control areas.

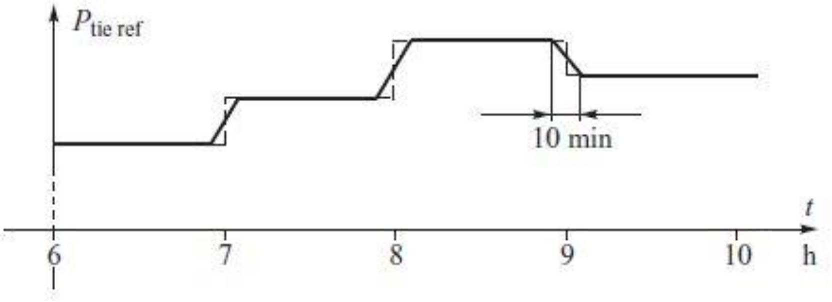


Figure 3.26

Since nowadays a lot of power plants are privatised, they are not directly controlled by the TSO, thus, the economic dispatch is done through the energy market. Based on the market structure, power station put their prices to a centralised pool or have bilateral contracts with distribution companies. The main task of the TSO is to adjust the contracts/bids to ensure that the networks standards and limitations are kept, and to purchase the required amount of primary and secondary reserves from the stations. The aim of the tertiary control in this kind of market structure is to regulate whether manually or automatically the set points of each governor to make sure that there is adequate spinning reserve in the generators in primary control, optimal dispatch of the generators that are part of the secondary control and so that there is a restoration of the bandwidth of the secondary control in a given cycle.[4]

Tertiary control is more about supervising, compared to secondary control, which is more about correcting the loading of generators of a control area. Tertiary control is done through automatic change of the reference value of the generated power, and through automatic or manual connection or disconnection of generators that are on its reserve.

The reserve is made up of generators that can be manually connected or disconnected within 15 minutes of the made request. It should be used in a way that the bandwidth of the secondary control is brought back to its initial stage.

3.3. Voltage Control

Terminal voltages of synchronous machines, line impedances, transmitted reactive power and the ratio of turns of transformers influence the overall voltage of a power system. Generators are usually

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[4] [2]

operated at a constant voltage, through the use of the automatic voltage regulator (AVR). The voltage drop that is caused by the generators transformer, is partially or fully compensated, due to that, the voltage can be kept constant on the high voltage side of the transformer. Synchronous compensators are synchronous machines without mechanical load or turbine that can produce and consume reactive power by controlling the excitation, and are mainly used for voltage control.

The reactive power has a big impact on the voltage profile. Large reactive transmission cause large voltages to drop, meaning that the reactive power production must be as close as possible to the reactive loads, which can be achieved by exciting the generators. Since it is rare when synchronous machines are close to the reactive loads, it is more cost effective have shunt capacitors used, which are switched in accordance with the load. Shunt reactors are sometimes installed to limit the voltages to a certain desirable level. Since the reactive generation is greater than that of the overhead lines, in case of larger capacitances comparing to reactance, it is necessary to have those shunt reactors.

A significant method of voltage control is using the tap changer transformer, shown in *Figure 3.27*, which changes the ratio of turns of a transformer. Voltage control can be obtained by switching between the windings. Normally the taps of the transformers are placed on the high voltage winding of the transformer.

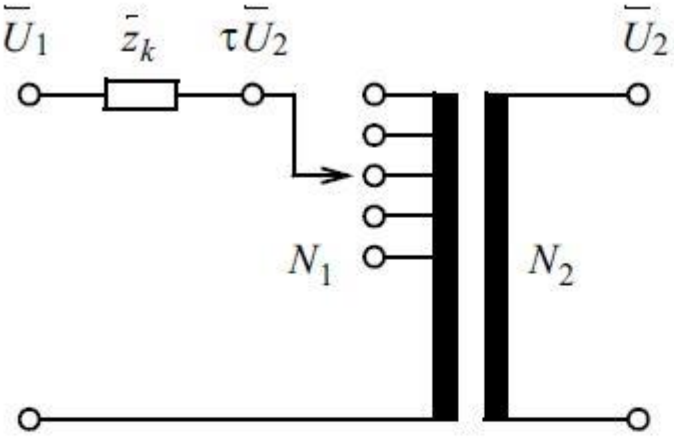

Figure 3.27

The turns ratio τ is defined as:

