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# Greenfield Planning of modern Metropolises

D. Audring, M. Hable, E. Lerch, K. Schilling

*Siemens AG, E D SE PTI*
*P.O. 3220, 91050 Erlangen, Germany*
`dirk.audring@siemens.com`

***Abstract*— This paper describes the challenges and opportunities of greenfield planning of economic power systems. Planning criteria and methodology of network planning have to be adapted and optimised for greenfield development of a new metropolises. The approach to designing a high voltage network for an entire city from scratch is explained. Necessary network studies and investigations are described. Efficient network concepts, including voltage level selection, transmission and distribution network topologies are discussed. Dynamic aspects are explained, such as frequency and voltage stability. As the new cities sometimes start their development at island operation, the power system has to be capable to operate islanded as well as connected to a national grid.**

## I. INTRODUCTION

Worldwide new development zones or complete new cities are planned from scratch in order to establish new industrial settlement and living space for a growing population [1, 2].

Planning of big cities from inception offers ideal conditions, as no constrains exist, e.g. generator configurations, network topology, voltage levels, equipment size, reliability requirements as well as operational aspects. The basic concept for the long-term development has to be set. The supply stages of equipments and assembling works have to be coordinated with the development phases of the cities. Major construction works, including installation of power transmission routes and bulk supply points, have to be finished before the city comes to its daily life. The power supply during the development phases has to follow the basic supply concept of the long-term scenario in order to avoid misleading investments and enable long-term utilization of equipment. Since new modern cities are planned with high rise buildings satisfying comfortable working and living conditions, very high load densities and high installed capacity are expected.

## II. DESIGN BASE OF GREENFIELD PLANNING OF NETWORKS

### A. Methodology

The objective of network planning is achieving the coordinated development of a secure, reliable, efficient and economical system for the transmission and distribution of electrical energy. This is ensured by applying the general network planning procedure (Figure 1).

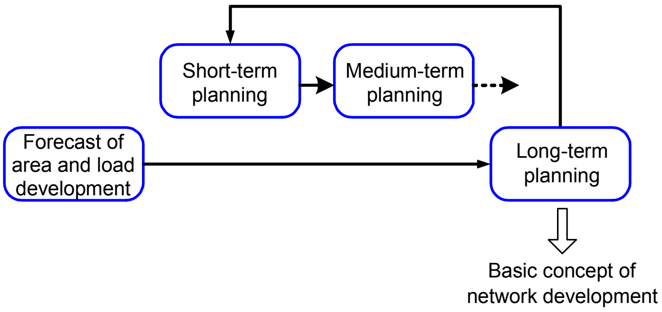

Figure 1: Network planning procedure

Proper scenarios of short-term and medium-term development of a new power system are influenced by the long-term concept. Therefore, the long-term concept is setting the course and gives the basis for sustainable investment decisions over the next years and decades.

The planning process involves a number of steps which are:

1. Develop forecasts for load and generation in steps
2. Define the planning criteria, see section II.B
3. Design the basic supply concept
4. Develop the economic future power system structure
5. Consider development options of network
6. Select preferred options
7. Determine optimum, economic development steps of power system

The methodology of developing a network concept starts with the construction of a long-term scenario about 20 years ahead. The basic supply concept of the city is designed according to the planning criteria of chapter II.B. The basic supply concept is applied to develop an optimised electrical power system for the long-term scenario and prior development steps.

The development steps have to be determined to install the network following both the increasing load demand and the building schedule of the infrastructure with respect to the network concept. Burying of cables and gas insulated lines (GIL) as well as erection of substations and bulk supply points (BSP) have to be finished before a certain development area comes to its daily life even if the load demand is only commencing to grow. The amount of transformers and additional switchgear bays may be installed when load

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demand and reliability requirements demand them. This offers flexibility according to the actual rate of growth of power demand.

The development steps of a commencing power supply may require different planning criteria, such as island operation and grid interconnection or adequate reliability. The design and rating of equipment as well as the compliance with the planning criteria have to be verified by detailed network studies.

