7. USE OF NON-CONVENTIONAL TECHNOLOGIES FOR INCREASING CAPACITY IN TRANSMISSION NETWORKS

Problem statement

- *Analysis of non-conventional technologies for improving transport capacity of gas and electricity. The analyses addressed:*
  - *Hardware technologies , which rely on the adoption of a new generation of components or the adaptation of already existing equipment to new operating conditions;*
  - *software solutions, based on IT and advanced communication protocols*

Methodology

- *Collection of data on the state-of-the-art of non-conventional technology*
- *Assessment of most favorable locations for non-conventional technologies and impact on the EU priority axes*

Major results

Electricity

- *the most mature non-conventional solutions are based on the installations of high voltage extruded polyethylene cables, connections in high voltage direct current and phase shifter transformers;*
- *Use of static Var compensators and static synchronous compensators is beneficial more on the local level to optimise the voltage profile rather than to enhance power transfer capacity;*

Gas

- *Ultra deep water offshore pipelines and high pressure on-shore pipelines are the most favourable solutions for the construction of new gas routes and for enhancing the capacity of the existing ones;*

Software based solutions

- *In the electricity sector, change of operating procedures and dynamic rating of components are two possible ways feasible to enhance transfer capacities with the mid-term perspective allowing to postpone investments in new lines*
- *In the gas sector, the adoption of new meters coupled with satellite communications will favour the on-line collection of a large amount of reliable data as required by the EU gas market;*
- *The design of new gas pipelines can be eased by the use of satellite three-dimensional charts.*

7.1 Introduction

The objective of this part of the Project is to present an overview of the possibilities to apply non-standard transmission technology to increase cross-border transfer capability in the Trans European Network (TREN), without resorting to the erection of new facilities or smoothing the need for new infrastructures: lines in the power transmission and pipelines in gas transportation.

The scope of the work includes:

- A description of the state of the art of non-standard transmission technologies, highlighting the features that make them suitable for application in the TREN.
- An analysis of the non-standard solutions investment cost and a comparison with their conventional counterpart where applicable.
- An analysis of the present use of non-standard technology in the different electric system in Europe.
- An outline of the perspectives of application of non-standard technologies to improve the utilization of existing transmission facilities.

This volume is organized as follows. Section 7.2 addresses non-standard technologies in the power sector. More in detail, Section 7.2.1 describes the principal elements constraining the capacity of a transmission system to transfer power. Section 7.2.2 illustrates which are the technical limits that actually constraint the transfer capacity of some of the most critical cross-border corridors in the Trans European Network. In Section 7.2.3 a description of the most relevant and promising non-standard technologies is presented. Section 7.2.4 presents the main possibility of implementation of software-based non-conventional technologies. Section 7.2.5 deals with costs of non-standard technologies and comparison with their conventional counterparts where applicable. Section 7.2.6 illustrates the possibilities of applying non-standard technologies to increase cross border transfer capacity in the Trans European Network. A description of non-standard technologies installations currently implemented in different European electric systems is presented. Some concluding remarks relevant the power sector are presented in Section 7.2.7.

Section 7.3 addresses non-standard technologies applicable to the European gas transmission grids; in the examination of the various innovative technologies examples are given about recently achieved project adopting these technologies or situations where they can be fruitfully used in the future.

Finally, Section 7.4 contains a list of all the references and bibliography used throughout the work.

7.2 Non-conventional technologies in the electricity sector

7.2.1 Constraints on Electric Transmission Systems

In general terms two kinds of constraint that limit the transmission capacity of a transmission systems can be distinguished, namely technical limits and operating philosophy. The former refers to those physical parameters that are to be kept within allowed limits to avoid damage of the physical assets. Also it includes some characteristics of physical behaviour of power system that under certain condition can jeopardize system integrity. The technical limits we discuss here in relation with the transfer capacity of interconnection are: thermal/current constraints, voltage constraints, stability limits and limits due to parallel flow phenomenon.

On the other hand, transmission constraints due to operating philosophies are related to the way physical limits are considered in the definition of the transfer capacity that can be used for power transaction in the market. That is, for example, if thermal limits must be observed only on normal operating condition, under single (N-1) outage, under multiple components outage, complex faults scenarios, etc. Thus, the operating constraints of bulk power systems stem primarily from concerns with security and reliability. It is clear that the criterion followed in each case can severely impact the transfer capability.

Technical limits

Thermal limits: Thermal limitations are the most common constraints that limit the capability of a transmission line, cable, or transformer to carry power. The actual temperatures occurring in the transmission line equipment depend on the current and also on ambient weather conditions, such as temperature, wind speed, and wind direction, since the weather effects the dissipation of the heat into the air. The thermal ratings for transmission lines, however, are usually expressed in terms of current flows, rather than actual temperatures for ease of measurement.