$$\tau = \frac{N_1}{N_2}$$

(3.27) – N_1 – upper number of turns; N_2 – lower number of turns

The relation between voltage on the upper side of the transformer U_1 and U_2 on the lower side, respectively at no load is given by:

$$U_2 = \frac{U_1}{\tau}$$

(3.28)

In case the voltage decreases on the high voltage side, the voltage on the lower side can be kept constant by reducing τ, for example by switching off a number of windings on the high voltage side.

The transformer that have automatic tap changer control are often used in distribution networks so that the voltage on the consumers' side can be kept nearly constant even if the voltage varies at high voltages. The time constants for these regulators are usually in the range of 10 seconds.

In case the taps cannot be changed automatically, it is done manually when the transformer is disconnected, so it can only change the voltage level but not control the voltage variations in the grid.

4. Blackouts

As it was mentioned earlier, the TSOs have to make sure that the grid is secure, reliable and that it distributes the demanded power to the consumer. Of course, many disturbances occur and some of them can lead to blackouts.

A blackout is characterised by its duration, depth, scale and its geographical position. The depth is related to the number of consumers that are not supplied and to the load that is lost during the occurrence. The importance of blackouts is defined by the geographical scale and the depth. The duration of the blackout shows directly how severe is the incident and its consequences, especially in economic terms, and it shows how difficult it would be to recover the power system back to its operational state.

Blackouts usually are a result of a succession of sequential events. They can be linked to an initial event that started the chain reaction, that results in outages of power system equipment. As a consequence, regions or entire countries can be blacked out for a certain period of time. The next factors can be related to blackouts:

- Natural factors – storms, earthquakes, lightning, contact between trees and lines etc.
- Technical factors – short circuits, equipment failure, overloading, poor maintenance of equipment etc.
- Human factors – switching mistakes, poor or inadequate communication between operators, lack of professional training including for emergency situations etc.

Combinations of some of these factors can lead to a domino effect which will lead to a catastrophic situation as a consequence. TSOs operate the system according to the situation, as it is shown in *figure 4.1*.

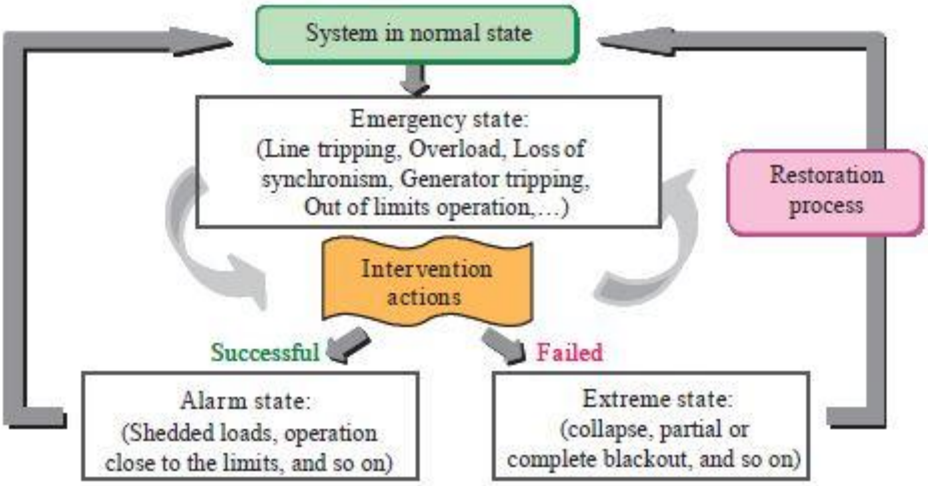

Figure 4.1

The power system operates under two main types of constraints: distributing electric power to customers constraint and the operating constraints, meaning that the customers must be supplied and that all the operating variables must be within the authorised thresholds.