### B. *Main planning Criteria*

- Voltage ranges:
  A voltage range of 95% to 105% of nominal voltage has to be achieved at normal operation. Power factor correction has to be designed to meet peak load and low load conditions. However, at contingency situation a voltage range of 90% to 110% of nominal voltage is acceptable.
- Thermal limits:
  Thermal capacity of equipment must not be exceeded under normal and contingency operation (according to reliability criteria) at planning process.
- Short-circuit current levels:
  Maximum short-circuit currents have to be lower than rating of equipment. This has to be proven by three-phase, two-phase-to-earth and single-phase-to-earth short-circuit calculation. Minimum short-circuit currents are calculated for protection coordination ensuring selectivity and tripping at a fault.
- Stability criteria:
  - Generator stability of single synchronous machine or a group of machines to the grid
  - Critical fault clearing time (referred to as the stability limit of a generator)
  - Network stability of different parts of the power system (interarea oscillations)
  - Voltage stability (incident which could lead to voltage collapse)
- Reliability criteria:
  A transmission network should always fulfil the (n-1) criteria, also during maintenance work. At important supply areas, like business districts of mayor cities, the (n-2) criteria are applied.
- Economical network structure:
  Network planning has to lead to a cost-effective power system considering both economic investments and efficient network operation. Misleading investments have to be avoided. Losses and other operational costs have to be minimized efficiently.
- Adequacy of the transmission and distribution level:
  The power system shall be capable to fulfil the requirements towards interconnection, power transfer, reserves, as well as the reliability criteria as stated above, on its own. This means that no transmission requirements should be assigned to lower level networks.

### C. *Challenges and Specific requirements*

The challenges of the power supply of a new metropolis are the high density of population and high load density due to high rise buildings in the city centres. Sophisticated skyscraper containing highest working and living comfort are planned at business and financial districts. Especially skyscrapers require a specific optimised power supply inside the buildings as well as redundant and reliable power infeed from the power system at medium voltage or even on high voltage level. Expected average load densities at the planned metropolis range from 30 to 60 MVA/km² at medium voltage network level. Comparing this with the average load density of about 3 to 15 MVA/km² of Berlin explains that these city developments need optimised network concepts and power transmission technologies to meet the demand.

Extensive air conditioning and building automation systems result in a high share of induction machines, which have to be specially considered at network planning of power system with regard to their short-circuit current contribution and influence on voltage stability. Planning new cities starting from scratch offers the opportunity to install district cooling systems instead of using many classical split unit air conditioners. The type of cooling system influences voltage recovery and short-circuit levels of the power system.

Power plants are erected outside the new cities. Therefore, the high power demand of the new metropolis has to be transmitted from outside to the load centres. This requires higher voltage levels than distributed power plants spread over the city. Reserve power supply from national grid or a backbone system has to be transmitted into the city as well.

Specific requirements can be defined to exploit sophisticated technologies to supply a modern city with regard to aesthetic, reliability and flexibility needs. Overhead lines and air insulated substations (AIS) should not disturb the cityscape. The network concept has to be optimised to fulfil all specific requirements of new ambitious metropolis such as:

- Economic and efficient power supply
- Concentrated location of power plants
- High power density and demand
- High reliability and redundancy especially for business and financial districts
- No overhead lines or AIS inside the city
- Grid interconnection and island operation
- Extensive air conditioning and building automation
- Specific side conditions such as ambient temperature etc.

It is a unique chance to design a modern, economic and efficient power system utilising modern technologies at greenfield planning of a new city. This is to be implemented at fully developed city as well as at all development phases.

## III. GENERATION CONCEPTS

Power plants capacity supplying a developing city has to meet an outage of the two biggest units at island operation. At grid interconnection a reliability of (n-1) may be sufficient if power balance at loss of the biggest power unit can be supplied from the grid. Reliability of power generation is determined by evaluating the complete conversion of energy including the transformation to transmission network.

Oil, gas and coal are the main primary energy sources. Gas turbines with a combined cycle offer the highest efficiency and best solution for a new city, since coal based steam power plants needs a good infrastructure for transportation of the coal. Scalability is much better with gas turbines in order to meet the increasing load demand of a growing city. As a first step gas turbines could be installed to power the first areas and should be extended to combined cycle power plants, when load demand is adequate.

Desalination plants are sometimes combined with the power plant in order to utilise the heat and power of the power plant. This combination determines the location at a coastline.