Thermal limits are imposed because overheating leads to two possible problems: (1) the transmission line loses strength because of overheating, which can reduce the expected life of the line, and (2) the transmission line expands and sags in the centre of each span between the supporting towers. If the temperature is repeatedly too high, an overhead line will permanently stretch and may cause its clearance from the ground to be less than required for safety reasons. Because this overheating is a gradual process, higher current flows can be allowed for limited time periods. A "normal" thermal rating for a line is the current flow level it can support indefinitely. Emergency ratings are levels the line can support for specific periods, for example, several hours.

Underground cables and power transformers are also limited by thermal constraints. Operating underground cables at excessive temperatures shortens their service lives considerably due to damage to their insulation. Power transformers are likewise designed to operate at a maximum temperature rise to protect insulation.

Voltage limits: The components of a transmission system are designed for specific voltage ranges according to international standards. The voltages must be kept within these ranges to prevent flashover, to maintain an adequate quality of supply and to avoid fast dynamic phenomena known as voltage collapse, which may cause major black outs. Reactive power support capabilities lies also within this technical limit, since is tightly related with voltage control.

Stability limits: In large interconnected electric power systems there are many electrical, mechanical and magnetic interactions due to the dynamic behaviour of the generation plants, the characteristics of the loads and the physical properties of the components of the transmission system. As a result significant power, voltage and frequency oscillations can occur within the electric power systems. Because of the danger of partial or total system collapse (black out) these oscillations must strictly be avoided or managed within an acceptable range. Measures implemented to avoid instabilities may induce limitations on operating conditions of transmission interconnections (transmission limits).

Power flows in interconnected network (parallel flows): In a widely interconnected electric grids such as the Transnational European Network (TREN), when a control area transmits power to another area, the resulting power flows along all paths joining the two areas, regardless if the lines carrying the actual flow belong to the involved areas or not. The amount of power flowing on each path of the transmission system depends on the impedance of the various paths. The impedance of a transmission line depends on the line's length and design details for the line. A low impedance path attracts a greater part of the total transfer than a high impedance path. Thus, when a transaction occurs between two countries or control areas, the actual power flows do not necessarily follow the path linking the physical interconnection lines between them, but may flow through parallel paths in transmission systems of other countries, depending on loading conditions and the time when the transfer occurs. These are referred to as "parallel path flows". When transmission systems are directly or indirectly interconnected with each other at more than one point, power flows can travel into the other systems' networks and return, thus forming "loop flows." Both loop flows and parallel path flows may limit the amount of power these other systems can transfer for their own purpose. Regarding the TREN, this physical feature limits the possibility for import/export in the European transmission systems between two countries, since it will depend not only on the realized transactions among the two considered countries but also between other countries. Hence, the maximum possible use of capacity between two given countries depends to some extents on all local as well as on all remote transactions.

7.2.2 Common constraints in the “TREN” interconnection that limit transfer capacity

Cross-border interconnections are in general composed of high voltage tie lines connecting substations located at different points within the network of the individual countries. Thus, congestion on cross-border lines that limits the possibilities of international trade is due network constraints both at cross-border lines as well as within the power grids of the involved countries. For this reason, the transfer capacity in each interconnection may differ largely form the simple summation of the individual line ratings comprising it, since such simplified consideration would not take into account a number of limiting factors like security margins, parallel flows, margins for reactive power transport (as far as values are given in MVA) and the “natural” power flow distribution in AC transmission systems. References [4] and [6] present a comprehensive analysis on the methods applied by the different TSOs for determining the cross border capacities that can be available to the market, and identify the main factors taken into account by TSOs when defining the net transfer capacity (NTC).

The objective in this section is (based on reports [4] [6]) to identify what kinds of transmission constraints play major role in the definition of the interconnection transfer capacity in different countries. In that way, proper solutions to increase transmission capacity based on non-standard technology can be recognized. In the sequel, the principal factors defining transfer constraints on several interconnections are summarized. It is to be noticed that the following summary is not intended to be an exhaustive list covering transfer restrictions of all the existing interconnection between the European countries.

Spain-Portugal: Under certain operating conditions, with a surplus of hydraulic generation in north-western Spain together with the load concentration in the Madrid, and units in western Spain (installed capacity of 1700 MW) inject power at the Cedillo and Oriol substations, i.e. at the Spanish terminal of the southern 380 kV tie line (Pego-Cedillo) from Portugal, there is a high loading of the Oriol-Aranuelo double circuit line, i.e. the continuation of the Pego-Cedillo tie line towards central Spain. The critical contingency is the failure of one of these circuits leading to **thermal overload** of the parallel system.
On other hand peak generation in northern Portugal injecting power into Span's 220 kV network must be limited to the capacity of the 220 kV tie lines, where thermal overload capacity is the limiting factor. Also, parallel flows through the Portuguese network occur under certain operating conditions.