The system is in normal state when the all the constraints are satisfied.

The system is in an emergency state when one or more of the constraints are violated. In case the intervention actions are able to restore the system back to its operational state, or if the constraints are not fully satisfied, then the system goes to the alarm state.

The system is in an extreme state when both constraint types are violated.

When unexpected perturbation occur, the system relies on emergency mechanisms, such as load shedding, defence plans on a large scale, safety relays etc., to keep the system safe.

Small-scale blackouts happen quite often, whereas large-scale ones are rare. When there is large-scale blackout, they cause large economic and social damages.

4.1. Islanding [4]

One of the methods for power system restoration is islanding. Islanding refers to the condition in which a distributed generator continues to supply a region though the grid’s power is absent. It can be dangerous for the utility workers, who might not realise that the system is still powered, and it could prevent automatic reconnection of equipment. In that case, the generators must detect islanding and stop generating power (anti-islanding).

In the case of intentional islanding, the generator is disconnected from the grid, and makes the distribute generator to power the regional system. This is usually done as a backup system for consumers that normally sell their excess power to the power system.

The success of islanding manoeuvre is related to the balance between power generation and the local network load. Initial scenarios of the power flows for import and export must be taken in consideration, considering the structure and the characteristics of the system.

Islanding in the case of initial import scenarios requires a radical load reduction of the local network, and in the case of the initial export scenario, it is necessary to have a proper energy control strategy to keep a stable and secure operating conditions of the system.

5. Wide Area Monitoring Systems [6]

Wide area monitoring system (WAMS) is a smart, automatic network that applies real-time measurements in automatic control systems in order to operate a reliable, efficient and secure electric transmission. WAMS continuously monitors power systems' performance. It provides operators with data of high quality and analysis tools in order to detect grid emergencies and to mitigate outages. Phasor measurement units (PMU) are used collect data. WAMS monitor the system's parameters in real time, eases the calculations for margin prices in real time in order to support market designs and assist in providing customers good price transparency.

WAMS are more and more used by TSOs nowadays as it helps investigate occurring problems, find the source of the problems and detect future possible disturbances. As a case study, I will use the case of the Czech power system, with additional three monitoring points outside the Czech Republic (in Switzerland, Denmark and Slovenia) that was analysed during my experience in my internship and trainee program at a WAMS department of a company, which I will not specify due to confidential reasons.

The data used for the analysis are from between July 2014 and June 2015. The oscillations that have been happening during that period will be briefly discussed.

5.1. Oscillations

A selection of low frequency (0.04 – 4 Hz) modes of oscillation commonly observed in the CEPS systems is described. The modes are observable in frequency, voltage phase angle difference and active power signals. Modes of particular concern in relation to system stability are reviewed in detail. The timeline of detected oscillatory events between July 2014 and June 2015 (the largest arrows represent the most sever event for each mode, where each mode is shown by a different colour, shown in the legend) is shown in *Figure 5.1*.

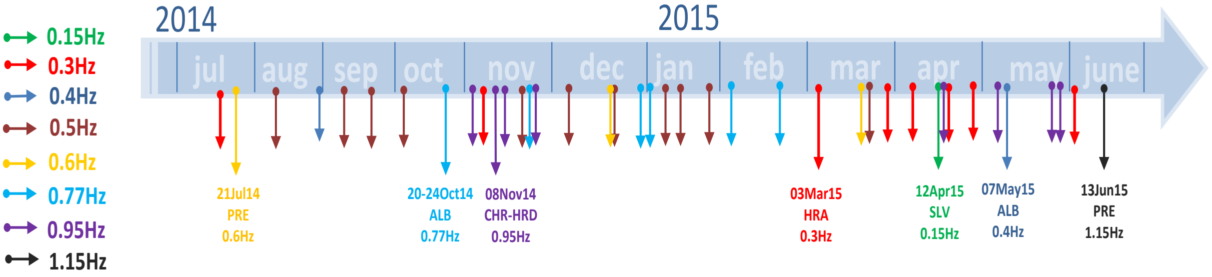

Figure 5.1

While events with large amplitude and/or poor damping were observed, none of the observed modes showed negatively damped behaviour. Even though, it is still important that they are identified and characterised, especially if they are related to frequent and/or regular generator dispatch profiles.

