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SOLUTIONS FOR LARGE POWER SYSTEM INTERCONNECTIONS

V. Sitnikov

Siemens, Russia

D. Povh, D. Retzmann
E. Teltsch

Siemens, Germany

0. Abstract

A worldwide trend in the development of power systems is to build interconnections with the goal to achieve economical benefits. Such large interconnected systems can cover many countries or even wide continental areas. Interconnections of power systems may offer significant technical, economical and environmental advantages, such as pooling of large power generation stations, sharing of spinning reserve and use of most economic energy resources taking into account also ecological constraints: nuclear power stations at special locations, hydro energy from remote areas, solar energy from desert areas and connection of large off-shore wind farms.

The liberalization in the power industry also supports more interconnections to enable the exchange of power among the regions or countries and to transport cheaper energy over long distances to the load centers. Examples for such interconnections are systems in Russia, North America, Europe and Asia. However, there are technical and economical limitations in the interconnections if the energy has to be transmitted over extremely long distances. In future, the situation can, however, change if ecological and political terms change or the present cost conditions alternate.

The interconnections are mostly realized by synchronous links where such solutions are technically feasible and economically justified. On the other hand HVDC links often offer technically better and more economical solutions. A large number of examples worldwide shows, that HVDC is a quite suitable solution. However, in many situations, hybrid solutions for interconnection are more advantageous: a synchronous high voltage AC link, supported by an additional HVDC link. In cases where the synchronous interconnection is technically at the limit, HVDC can support the operation of the interconnected systems and thus makes the synchronous AC link more reliable.

In the paper, examples of system interconnections throughout the world are shown. Benefits of asynchronous DC and synchronous Hybrid solutions including DC for system expansions are demonstrated and preferences are explained. Study and project examples are given.

Keywords:

Development of Power Systems - Power System Interconnection - System Dynamics - Transmission Efficiency - AC, DC and Synchronous Hybrid Transmission Technology

1. Introduction

Global studies show that power consumption in the world follows closely the increase of population (Fig. 1). In the next 20 years, power consumption in developing and emerging countries is expected to increase for 220%, in industrialized countries, however, only for 37%.