Spain-France: During peak hours, the dimensioning incident is the outage of a nuclear power plant in northeastern Spain, due to the subsequent lack of local **reactive power support.** In off-peak periods with lower load, the voltage profile is less critical. Here, **thermal currents become the limiting** phenomenon: A failure of the eastern tie line Baixas-Vic leads to a violation of the current limit for the second 380 kV line Mouguere-Hernani. (The central 220 kV line Pragnères-Biescas, although being closer to the tripped line, is prevented from overload because of the phase shifting transformer in Pragnères.). On the other hand, export to France is usually limited by the **thermal ratings** of internal Spanish lines. Additionally, RTE (French TSO) reports occasional problems with **voltage stability**.

France–Belgium: There is a predominant load flow in northbound direction. Because of the high degree of meshing, the French-Belgian border must be assessed in conjunction with the northernmost French- German (double circuit) tie line Vigy-Uchtelfangen. Power transfer is limited by **thermal current ratings** which are reached when either one of the French-Belgian 380 kV lines or one of the Vigy-Uchtelfangen circuits fails.

Netherlands-Belgium/Germany: Despite the large amount of tie line capacity, allocable capacity is much lower. Among the reasons for this are generally applicable aspects like reactive power transfer, load flow based security criteria and the Transmission Reliability Margin. However, the largest part of the theoretical capacity remains unused because of the inhomogeneous load flow distribution and its sensitivity with respect to the locations of physical power sources and sinks which are not known at allocation time. The dimensioning situation for transfer capacity is the violation of thermal current limits after a line outage.

German-Denmark: Transport capacity in southbound direction is mainly limited by static stability problems that have been observed by Eltra (DK). If stability was not critical, transmission capacity could, according to Eltra, be set by thermal limits. Allocable transmission capacity in northbound direction amounts is significantly lower than the southbound value. The reason for a such a low value is, according to E.ON Netz, transport of reserve power in case of a generator outage in southern Denmark, and according to Eltra, the outage of the internal Danish 380 kV line Tjele-Kassø that leads to a violation of thermal current limits in the 150 kV. The amount of cross-border power transfer via the DC connection is only limited by the DC link itself.

Germany-Sweden*:* The AC sides of the DC link's converter stations have a nominal voltage of 380 kV. On the German side, however, no connection to the 380 kV network exists. Therefore, power transfer to and from Sweden must go across the regional 110 kV network. Here, the requirements on steady-state voltage impose restrictions impeding the full utilisation of the DC link's capacity. Further restrictions may occur in the southern Swedish grid.

Finland-Sweden: Power transfer from Finland to Sweden is limited by static stability (oscillation between Finnish and Swedish generators). For the reverse direction, thermal limits constitute the critical factor, but depending on the scenario, voltage stability can also be critical.

Norway-Sweden*:* For the northern border section, transfer capacity is limited by a potential loss of static stability after a line failure (either one of the tie lines or an internal Norwegian line). On the central interconnection Järpströmmen-Nea, thermal current rating constitutes the most restrictive limit. Power transits from Denmark/Germany via Sweden to Norway are also restricted by thermal limits, in this case on an internal line in south-western Sweden. Regarding transmission from southern Norway to Sweden, capacity is limited by different phenomena depending on the ambient temperature and the load in the Oslo region. Transmission capacity is restricted by steady state stability, voltage stability and in times of high temperature by thermal limits.

Slovenia – Italy – Austria*:* A **loop flow** from Austria to Italy via Slovenia has been occurring since 1070's during operation of the former JUGEL. This was due to contracted energy deliveries in such direction on one hand, and absence of direct interconnection lines of proper capacity on the other hand. The problem persisted through this period, and became even more serious after interconnection with the UCTE, and when Italy continued to increase its energy imports.

The following table summarizes the above descriptions:

Interconnection	**Binding constraint**				
	Thermal overload	**Voltage overload**	**Stability**	**Parallel flows**	**Binding under**
Spain-Portugal	●			●	
Spain-France	●	●			CO
France–Belgium	●				CO
Netherlands-Belgium/Germany	●			●	CO
German-Denmark	●		●		NC, CO
Germany-Sweden	●	●			NC, CO
Finland-Sweden	●	●	●		NC, CO
Norway-Sweden	●	●	●		NC, CO
Slovenia – Italy – Austria	●			●	CO

Tab 7.1 - NC: Normal condition – CO: component outage

7.2.3 Hardware non-conventional technologies to increase power transfer capability

Although conventional methods can be successfully applied in some cases for transmission systems reinforcement, their practical implementation is limited by several technical factors that make them unfeasible for massive application. A number of new technologies for increasing the short-term capacity of transmission system have been, and continue to be under development. Moreover, many of them are being implemented by utilities worldwide. In this section a description of the most important and promising hardware non-standard technologies that can be used to increase capacity of transmission networks are described, based on the following classification:

- Upgrading of existing installations,
- Flexible AC Transmission Systems (FACTS).