Oscillation measurement and identification of key plants is important for risk reduction. This information can help providing early operational warning in case these modes become poorly damped due to planned or unplanned system events, along the real-time monitoring. It also provides information to operators that will make them take action where it is necessary.

5.1.1. 0.15 Hz Mode

At 0.15 Hz a low frequency mode was seen in the system mainly observed in active power and angle difference. The mode is generally well damped with an average decay of 5-6 seconds (17% damping ratio), and with an average amplitude of approximately 5-6 MW at the location showing the largest amplitude.

One event has been reported over the reviewed period on the 12th April 2015, showing peak-to-peak amplitude of up to 30MW (*Figure 5.2*). During the event, the oscillations are also observed in the system frequency across Denmark, Switzerland and Czech Republic. The mode is likely to be an interarea mode across the entire interconnected system between east and west Europe, with good observability of the mode in active power between the two areas (through the CEPS system). It also shows the largest power swings on the interconnectors which suggests that it is at the sources that are outisde the CEPS network.

The potential implications of the 0.15Hz mode are:

- Potential for growing oscillations throughout the grid if the system mode becomes more lightly damped
- Large mechanical and electrical stresses on the system, especially as the 0.15Hz mode is seen interconnection-wide
- Wide-area phenomenon that can limit power flows across interconnections
- Power swings can cause line protection equipment operation and weaken the system. Increases chances of voltage and transient stability issues.