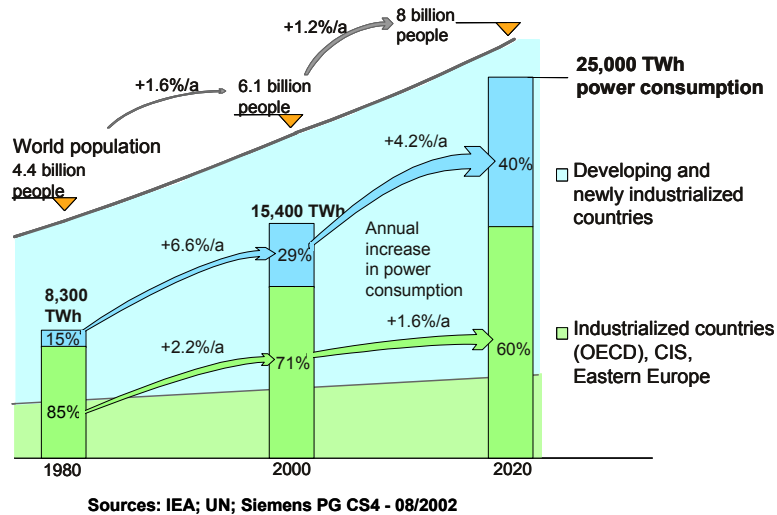


Fig. 1: Development of World Population and Power Consumption, 1980 to 2020

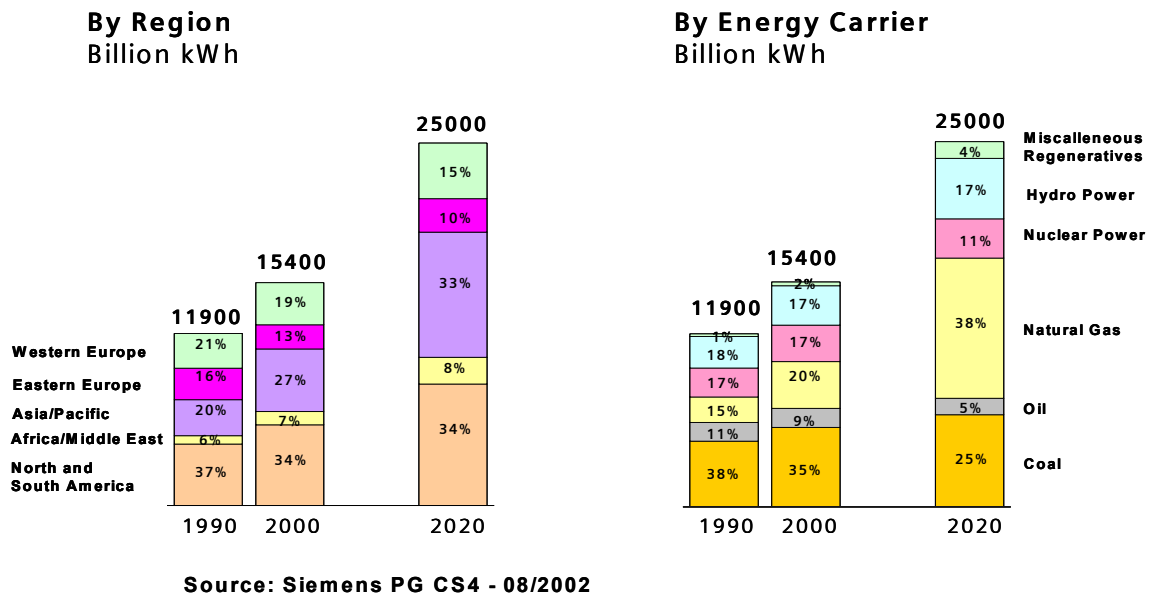


Fig. 2: Worldwide Power Generation

This means, that fast development of power systems can be expected in the areas of developing and emerging countries. This can also be seen in Fig. 2 where the worldwide installed generation capacity is shown by regions and by energy sources. The importance of gas as energy source will further increase, the relative importance of coal, oil and nuclear power will decrease. The regenerative energy sources excluding hydro are expected to increase fast, however, in total they will still be only in the range of about 4 %.

The development of power systems takes into account locations of expected load demands on one hand and the suitable location of power stations on the other hand, to transport the energy from generation to consumers. Based on different studies on the development of power systems in different world regions, general trends can be expected [1]:

- Further extension of interconnected systems enables the increase of power exchange between the systems.

- Transmission of large power blocks over long distances, mainly from hydro power stations and other renewable energy sources via bulk power transmission corridors or through the interconnected systems.
- Increasing part of the installed capacity will, however, be connected to the distribution levels (dispersed generation).

2. Solutions for Interconnections

The advantages of power system interconnection are listed in Fig. 3. They are generally valid and do not depend on the kind of the interconnection. Fig. 4 shows schematically different alternatives of system interconnections.

- Possibility to use larger and more economical Power Plants
- Reduction of the necessary Reserve Capacity in the System
- Utilization of most favorable Energy Resources
- Flexibility of building new Power Plants at favorable Locations
- Increase of Reliability in the Systems
- Reduction of Losses by an optimized System Operation