Future power plant development focuses on improvement of efficiency and carbon capture and storage technologies. Improvement of steam power plants aiming on higher pressure and temperature of steam to increase efficiency. Due to climate impact of $CO_2$ emissions, carbon capture and storage technologies are investigated and developed for conventional coal power plants and for Integrated Gasification Combined Cycle (IGCC) power plants.

Renewable energy sources may not be suitable for the high load density inside the cities, but large solar, wind and ocean power plants outside the city may become economic and a good enrichment of the energy mix. A big proportion of reliable distributed generation and small power plants spread over the city may reduce the needs of transmission capacity. However distributed generation is not expected as main electrical power source at present projects.

## IV. NETWORK CONCEPTS

### A. Voltage level selection

The voltage level selection focuses on:

- Minimising number of voltage levels in order to reduce the variety of equipment for operation and maintenance
- Make use of standardized equipment
- Define transformer substation size which minimises the amount of equipment as well as meet short-circuit rating

Table I shows appropriate voltage levels of networks for newly designed networks. Reference of system capacity is made to a load current of 3150 A.

Due to the expected high load densities in the city centre and location of power plants outside the cities higher voltage levels as at conventional urban networks are required for power transmission to the load centres. It might become necessary to go with 400 kV or 500 kV right into the city centre.

TABLE I
PREFERRED VOLTAGE LEVELS

| Network Level | Voltage level | System capacity at 3150A | Typical Short-circuit rating |
|---|---|---|---|
| L.V. Distribution network | 0.4 kV | 2 MVA | 50 kA |
| M.V. Distribution network | 22 kV | 120 MVA | 25 kA |
| Subtransmission network | 110 kV,<br>132 kV | 600 MVA,<br>720 MVA | 40 kA |
| Transmission network | 400 kV<br>(500 kV) | 2200 MVA<br>(2700 MVA) | 63 kA |
| Backbone | 765 kV,<br>1000 kV | 4100 MVA,<br>5400 MVA | 63 kA |

### B. Network Topology

Layout of substations and switchgears has to be optimised to combine both high reliability requirements as well as efficient operation of power system. Network topology determines OPEX and CAPEX. Gas insulated switchgears (GIS) should be installed in order to minimise the required space for substations. (n-1) reliability should be at least ensured at all medium and high-voltage substations (S/S) by installing transformer reserve capacity and switchgears with different busbar sections. Double busbar or 1½ circuit breaker configuration switchgears offer more flexibility for operation and at contingency situation for all feeders. (n-2) reliability for high-voltage transmission network and important areas, like business and financial districts, has to be achieved by redundancy in both substations and network topology.

### C. Modern Technologies for Power Systems

Modern technologies such as gas insulated lines (GIL) and HVDC PLUS offer new possibilities to transport high amount of power into the city combining both aesthetic requirements of ambitious cities, e.g. no overhead lines, and design of economic power systems. Advantages of HVDC PLUS are low short-circuit current contribution and independent P/Q control at all 4 quadrants due to the multilevel voltage source converter technology.

Especially at high-load areas, 400 kV cable connections with several cable systems in parallel require huge space of right of way and reactive power compensation equipment. By introducing GIL space requirement is minimised, capacitive charging load and magnetic field emission is much less than 400 kV cables [5]. Building of tunnels is much more cost-effective at an early phase of the city development. This enables economic installation of high-voltage underground transmission with lowest requirements of right of way (Figure 10). E.g. a power transmission route of 4 GVA would require a right of way of about 50 m for two OHL systems, 30 m for 5 cable systems or 10 m using two GIL systems in a tunnel. An installed example is the 550 kV GIL at Sai Noi (Thailand) with a current rating of 4000 A. This GIL was commissioned in 2002.

Modern protection and control concepts enable fast locating of faults and immediate re-supply for customers. Load demand management and online metering offers efficient operation of the power system of the city. Especially the introduction of electric vehicles with charging stations spread over the city requires a sophisticated load demand control.

## V. Design and Evaluation of High Voltage Networks from Scratch using PSS®Sincal

### A. Approach

The following step describes the approach to design a high voltage network from inception using the powerful network planning program suite PSS®Sincal. Typically the land allocation is defined in the Masterplan of the city. The Masterplan defines the load demand with a topographic reference. This sets the basis for the designing of an appropriate network structure. The load demand of the entire new city can be modelled in PSS®Sincal with topographic reference. The investigation starts with the lowest voltage level under investigation and the steps 1 to 5 are repeated with the next higher selected voltage levels successively.