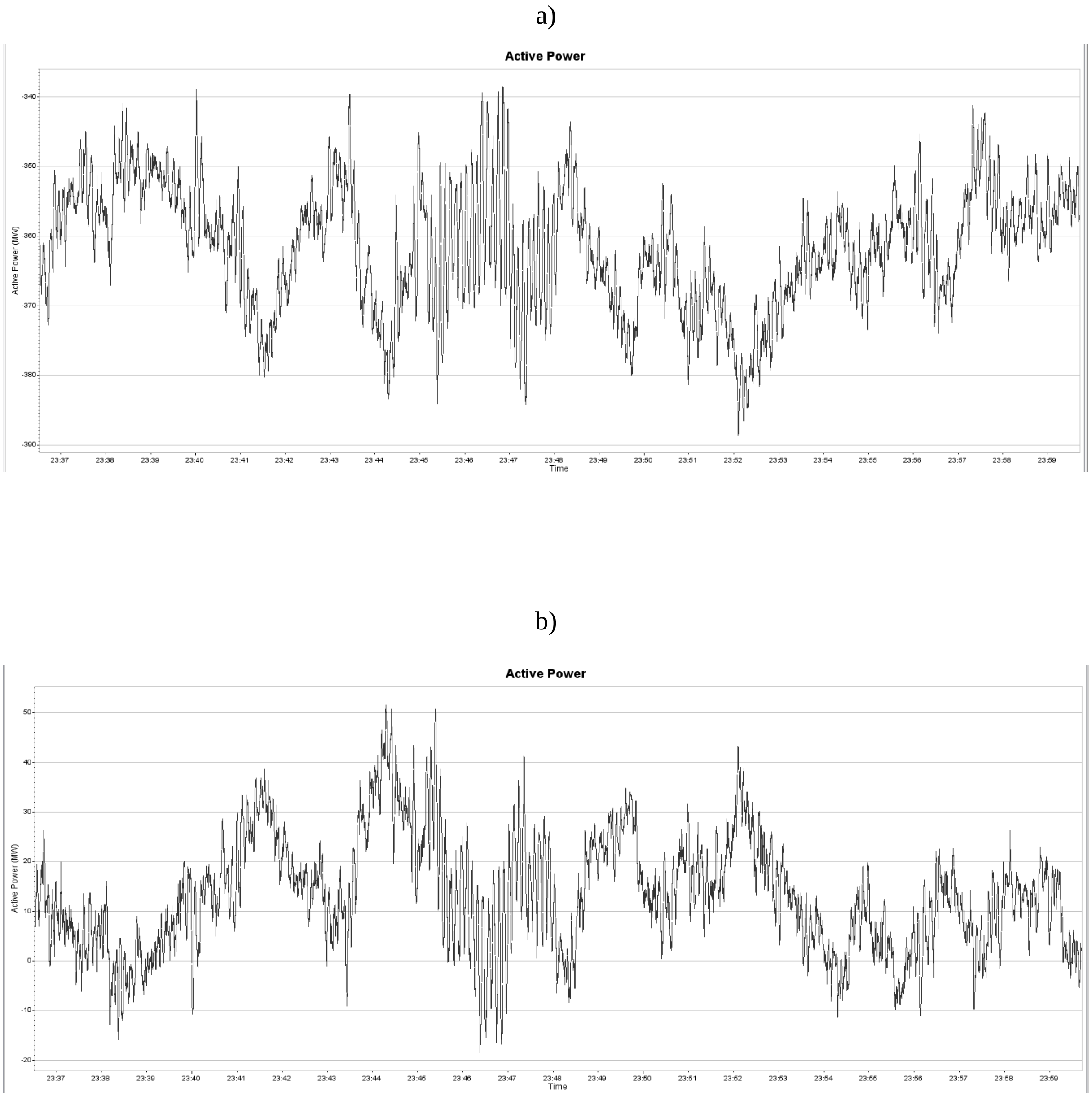

Figure 5.2 – a) SOK4-v497i, b) HRD – v455i

5.1.2. 0.25 Hz – 0.31 Hz

A mode around 0.25Hz-0.3Hz is observed in frequency, active power and angle difference throughout the system. The mode is generally well damped with an average decay time of around 4 seconds (14% damping ratio) and with an average amplitude of around 3MW/1.4 mHz at location reporting largest amplitude.

Eight poorly damped events with large amplitude oscillations have been detected over the analysed period. The largest event was observed at HRA4 V411i (Active Power) circuit on the 3rd and 30th March 2015, with a peak-to-peak amplitude that was up to 35 MW/10mHz, as it is shown in *Figure 5.3*. During the event, the oscillations are largest at HRA V411 active power and HRAV411 frequency (*Figure 5.4 – note that the HRA frequency leads the rest of the system phasor frequencies*), which tend to indicate that the plant located close to HRA (PRU or TUS) is contributing to the oscillation.

The potential implications of the 0.31Hz mode are similar to those discussed above. However, since there seems to be a negative contribution coming from within the CEPS network, the proximity to instability may be less than in the case where the CEPS generator simply responds to the source elsewhere in Europe. The plants that negatively contribute to the oscillation may also experience higher stresses given that they may oscillate at higher amplitudes then the other generators participating in the mode.