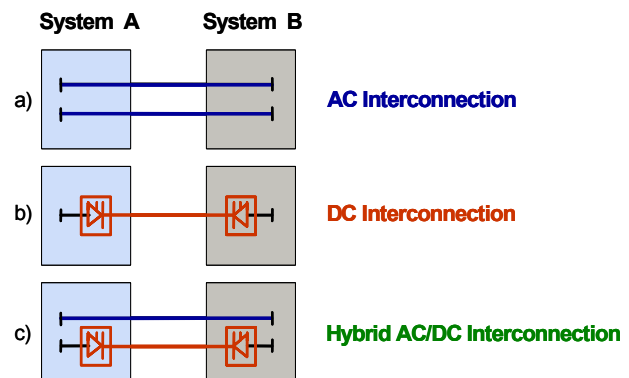


Fig. 3: Advantages of Interconnected Power Systems

Fig. 4 a)-c): Alternatives of Power System Interconnections

In the past, the synchronous operation of power systems was the normal way to build up an interconnected system (Fig. 4 a). Best example is the development of the UCTE system in Western Europe, which has been expanded in steps to the today very complex configuration, with the expected further extension to Romania and Bulgaria.

Fig. 5: Technical Problems in AC Systems

Interconnected Systems	Long Distance Transmission Systems
○ Load Flow Control	○ Voltage Control
○ Voltage Stability	○ Reactive Power Control
○ System Oscillations	○ Steady-State Stability
○ Inter-Area Oscillations	○ Dynamic Stability
○ Subsynchronous Oscillations	○ Subsynchronous Oscillations

Fig. 6: Problems of large Synchronous System Interconnections

- High costs for system adjustments (frequency controls, generation reserve)
- Need for close coordination of joint system operation
- AC interconnections normally weak at the beginning (additional lines needed to prevent dynamic problems)
- Bottlenecks in the system because of uncontrolled load flow
- Spinning reserve in the system to be transmitted over long distances (additional loading and cost increase)
- Reduction of economic advantages because of large transmission distances at relatively low transmission voltage (e.g. 400 - 500 kV)
- In liberalized market disadvantages and higher costs when transmitting power through a number of systems and involvement of a number of partners

However, with the increased size of the interconnected system over thousands of kilometers, most of the advantages offered by interconnections are reduced. Reasons for this are technical problems of large systems resulting from meshed structures on the one hand and problems of long distance transmission on the other hand. They are summarized in Fig. 5. To avoid these problems, additional improvements of the system are needed and operation of joint systems becomes very complex and less reliable [2, 3]. The technical limitations of very large interconnected systems have also impact on the cost benefits of the interconnection. The reasons for these limitations are listed in Fig. 6.

An AC interconnection requires the coordination of a number of system parameters. An important one is the strength of the interconnection. If few lines connect two strong systems, the interconnection becomes unstable. Only if additional lines are built, which increase the strength of the link, the interconnected system achieves stability. In large interconnected systems, power which should be transmitted over long distances has to flow through the meshed systems thus causing additional losses and overloading of existing bottlenecks. Using the HVDC solution, it is, however, possible to install the link directly between the locations which require power exchange, without negative effects on the systems.

Hence, the easiest way to interconnect systems is to use HVDC (Fig. 4 b). This interconnection can be either long distance transmission or a back to back link. In such cases, there are no special needs to coordinate the dynamic behavior of both systems or to provide strong interconnection to establish a dynamically stable interconnection. The advantages of the interconnection can fully be utilized without coordinating the frequency characteristics of both systems. Furthermore, HVDC can be built in stages, following closely the demands of the interconnection, thus saving investment costs.