1st Step: Define the basic supply concept:

First the basic supply concept is to be developed by selecting the adequate voltage levels, defining the standard equipment and standard substation layout. Transformer and cable sizing for the standard equipment has to be performed.

2nd Step: Tailoring of suitable supply areas:

The supply areas are determined by the dedicated power supply according to the basic supply concept and geographical constrains such as rivers, city limits, major streets etc. E.g. a 132/22 kV substation has to feed 120 MVA, the supply area is to be tailored that the sum of loads is not exceeding 120 MVA at overall completion, as shown at Figure 2. The voltage level defines the size of the supply areas. Higher voltage levels feed larger supply areas with higher load demand.

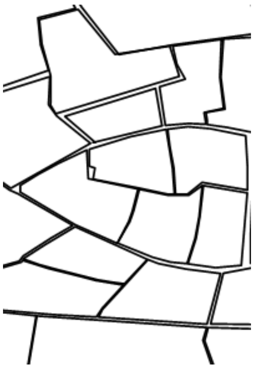

Figure 2: Tailoring of suitable supply areas

3rd Step: Calculating the load focus of the supply areas:

The load focus of the supply area is calculated by PSS®Sincal. Figure 3 shows an example, where the black dots mark the load focus. This calculation has to be done for all considered voltage and their supply areas.

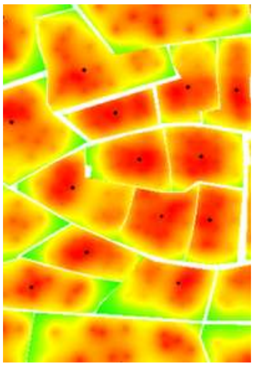

Figure 3: Calculating the load focus of the supply areas

4th Step: Determine optimum location of substations:

After determining of the entire load focuses at all considered voltage levels, the optimum location of substation is placed. The placement of substation has to consider all load focuses as well as the basic supply concept and predetermined energy corridors (if existing). Some substations may be shifted to the next bulk supply point (BSP) in order to reduce the space requirements of substations (Figure 4)

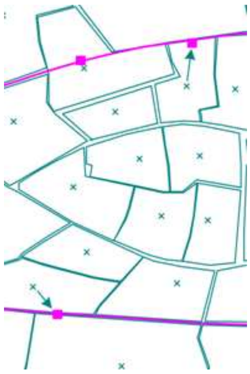

Figure 4: Determine optimum location of substations

5th Step: Design the network topology:

Once the location of substations is determined, the network topology is to be designed considering the reliability requirements (Figure 5). Mature network concepts are:

- Meshed network,
- Network with remote redundancy,
- Loop configuration,
- Express feeder concept and
- Open ring configuration.

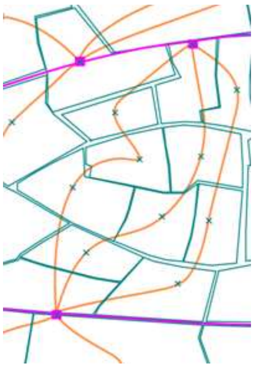

Figure 5: Design the network topology

Next Steps: Detailed network studies:

The designed network topology has to be verified and equipment has to be dimensioned by detailed network studies such as:

6. Load Flow Analyses:
   - Steady state current and power flow
   - Voltage profile
   - Transmission system active losses
   - Determining the rating of the equipment

7. Reactive power management and balance study:
   - PF correction
   - Location and size of necessary shunt devices

8. Contingency Analyses:
   - Verification of required redundancy
   - Improvement of network layout

9. Short-circuit current calculation:
   - Minimum and maximum fault levels according to IEC 60909
   - Switchgear fault withstand ratings

10. Dynamic and transient network studies:
    - Critical clearing times of generators (stability studies)
    - Voltage recovery upon removal of fault
    - System performance at partial generation or load loss
    - Load shedding settings

11. Protection philosophy and coordination study:
    - Design the protection philosophy
    - Define the protection concept
    - Specify standard protection devices
    - Predefine basic protection settings

12. Communication system:
    - Design for optimum control
    - Utility internal communication
    - Communicating protection scheme
    - Wide area monitoring with phasor measurement units (PMU)

After finishing the long-term concept for all voltage levels, the same planning steps are repeated to develop the short and medium-term concept using the long-term concept as target network.