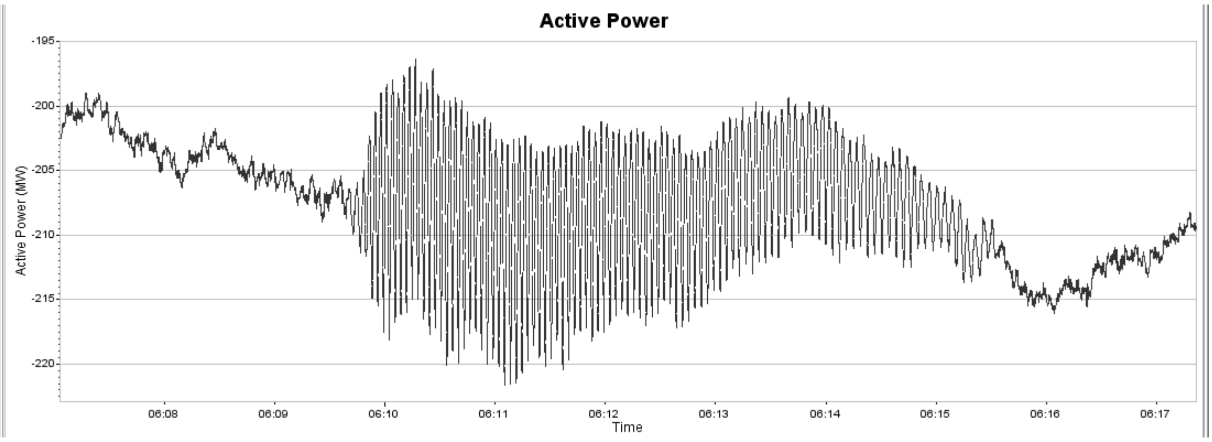

Figure 5.3

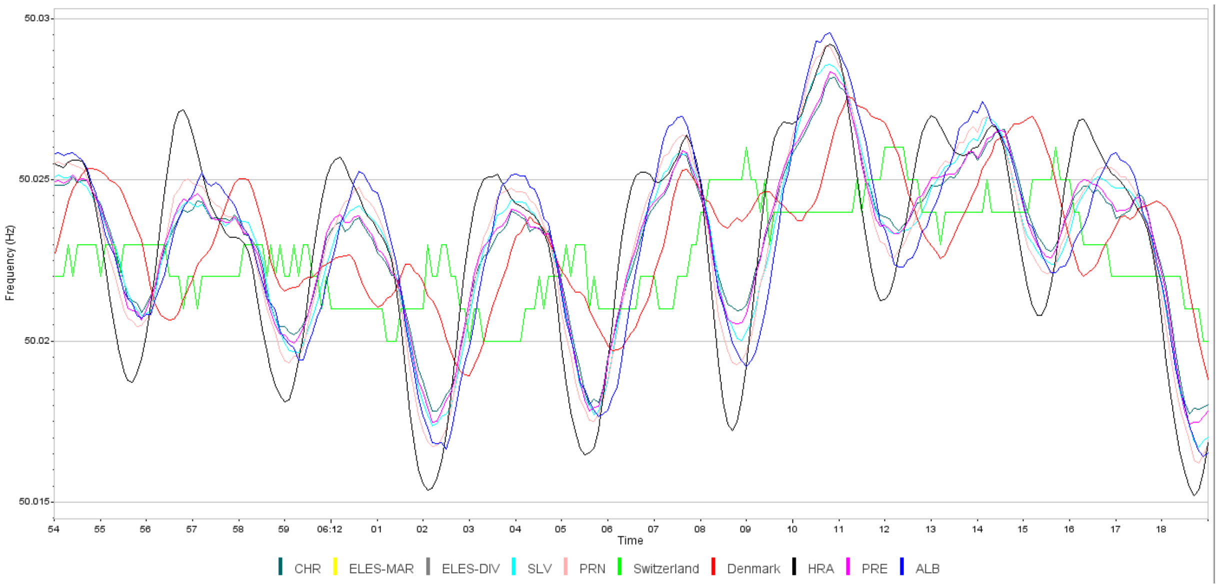

Figure 5.4

The ~0.25Hz mode involves Western Europe (Portugal, Spain) and Eastern Europe (Poland, Slovakia, Czech Republic) oscillating against Central Europe (France, Belgium, Switzerland, Italy). From the measurements it is likely that Czech generators close to HRA4 participate in the ~0.25 Hz mode.

5.1.3. 0.38 Hz – 0.49 Hz

A mode around 0.4 Hz – 0.4 Hz is observed mainly in active power at the NOS 444i circuit, and in the system frequency at ALB 443 bus. The mode is generally well damped with an average decay time of around 3 seconds (12% damping ratio) and an average amplitude around 2.5MW/0.7mHz at the locations reporting the largest amplitude.