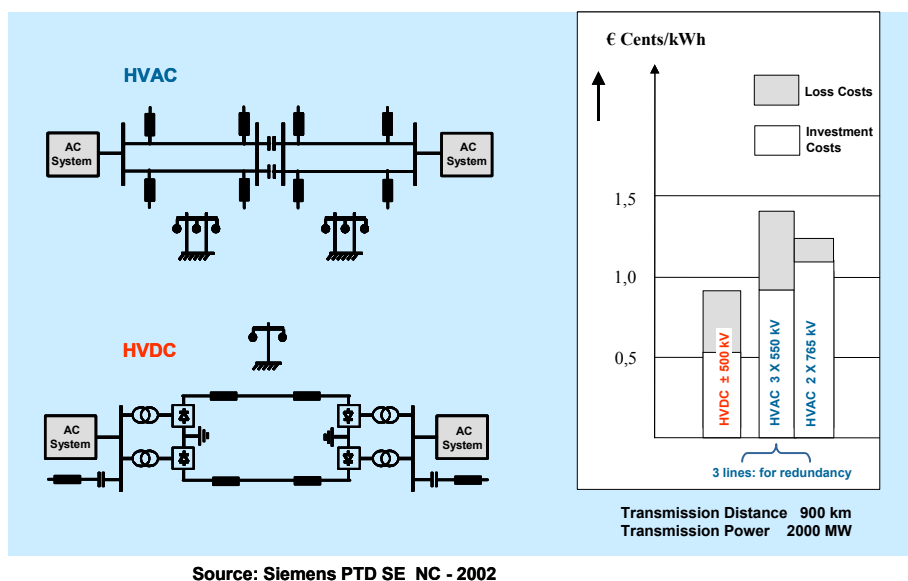


Fig. 7: Costs of High-Voltage Transmission

Fig. 7 shows both alternatives of long distance transmission, HVAC and HVDC. For HVDC, a $\pm$ 500 kV bipolar line and for AC three 500 kV, alternatively two 765 kV lines have been assumed. These transmission configurations are nearly equivalent with respect to the reliability. Costs in Euro-Cents/kWh, including cumulated loss costs have been evaluated for 2000 MW transmission power over a distance of 900 km. It can be seen that the DC alternative is much more economical. Results of other, similar studies show, that in general the HVDC interconnection is the cheapest solution at transmission distances over about 800 km. This is also valid if the energy is transmitted through a large interconnected AC system

on a distance of 800 km. This means, the integration of an HVDC long distance transmission into the interconnected system could be more economical than the power transmission through the AC system itself.

The third possibility is a hybrid interconnection, consisting of an HVDC transmission and a parallel AC interconnection, ref. to Fig 4 c). The interconnection could start with HVDC and then later be extended by additional AC links. A major benefit of such a solution is, that the HVDC can support the operation of the AC interconnection at faults in the system and can also control the load flow. An example of stability improvement is given in Fig. 8 b) for a system according to Fig. 8 a).

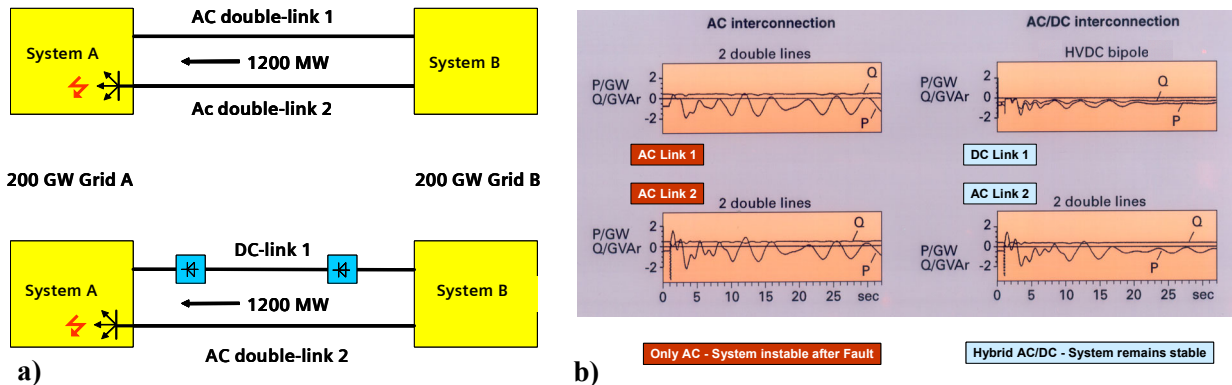


Fig. 8: Comparison of System Stability for synchronous AC and synchronous Hybrid Interconnection.

a) Set-up of the Systems b) Dynamic Results

The hybrid interconnection could therefore offer the best possibility for large system interconnections in the case of continental interconnected networks, consisting of a number of small systems. A configuration according to Fig. 9 could be technically and economically the best solution.