7.2.3.1 Upgrading of Existing Installations

This subsection discusses new technologies that can be used to reinforce AC transmission lines, cables and related equipment. New conductor materials and transmission lines configurations are included in this category.

a) Conductors

Advances in conductor technology fall into the areas of composite materials, and high-temperature superconductors. Three of the most promising conductor technology for high voltage applications, namely high temperature superconductivity (HTS), XLPE and gas insulated lines/cables (GIL), are briefly described in the sequel:

High-Temperature Super-Conducting (HTSC) Technology *[8], [10]*

Over ten years ago, a new class of superconducting ceramic materials was discovered that required much less expensive refrigeration than older, metallic superconductors. Such high-temperature superconductors are now being developed for use in power delivery systems, where they have the potential to reduce energy losses, lower operating costs, and increase the transfer capacity of existing transmission corridors. This technology can be used for transmission lines, transformers, reactors, capacitors, and current limiters.

The main advantages apart from lower transmission losses (less than 1 percent compared to 5 to 8 percent for traditional low/medium voltage power cables) is that HTSC cables can carry up to ten times as much power as the same thickness of copper wire. Among the benefit of applying HTSC technology, the following can be mentioned: Cable occupies less space (AC transmission lines bundle three phase together; transformers and other equipment occupy smaller footprint for same level of capacity). Besides, cables can be buried to reduce exposure to EMFs and counteract visual pollution issues. It can be applied to transformers to reduce or eliminate cooling oils that, if spilled, can damage the environment. The HTSC itself can have a long lifetime, sharing the properties noted for surface cables below.

The main disadvantage of HTSC is the high investment and maintenance cost, refrigeration equipment is required and this demands trained technicians with new skills; the complexity of system can result in a larger number of failure scenarios than for current equipment, also equipment requiring more advanced protection schemes.

Underground cables – XLPE

Extruded polyethylene is used extensively worldwide at voltages up to 132kV but to date there has been only limited use at voltages of 220kV and above. XLPE involves chemically treating the polyethylene at high temperatures to improve its mechanical properties. The main advantages of XLPE cables over copper cables are flexibility, lightness, strength and lower maintenance costs. There is also no need for an auxiliary fluid-pressure system. At voltages of 220kV and above, higher operating stresses have to be used or the insulation would be too thick for installing practical cable systems. These higher stresses introduce the risk of premature failure particularly to the joint insulation. In the past, this has led to difficulties in calculating the cable’s service life and reliability. As a consequence, technical bodies in North America, Japan and Europe have required long term pre-qualification tests and after laying tests on EHV XLPE cable systems [10], [11].

At present XLPE cables are possible at the very high voltage of 400 kV and almost a total of 2000 km of various projects exist in various parts of Europe. The manufacturing of optimised cables based on these solid insulation materials is more efficient, and when used together with standardised pre-moulded accessories, allows for easier and less costly installations than those for fluid filled cables. Reference [37] describes a 400 kV XLPE cable developed by ABB Power Technologies. The cable’s copper conductor is divided into five segments to reduce skin effect losses. Segmented conductors made of stranded are used for cross-sections greater than 1000 mm2. For cross-sections smaller than 1000 mm2, the conductors are highly compacted to obtain a rounder smoother surface. The metallic screen consists of copper wires on a bedding of crepe paper to reduce the mechanical and thermal impact transferred to the insulation.

Concerning practical applications of EHV XLPE cables in the EU, the first 225 kV extruded cable installed in France in 1969 is still in operation with an excellent service record. More recently, 400 kV cables with extruded insulation were installed at French nuclear plants in 1985 and are still in service. Following these installations, large 400 kV underground cable systems with extruded insulation were installed in Germany, Denmark and Spain. Further major projects are planned or are under construction. Use of EHV XLPE cables is the most promising technology for undergrounding overhead lines.

Gas insulated lines/cables (GIL)

For 400 kV links a new technology of GIL offers a complementary solution to XLPE cables. Gas insulated transmission lines are composed of pipes that house conductors in highly isolative sulfur hexafluoride (SF6) gas, which have high load-transfer capacity. The conductor lies in the middle of the tube separated from the tube by regular spacers. There is finally an outer protection of anticorrosion coating.

GILs are useful for underground transport of high loads of power (above 2.000 MVA) in metropolitan areas and can be laid into tunnels or directly in the ground. They have a high overload, high short circuit withstand capability and can be integrated easily into a network of overhead lines without having to adapt any of the existing protective configurations. The laying of GIL is a complex operation as great care is required to avoid any infiltration of dust or other particulates and joints are required around every 20 meters.

Among the main disadvantages is the big diameter of each phase and the big quantities of SF6 (green house effect) with danger of leakage and need of continuous control. Also GIL is less flexible than XLPE cables and is more expensive than these alternatives.

b) Transmission line configuration

The main objective here is to replace or upgrades existing transmission facilities through an optimally designed installation, in which the height, strength, transmission towers span, insulators, and associated equipment is designed to fulfil engineering standards while increasing power transfer capacity and reduce maintenance.

This is an attracted alternative considering that, traditionally transmission lines have been rated in very conservative way. By means of a careful analysis the unused potential of existing installations can be found out.