Two main poorly damped events of large amplitude oscillations have been detected over the analysed period. On the 30th August 2014, the amplitude was reported with the largest period in the KOC system frequency. The largest power oscillations are also seen at KOC4 V432i. The magnitude of the power oscillation reached 60 MW peak to peak as shown in *Figure 5.5*.

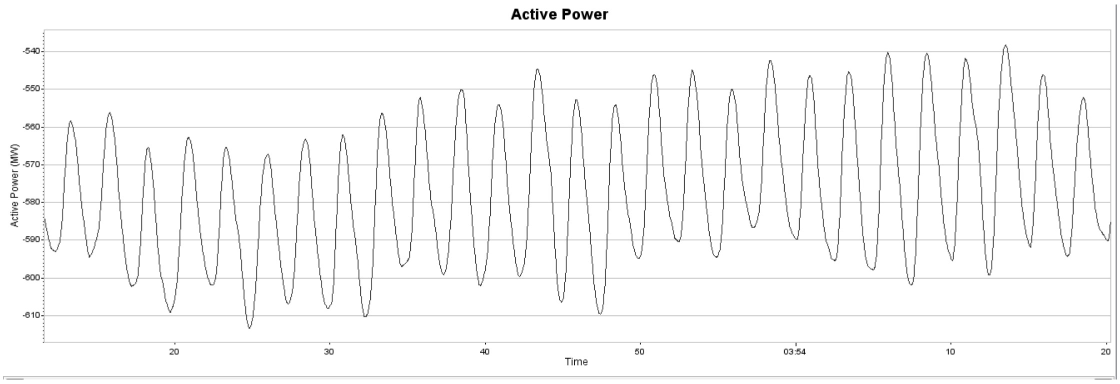

Figure 5.5

Figure 5.6 shows the active power for the mode event on the 7th May. *Figure 5.7* shows the mode shape for the event. In both cases ALB has the most leading phase indicating that it's the closest PMU to the source. In addition, the largest power swings that were seen on the line ALB 443i, which is connected to Poland. Since ALB is located close to the Polish border it is likely that the source is outside the CEPS system. However, the event on the 30th August demonstrates that the mode is a threat to the system stability when the KOC region is leading the phase.

The potential implications of the 0.38Hz mode are:

- Major stresses on generator rotors that are participating in the event
- Constraints on internal and international flows due to high amplitude oscillations
- Risk of protection operating (overcurrent, distance) and loss of synchronism or loss of major generation
- Reduced frequency reserve response of generators oscillating at high amplitude

The size and duration of the oscillations during the 30th August are a concern due to the fact that the source seems to lie within the CEPS system.