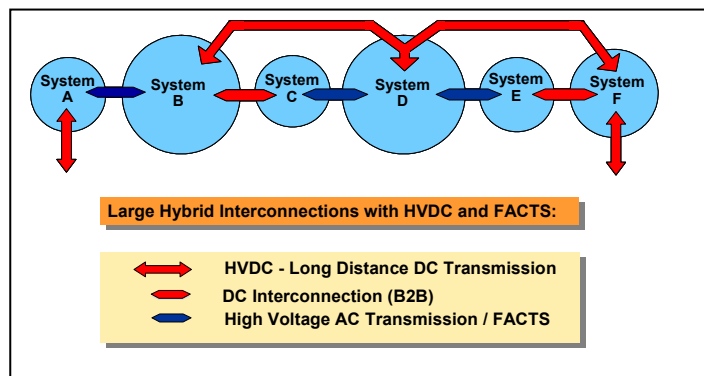


Fig. 9: Large Power System Interconnections

Both AC and DC (B2B) links between the neighboring areas of the interconnected systems enable power exchange among these areas. Transmission of larger power blocks over long distances is however utilized by HVDC point to point transmissions directly to the locations of power demand. HVDC at the same time can strengthen the interconnections to avoid possible dynamic problems, which exist in such huge interconnections.

3. Power System in China

China is one of the countries with the fastest increase of power demand. The installed generation capacity in the last 10 years, from 1990 to 2000, grew from 135 GW to 319 GW; this is more than 230 %. Main energy resources in the country are hydro in the central and southern areas and coal in the north [4]. In addition, some nuclear power stations are built close to the load centers. Because of large distances in the country, in the early system development, smaller isolated regional systems have been built up and developed to seven large independent regional systems, in addition to some small local systems in less populated areas of Tibet and Xinjiang (Fig. 10).

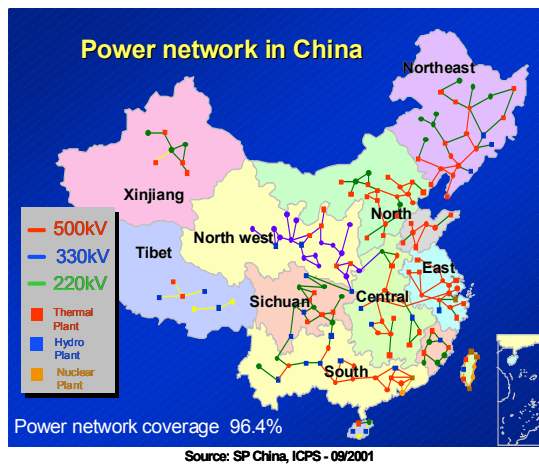


Fig. 10: Regional Power Systems in China

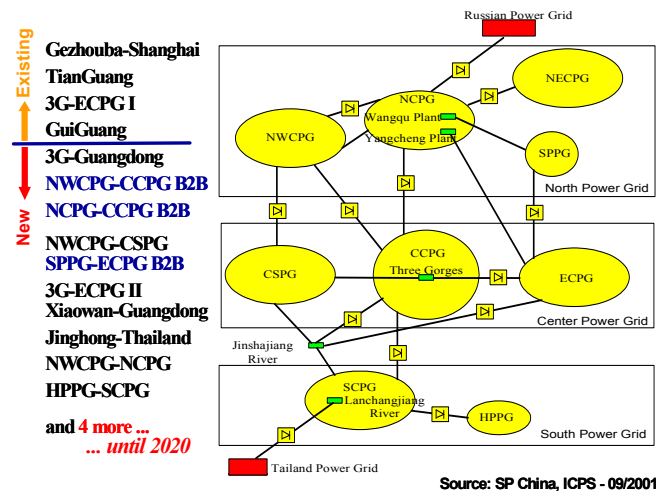


Fig. 11: China goes hybrid: AC plus 18 HVDC Interconnections

Main AC transmission voltage levels in China are 330 kV and 500 kV. Large power blocks, produced by hydro power stations, e.g. at Three Gorges, have to be transmitted to the load centers over distances of 1000 km and more. For this task mainly HVDC transmission is used. However, for the transmission inside of the regional systems also 500 kV AC is utilized.