The main benefit of this strategy is the possibility to use an existing right of way, which in many cases is the principal obstacle for the erection of new transmission facilities.

c) Conversion AC to DC lines

Other method of mitigating power transfer constraints is converting alternating current (AC) lines to high-voltage direct current (HVDC) lines. The conversion of an AC line to HVDC, or the replacement of an AC line, is a consideration when large amounts of power are transmitted over long distances. HVDC lines are connected to AC systems through converter systems at each end. HVDC circuits have some advantages over AC circuits for transferring large amounts of power. HVDC circuits have resistance but do not have reactance associated with AC, so they have less voltage drop than AC circuits. Also HVDC circuits can be controlled to carry a specific amount of power, thus improving controllability of power flows, helping to avoid overload, especially after components outages, and to mitigate loop flows problems.

7.2.3.2 Flexible AC Transmission Systems (FACTS)

The term FACTS describes a wide range of controllers which incorporate large power electronic converters that can increase the flexibility of power systems making them more controllable. A higher controllability allows for a more flexible system operation, thus transmission systems efficiency can be highly improved.

Power electronic controllers form the basis of a Flexible AC Transmission System (FACTS) device, which has been under development for nearly twenty years and is now entering its third generation. The first generation of FACTS devices used power electronics to control large transmission circuit elements, such as capacitor banks, to make them more responsive to changing system conditions. Second generation FACTS devices were able to perform their functions, such as providing voltage support to a long transmission line, without the need for large, expensive external circuit elements. Both first and second generation FACTS devices are currently in operation in utility transmission networks.

The use of FACTS devices can be an effective to remove or at least alleviate the transmission constraints that limit transfer capacity without having to undertake major system additions. Given the nature of power electronics equipment, FACTS solutions will be justified wherever the application requires one or more of the following attributes: rapid response, frequent variation in output and/or smoothly adjustable output.

d) Description of the principal FACTS devices

Along these almost two decades of ongoing development many different FACTS devices have been proposed, performing a wide variety of functions. In what follows, we describe the main systems, which are:

- Static Var compensator (SVC)
- Synchronous static compensator (STATCOM)
- Thyristor controlled series capacitor (TCSC)
- Synchronous static series compensator (SSSC)
- Phase-shifting transformer (PST)
- Universal power flow controller (UPFC)

The main applications of the FACTS devices are sumnarized here below.

SVC applications:

- Dynamic voltage stabilization: increased power transfer capability, reduced voltage variation
- Angle and voltage stability improvements
- Dynamic load balancing
- Steady-state voltage support

STATCOM applications:

- Dynamic voltage stabilization
- Angle and voltage stability improvements
- Improved power system damping, damping of SSR
- Dynamic load balancing
- Power quality improvement
- Steady-state voltage support

Applications of thyristor controlled series capacitor (TCSC)

- Improve transient and voltage stability
- Control line power flow
- Increase energy transfer capacity
- Damping electromechanical oscillation
- Aid in mitigating subsynchronuos oscillations

Applications of synchronous static series compensator (SSSC)

The functions that a SSSC can perform are basically the same as TCSC, however the control range and flexibility of this device is considerably greater. From the standpoint of practical applications related to steady-state flow control or stability improvements, the SSSC clearly has considerably wider control range than the controlled series capacitor of the same MVA rating.

PST Applications

The principal application of a phase shifter is for steady state power flow control. However, if the PST is provided with a fast acting switching device, i.e. thyristor switches, the PST is renamed in to **TCPST**, **Thyristor Controlled Phase Shifting Transformer**, and can be used for Power Oscillation Damping as well [20].

Applications of universal power flow controller (UPFC)

The Unified Power Flow Controller (UPFC) is the most versatile device of the Flexible AC Transmission Systems (FACTS) family using power electronics to control power flow on transmission grids [20]. It can control, individually or in combination, three transmission parameters – voltage, impedance, and angle -, or directly, the active and reactive power flow in the line. The UPFC uses a combination of a shunt controller (STATCOM) and a series controller (SSSC) interconnected through a common DC bus.

7.2.3.3 Technical benefits of FACTS technology

From the above description, it can be summarized that, in general, FACTS technology offers the following basic technological attributes:

- Provide dynamic reactive power support and voltage control.
- Improve system stability.
- Control real and reactive power flow.
- Mitigate potential Sub-Synchronous Resonance problems.

Consequently, the application of FACTS devices can be effectively used to alleviate to a greater or lesser extent most of the principal constraints that limit transfer capacity. Thus, a better utilization of transmission assets can be achieved. It is clear that the decisive objective of applying FACTS technology is indeed to attain a more efficient use of the existing transmission facilities, since this directly reduces the need for construction of new transmission lines, which mitigate environmental and regulatory concerns and improve aesthetics by reducing the need for construction of new transmission facilities.

Tab 7.2, from reference [21], exhibits technical benefits of FACTS in addressing problems of voltage limits, thermal limits, loop flows and short circuit level, whereas *Tab 7.3* shows application of FACTS to cope with dynamic problems like transient stability, oscillation damping post contingency voltage control and voltage stability. For each case the conventional solution is also provided for the sake of comparison. Conventional solutions are normally less expensive than FACTS devices, but restricted in their control performance.