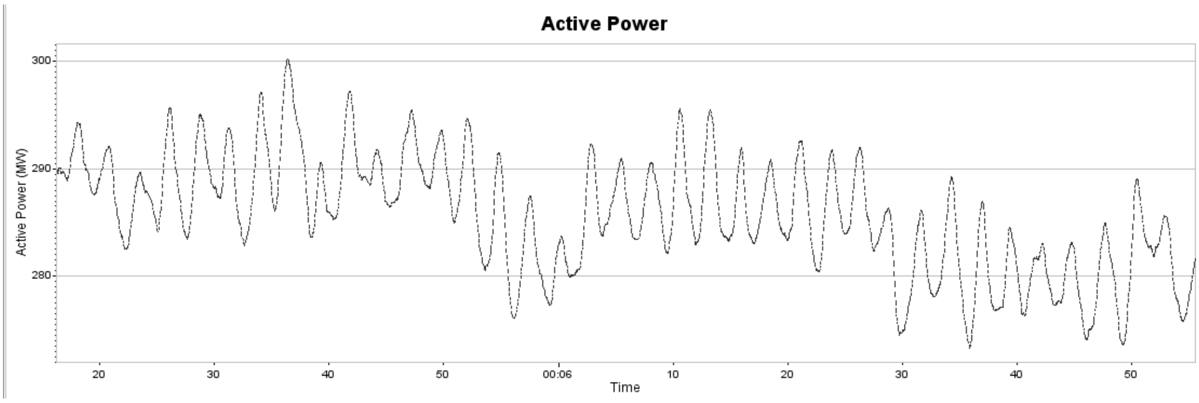

Figure 5.6

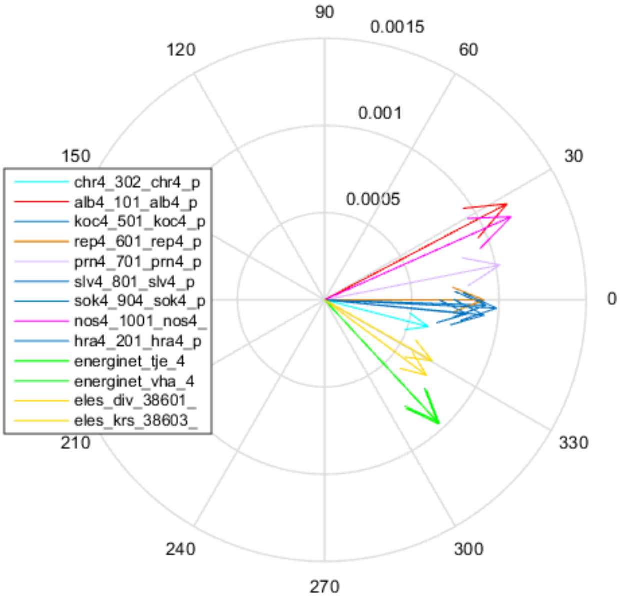

Figure 5.7

Both events discussed above show that there is likely a characteristic mode in the interconnection at around ~0.31Hz. This mode is likely a North-South mode which involves the North (Denmark, Belgium) oscillating against the South (Italy, Hungary). However, this mode may be excited in different ways and the source may lie within CEPS, i.e. near KOC, or inside the Polish system. It is important that CEPS are able to identify the source, meaning that restoring action can be taken.

5.1.4. 0.7 – 0.77 Hz

A mode around 0.7Hz-0.77Hz is best observed in active power at CHR v430i and PRE v430i circuits. The mode is generally well damped with an average decay time of approximately 2 seconds (10% damping ratio) and an average amplitude of around 0.65 MW at locations reporting largest amplitude.

Six main poorly damped events of large amplitude oscillations have been detected over the analysed period. The largest event was observed at the ALB4 V443i P circuit on the 22nd October 2014, with the peak-to-peak amplitude seen up to 25 MW/10 mHz, as seen on *Figure 5.8*.

A sudden end of the poorly damped oscillation clearly coincides with a system state change just after 14:53 Local time. Identifying the action that changes the system state could be used for future action to prevent or reduce the oscillation.

The potential implication of the 0.38Hz mode is the reduced power flow due to oscillation constraints between Poland and Czech Republic.

The analysis on the flow direction and SCADA data can point to where the oscillation source is, for example Poland or Czech Republic.

Figure 5.8

5.2. Conclusion

The data analysis demonstrates the benefits of using WAMS for managing power system dynamics. Some relatively large amplitude oscillations have been observed and there are modes that are sometimes lightly damped and change in response to changing the system conditions. These may be related to changes in the CEPS system internal generator dispatch internal. In some cases the changes in mode amplitude/damping are related to changes outside the CEPS grid, which can be manifested in changes in interconnector power flows.

With appropriate applications, WAMS can provide a significant improvement in the security of the system against dynamics issues.

Specifically, it is suggested that the future work on oscillations should include:

- Further investigation of the causes of the 0.4Hz mode to determine what plant(s) contribute to the mode. This will require further study of the SCADA data and possible installation of PMU’s near the generators in question
- Investigation of the cause and impact of the 0.31Hz mode to determine of the source of oscillation is constant or if it moves around the network depending on system conditions
- Further study of the 0.77Hz mode to determine contribution from within CEPS network though the source is likely to be in Poland.

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