Coal fired power stations can be partly built closer to the load; however they are more concentrated in the north of the country. Power Exchange among the regional systems is still relatively low in relation to the installed capacity of the systems. Therefore, only few AC lines would be sufficient for such interconnections to cover needs for power exchange. However, due to dynamic problems and the needed high additional expenditures for adjustment of the systems to enable synchronous operation, mainly HVDC transmission is used for the interconnections.

In the future, the today existing seven independent regional systems will emerge into three large interconnected systems (North, Center and South Power Grid). The interconnection among these grids will be done mainly by HVDC as shown in Fig. 11. In addition to the existing four HVDCs, further 14 HVDC transmission links are planned. Only for some smaller and remote local networks, the connection to the larger regional grids should be realized by AC, and, due to the long distances, probably using 765 kV. Possible interconnections to neighboring countries should also be realized by HVDC.

4. Power System in India

India is the second largest country, a subcontinent with a population of over 1 billion people and in the last decades with a very rapidly growing economy. In the 1960's with, at that time,

still low demands for energy, the Indian power industry consisted of individual isolated grids within each state, with local state power plants. In the 1970's some of these state grids were interconnected to form regional grids. With the increasing power demand, the step was envisaged in the 1980's to build a national grid by the interconnection of the regional networks to gain the advantages of power exchange, sharing generation resources, to increase the reliability and to reduce the power outages in some areas. At present, the installed generation capacity is 110 GW, 71% produced in coal fired plants, 25% in hydro plants and 4% in nuclear plants and others, in which the wind generation is the most important one [5].

Large hydro energy resources in India are available in the north and north-east of the country, near the Himalayan Mountains. 25 GW hydro potential is already used, 19 GW in implementation and further 66 GW are still available. Huge coal reserves are available in the West and East areas of the country. Power produced in hydro stations and coal fired plants has to be transmitted to the loads over large distances of 1000 km and more. Interconnections between the regional grids started by the realization of HVDC back to back stations and the HVDC long distance transmission Rihand-Delhi. The interconnections in the Year 2002 (Phase I) are shown in Fig.12, an additional HVDC long distance transmission is in operation now (East-South Interconnector II, 2000 MW).