Issue	Problem	Corrective Action	Conventional solution	FACTS device
Voltage limits	Low voltage at heavy load	Supply reactive power	Shunt capacitor, Series capacitor	SVC, TCSC, STATCOM
	High voltage at light load	Remove reactive power supply	Switch EHV line and/or shunt capacitor	SVC, TCSC, STATCOM
		Absorb reactive power	Switch shunt capacitor, shunt reactor	SVC, STATCOM
	High voltage following outage	Absorb reactive power	Add shunt reactor	SVC, STATCOM
		Protect equipment	Add arrestor	SVC
	Low voltage following outage	Supply reactive power	Switch shunt capacitor, reactor, series capacitor	SVC, STATCOM
		Prevent overload	Series reactor, PAR	TCPAR, TCSC
	Low voltage and overload	Supply reactive power and limit overload	Combination of two or more devices	TCSC, UPFC, STATCOM, SVC
Thermal limits	Line or transformer overload	Reduce overload	Add line or transformer	TCSC, UPFC, TCPAR
			Add series reactor	SVC, TCSC
	Tripping of parallel circuit (line)	Limit circuit (line) loading	Add series reactor, capacitor	UPFC, TCSC
Loop flows	Parallel line load sharing	Adjust series reactance	Add series capacitor/reactor	UPFC, TCSC
		Adjust phase angle	Add PAR	TCPAR, UPFC
	Post-fault sharing	Rearrange network or use "Thermal limit" actions	PAR, Series Capacitor/Reactor	TCSC, UPFC, SVC, TCPAR
	Flow direction reversal	Adjust phase angle	PAR	TCPAR, UPFC
Short circuit levels	Excessive breaker fault current	Limit short circuit current	Add series reactor, new circuit breaker	SCCL, UPFC, TCSC
		Change circuit breaker	Add new circuit breaker	
		Rearrange network	Split bus	
Subsynchronous resonance	Potential turbine /generator shaft damage	Mitigate oscillations	series compensation	NGH, TCSC

Legend for Exhibit 3

NGH = Hingorani Damper
PAR = Phase-Angle-Regulator
SCCL = Super-Conducting Current Limiter
SVC = Static Var Compensator
STATCOM = Static Compensator
TCPAR = Thyristor Controlled Phase-Angle Regulator
TCSC = Thyristor Controlled Series Capacitor
TCVL = Thyristor Controlled Voltage Limiter
TSBR = Thyristor Switched Braking Resistor
TSSC = Thyristor Switched Series Capacitor
UPFC = Unified Power Flow Controller

Tab 7.2 - Steady state application of FACTS (Source [21])

Issue	Problem	Corrective Action	Conventional solution	FACTS device
Voltage limits	Low voltage at heavy load	Supply reactive power	Shunt capacitor, Series capacitor	SVC, TCSC, STATCOM
	High voltage at light load	Remove reactive power supply	Switch EHV line and/or shunt capacitor	SVC, TCSC, STATCOM
		Absorb reactive power	Switch shunt capacitor, shunt reactor	SVC, STATCOM
	High voltage following outage	Absorb reactive power	Add shunt reactor	SVC, STATCOM
		Protect equipment	Add arrestor	SVC
	Low voltage following outage	Supply reactive power	Switch shunt capacitor, reactor, series capacitor	SVC, STATCOM
		Prevent overload	Series reactor, PAR	TCPAR, TCSC
	Low voltage and overload	Supply reactive power and limit overload	Combination of two or more devices	TCSC, UPFC, STATCOM, SVC
Thermal limits	Line or transformer overload	Reduce overload	Add line or transformer	TCSC, UPFC, TCPAR
			Add series reactor	SVC, TCSC
	Tripping of parallel circuit (line)	Limit circuit (line) loading	Add series reactor, capacitor	UPFC, TCSC
Loop flows	Parallel line load sharing	Adjust series reactance	Add series capacitor/reactor	UPFC, TCSC
		Adjust phase angle	Add PAR	TCPAR, UPFC
	Post-fault sharing	Rearrange network or use "Thermal limit" actions	PAR, Series Capacitor/Reactor	TCSC, UPFC, SVC, TCPAR
	Flow direction reversal	Adjust phase angle	PAR	TCPAR, UPFC
Short circuit levels	Excessive breaker fault current	Limit short circuit current	Add series reactor, new circuit breaker	SCCL, UPFC, TCSC
		Change circuit breaker	Add new circuit breaker	
		Rearrange network	Split bus	
Subsynchronous resonance	Potential turbine /generator shaft damage	Mitigate oscillations	series compensation	NGH, TCSC

Legend for Exhibit 3

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TSBR = Thyristor Switched Braking Resistor
TSSC = Thyristor Switched Series Capacitor
UPFC = Unified Power Flow Controller

Tab 7.3 - Dynamic applications of FACTS

From the tables above it is observed that different types of FACTS devices can be used for different applications. While the static VAR compensator (SVC) can be used for stability improvements, it is in general not well suited for increasing transfer capacity over a congested link. It is primarily used for reactive compensation of long transmission lines. To control power flow for increasing transfer capability the thyristor controlled series capacitor (TCSC) or the unified power flow control (UPFC) are best suited. The UPFC is the most versatile device and can be used in all areas, but it is also the most expensive [28].