Finally a bill of quantity specifies the required equipment detailed for each development step. The development of the power system has to consider the load development of the different areas of the new city as well as the entire long-term network concept. This gives an outline for CAPEX planning and constructional engineering.

### B. *Results*

Figure 6 shows a network concept of a 400 kV transmission network as a doubled loop configuration designed at greenfield planning of a new city. The 400 kV transmission network has to meet the (n-2) criteria. The bulk supply points (BSP) feed the subordinated 132 kV subtransmission networks.

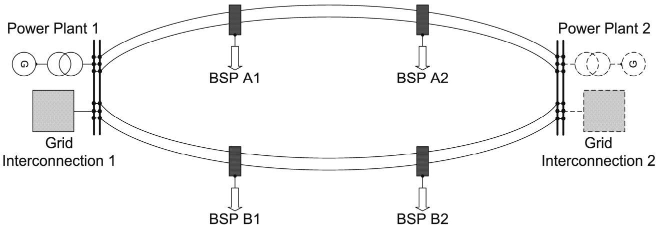

Figure 6: Transmission network concept with GIL

The 132 kV subtransmission networks are designed for (n-2) reliability as networks with remote redundancy or loop networks. The main advantage of the network concept with remote redundancy is the utilization of transformer reserve capacity at a contingency situation. Each BSP is only equipped with a transformer reserve capacity of one unit. If two transformers are out of service at a contingency situation, the transformer reserve capacity of both BSPs will be utilised. Figure 7 shows the configuration at normal operation and contingency situation at loss of two transformers at one BSP.

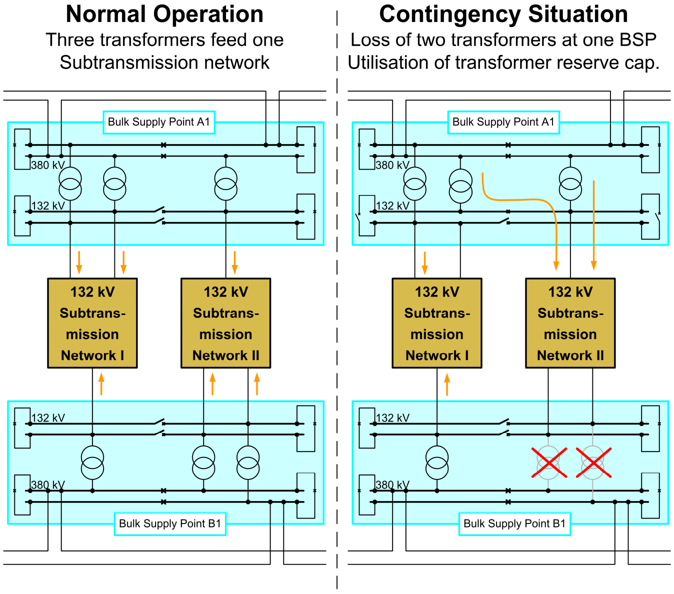

Figure 7: Subtransmission network with remote redundancy

The distribution networks are designed for (n-1) reliability following the express feeder or open ring network concept. Important costumers, such as public buildings, business and financial centres or sensitive industrial loads, should be connected with (n-2) redundancy.

Looking at future development of power systems, the networks of a modern city have to be as well capable to interconnect to extra high-voltage backbone systems, since large meshed 400 kV networks may be split and fed by a 765 kV or even 1000 kV AC backbone (Figure 8) in order to reduce the short-circuit current levels. Likewise, backbone systems as ultra high voltage direct current (UHVDC) systems may be installed using voltages up to ±800 kV DC.