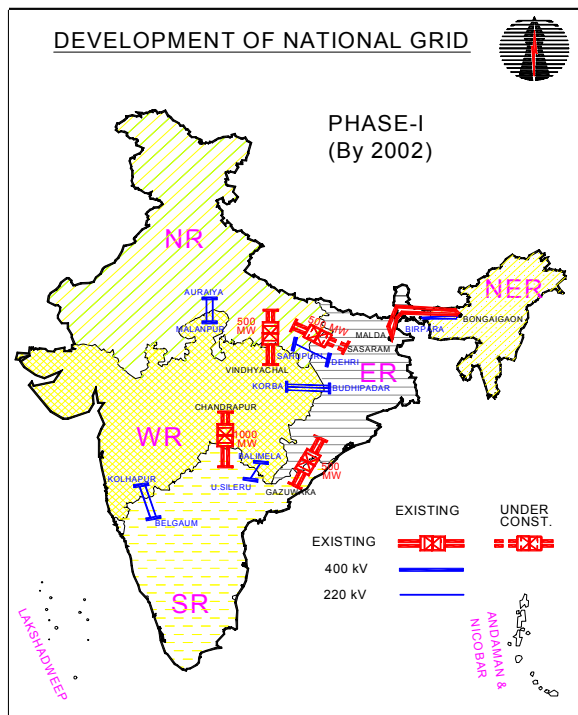


Fig. 12: India Power Grid 2002

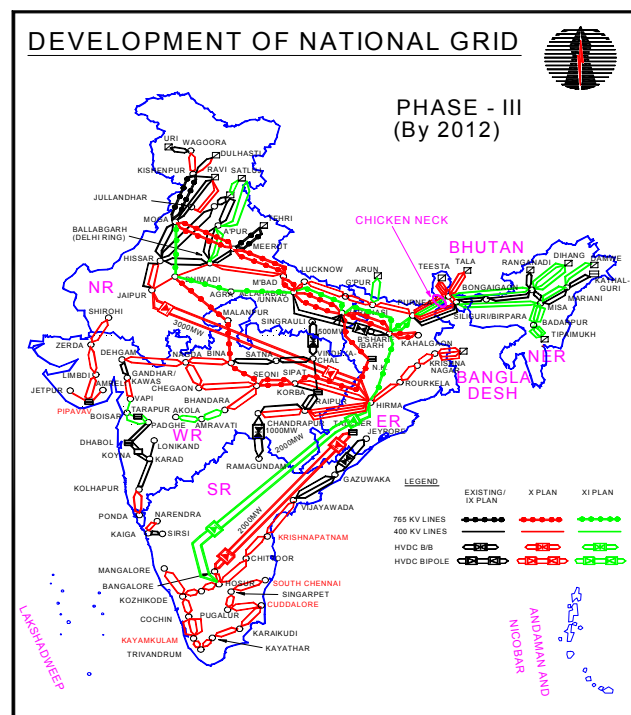


Fig. 13: India Power Grid in the Future

The main reason for the decision towards HVDC was that the costs to improve the regional systems to enable them for synchronous operation would be very high and would need long time to build up sufficient generation reserve. The second reason was that HVDC offers also technical advantages supporting the operation of the AC systems.

At present, the cumulative interconnection capacity is about 5 GW, about 6% of total peak power. Also in the next development step towards a national grid, the interconnections between the regional systems will be realized mainly by HVDC. In the phase II of building the national grid, however, also the AC interconnections at a voltage level of 400 kV will be extended and the higher voltage level of 765 kV will be introduced to build high power "transmission highways". The capacity of the interconnections in this phase (year 2006-07) should reach 23 GW.

The interconnection capacity will further be increased to 30 GW in the years of 2011-12. In this phase III, a strong AC interconnection will be established on 765 kV level, synchronizing Northern, Western and Eastern regions. However, also in this stage further HVDC links will be built up to strengthen the interconnections to the Southern region (Fig. 13).

5. Summary

System interconnections offer technical and economical advantages. However, when using only AC interconnection, the advantages decrease with an increasing size of the systems to be interconnected and the expenditures and costs to adjust the system parameters for synchronous operation rise.

An HVDC interconnection doesn't need such system adjustments and provides therefore a more economic solution. In addition, when power has to be transmitted through the system over longer distances, the HVDC transmission is technically and economically the superior solution. On long term, however, a synchronous hybrid solution, consisting of both HVDC and AC links, is the most promising solution for large national and continental interconnections.

The paper demonstrates the technical features and discusses the pros and cons - and limits - of synchronous interconnections and shows possibilities how to use the HVDC interconnection as an "Energy Bridge" in combination with existing AC lines or as a point to point long-distance DC transmission, both with the goal of extension to a larger hybrid interconnection. The presented examples in the development of Chinese and Indian national grids show in a very clear way that hybrid interconnections offer best possibilities to build a large interconnected system using a pragmatic solution: At the beginning the asynchronous interconnections with HVDC, and then, step-by step, depending on the requirements, to apply also the synchronous AC interconnection in a hybrid way.

There are no technical limits to build continental and even intercontinental interconnections by such synchronous hybrid solutions. However, the exchange of electric power over distances of over 3000 km seems not to be economically feasible at the to-day cost relations.

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7. References

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