7.2.3.4 Remarks on controls for optimal use of FACTS

It was mentioned that the speed and continuous control capability of FACTS devices make them especially useful for corrective control since they can adapt to new flow situations much faster than any traditional devices like phase shifting transformers.

In a highly meshed network as the TREN, a real increment in the transfer capacity between areas by means of fast controller (corrective control actions) can be accomplished in an appropriate manner only if a coordinated control scheme is implemented. A coordinated control implies that a devices located somewhere in the interconnected network must actuate in a coordinated fashion with other controls to relieve overload or voltage limit constraint at some specific point after a contingency occurs.

Coordinating the operation of multiple FACTS devices on such a time scale will require several other technological advances, including development of a wide-area, real-time information gathering system, on-line system analysis, and a sophisticated hierarchical control system. A remote feedback control scheme using remote feedback measurement can be implemented to determine FACTS controller setpoints so as to achieve the required control action. More sophisticated control approaches could be implemented if high observability of the entire gird is available. This can be achieved by wide are measurement system (WAMS) based on phasor measurement units (PMU) [27].

The controllers that are typically embedded in the FACTS devices are generally of Proportional (P) or Proportional–Integral (PI) type, with special supplementary controllers like damping controllers [29][26]. This embedded control can be referred as primary control. Normally, the setpoints for FACTS devices are kept constant or changed manually on a slow timescale based on market activities or optimal power-flow calculations. Typical FACTS device controllers operate purely based on local criteria with the objective to control a single local quantity such as voltage or power-flow. The performance objectives of the controllers do not consider their effect on the power system as a whole. The aforementioned coordinated control, applied to different FACTS devices, is in fact a secondary control that acts on the setpoints of such devices to avoid overloads and/or voltage limit violations in the post fault system.

Reference [29] proposed a control approach in which several FACTS devices are coordinated by a secondary control loop that generates the optimal setpoints for the primary FACTS controllers. In such a control scheme, to ensure that several FACTS devices work together to optimise power flows across the system as a whole, global information is used by means of wide-area measurements (WAMS). It is based on an optimization model that maximizes an arbitrary defined loadability criterion (i.e.: power transfer to a set of critical load buses), incorporating FACTS devices setpoints as additional control variables. Results of simulation studies on realistic test system spresented in the paper show that an increment of about 10% of the total transfer capacity is achieved through the use of the proposed wide-area control.

Interaction among controllers

A coordinated control of different FACTS devices aimed at improving transfer capacity can be seen as an upper level of a hierarchal control scheme in which the embedded primary control is a local level. In the case of TCSC, if such a scheme is implemented, the different control levels will actuate on the same control variable, namely: the TCSC fundamental frequency equivalent impedance, so that, adverse interactions between them should be expected when not properly coordinated [32] [34].

When a TCSC has a supplementary control loop for transient stability improvement, if prior to a disturbance the setpoint is too close to the limits of the allowable operating range (upper or lower limits on the allowable variation range for the net equivalent reactance), the performance of the stability control can be severely affected. Reference [32] proposed two control strategies to avoid adverse interactions between the different control loops of the same TCSC installation, i.e., power flow and stability control loops. In the case of wide-are control scheme, the higher level or secondary control will act on the power flow control loop, sharing it with the primary control. Hence, control laws must be carefully designed to avoid possible adverse interactions between the different control levels. Specifically on this matter, reference [29] indicates that the objective of the secondary control is sometimes conflicting with the objectives of the local primary control loops. For example, using a power-flow control device to reduce power flow towards a load area can jeopardize system stability, since it would introduce additional (apparent) reactance, which could cause or contribute to voltage instability. When the system is operating close to or possibly even beyond stability limits, it would be wise to relax the two normal control objectives in favour of the objective to improve stability margins. The task of the secondary controllers is thus to detect when stability margins are small and to carry out appropriate setpoint corrections to improve stability margins.

7.2.3.5 Regulatory issues regarding the use of Wide Area Control Scheme

The implementation of a control scheme using FACTS along with wide area measurements would imply the need of introducing specific rules to coordinate the action of the different parties involved (mainly the TSOs), and to assign responsibilities related with the operation of the control scheme and with system safety and security.

The operation of the interconnected network is founded on the principle that each partner is responsible for its own network. In order to give practical application to this basic principle, supranational organization like UCTE introduce a number of rules (i.e.: UCTE Operation Handbook) intended to establish methods of co-operation also in operational situations when factors outside of the control area can reduce the ability of a TSO to operate its system within the security limits. The most relevant rules for the security of interconnected operation are related mainly to the functioning of interconnections. All these co-ordinating rules complement any other existing national commitments for network access (legal and contractual) for the transmission networks when they exist. The control of performances of facilities connected to networks remains under the responsibility of TSOs to the extent of their national commitments [36].