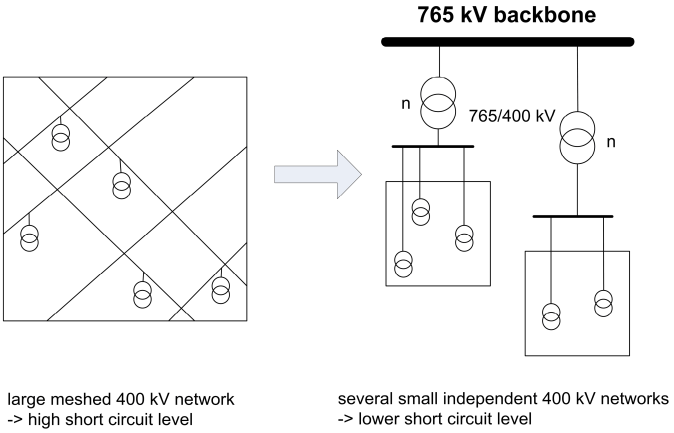

Figure 8: Splitting of 400 kV networks with a EHV backbone structure

The building of a city from inception may require both island operation and grid interconnection. From the stability point of view, two major effects have to be considered:

- Frequency stability and critical clearing time of generators at grid interconnection
- Voltage stability at island operation

Generator protection must be designed to prevent instability at grid interconnection. Protection concept of network has to clear faults until the critical clearing time of generators is reached. These requirements are usually described in detail in the national grid code.

As the new cities are supplied by one or two main power plants, frequency may float at island operation in certain range, but generators are keeping the same frequency. Voltage stability is a more severe problem at island operation, as the growing demand of air conditioners and building automation for high quality of life increase the amount of induction machines with different torque characteristics.

Both effects, frequency stability at grid interconnection and voltage stability at island operation require a sensitive fast acting protection scheme.

## C. *Example*

The application of the described planning process can be shown on one planning example performed by the authors. In the desert close to the coast line between Dubai City and the border to Abu Dhabi the developer Nakheel builds the city of Dubai Waterfront. This modern city (Figure 9) is characterized by the following facts:

- Expected number of inhabitants: 2 million
- Totally developed area: 127 km$^2$
- Expected demand on the high voltage level: 7 GVA (app. 60 % of the demand of New York City) in about 15 years
- Expected load density in the city centre: > 120 MVA/km$^2$

This city is to be supplied by one dedicated power plant. For reserve reasons it is connected to the national grid. As there is only desert in the moment, the planning procedure described in this paper is conducted and planning options are not limited.

Due to the high load density it was proposed to use two 400 kV GIL tunnels as transmission system, which transport the power right into the city centre (Figure 9). A loop structure is used with two parallel systems to achieve (n-2) reliability. This is an aesthetic solution as no lines are visible. Compared to solutions with high voltage cable systems, the reactive power demand is much lower. Because there is no interfering infrastructure existing, the tunnel can easily be built at this stage. The subtransmission network is designed as a 132 kV network with cables. The medium voltage distribution network is proposed as a 22 kV network.

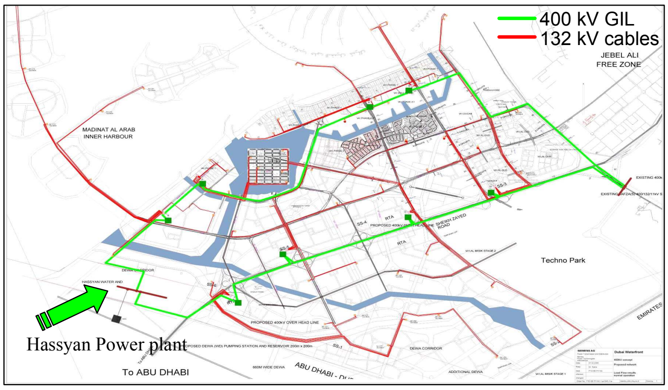

Figure 9: Example of planned 400 kV GIL double loop network of Dubai Waterfront [1, 3]

## VI. CONCLUSIONS

Network planning including detailed network studies are necessary at an early stage at development of a new metropolis in order to avoid misleading investments. The long-term scenario determines the future network concept. Development steps will be applied when required, but have to lead to the long-term network topology. Substation, cable and GIL routes should be completed before the city becomes busy. This sets the challenging frame for generation, network topology design and operation of economic power systems of new ambitious cities.

Powerful network planning tools, such as PSS®SINCAL, are essential for efficient and productive network planning. The proposed planning procedure and methodology has been applied successfully by the authors amongst others to the cities of Tripoli and Dubai Waterfront [3, 7, 8].

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