In the case of an integrated control covering devices scattered over a wide region, the situation is more critical, since a control action intended to alleviate a constraint in some control area could imply to “move” controls in other area. For instance, the wide control system could order to change a setpoint of a FACT device in some control area, say area A, to relieve overload in control area B. It is clear that under such a situation power flow pattern and accordingly operating condition of area A is modified, which could somehow affect market players’ interest. Therefore, it is necessary to define the common rules that will govern operation of a control scheme of such nature, defining clearly interactions between the involved TSOs and to what extent a control action from wide area control can interfere with local control objectives.

7.2.4 Software non-conventional technologies to increase power transfer capability

7.2.4.1 Operational solutions

Operational solutions refer to a number of techniques designed to be applied during the operation of power systems. They are aimed at adapting transfer capacities to the different operating condition via on-line applications or real time monitoring systems. We can classified among “operational solutions” the following techniques:

- Dynamic rating
- Changes in Operating Philosophies

7.2.4.2 Dynamic Rating

The operation of most of the individual devices in a power system (such as transmission lines, cables, transformers, and circuit breakers) is limited by each device's thermal characteristics. In short, trying to put too much power through a device will cause it to heat excessively and eventually fail. Because the limits are thermal, their actual values are highly dependent upon each device's heat dissipation, which is related to ambient conditions. The actual flow of power through most power-system devices is already adequately measured. The need is for improved sensors to dynamically determine the limits by directly or indirectly measuring temperature.

e) Application to Overhead Transmission Lines

The dynamic thermal rating of an overhead line may be defined as the steady load that produces the maximum conductor operating temperature, computed on an instantaneous basis for actual loading and weather conditions. In the case of overhead transmission lines, usually the ultimate limiting factor related with thermal effects is the conductor sag. As the load of the lines increases, the temperature of the conductor increases causing the conductor to elongate, thereby reducing the clearance to other conductors and objects. The amount of sag for a given current loading is directly affected by the weather conditions including ambient temperature and wind speed. This characteristic makes it possible to adjust transmission limits dynamically by **measuring** the actual sag on critical segments. This allows increasing the power capacity under most operating conditions, given that traditionally transmission line rating has been overlay conservative, since they are based on worst case weather scenario.

Clearly, the full utilization of dynamic thermal rating in overhead lines for transfer capability improvements is the case of short transmission lines, where the limiting factor is indeed thermal rating. In long transmission lines the element that limits the power handling capability is the maximum phase angle difference across the line that is allowed for security reasons.

Two main systems for dynamic rating of overhead transmission lines can be distinguished: Indirect Measurement of Conductor Sag and Direct Measurement of Conductor Sag.

e.1) Indirect Measurement of Conductor Sag

Within this category there are currently two main hardware technologies available for dynamic line rating: Direct measurement of conductor surface temperature and direct measurement of the tension in the conductor. These are used in combination with real time weather data to develop the conductor physical sag, and the dynamic line rating. Typically, the methods are accurate to approximately 30 cm for the measurement of sag [13]. Commercial systems for dynamic conductor rating based on indirect measurement of conductor sag are available.

- ***Direct measurement of conductor surface temperature:*** The temperature of a conductor is measured by a device directly mounted on the line, such as a power donut. This data is transmitted to a ground-based station by means of an internal radio transmitter, and is then transmitted to a control via spread spectrum radio, or the equivalent. The conductor sag is calculated from the conductor temperature. One drawback is that the temperature is measured only at one point, and this may not represent the average temperature of the line. It is known that the temperature of a conductor can vary significantly along its length, even within a single span [12].

- ***Measure of tension in the conductor:*** This method consists of a load cell placed in series with a conductor at a dead-end structure to measure tension. The tension is used to calculate the ground clearance down line of the dead-end. This requires the use of ruling span assumptions, and is not a direct measurement of ground clearance. Also, because the load cell is placed in series with the conductor, the line must be taken out of service for installation, or live-line installation techniques must be used [12].

e.2) Direct Measure of Conductor Sag

- ***Differential Global Positioning System (DGPS):*** More accurate methods to directly measure the conductor sag has been developed based on the Global Positioning System (GPS). Reference [14] describes a method that uses two GPS measurements with one at a precisely known point: in this way a correction for errors in the remote measurement may be made. The method is known as differential GPS. *Fig. 7.1* shows the proposed basic configuration of a DGPS method to measure overhead transmission conductor sag. Normally only one phase of a circuit would be instrumented in a critical span. From the base station, hard-wire is used to bring position data to power system operators. There is a data processing burden in the implementation of the DGPS: this is needed to attenuate noise and enhance accuracy. This burden is calculable in real time using serial on-line processing. The DGPS measurement of overhead conductor sag has produced accuracy in the range of a 17 cm worst error for 70% of the time [13].

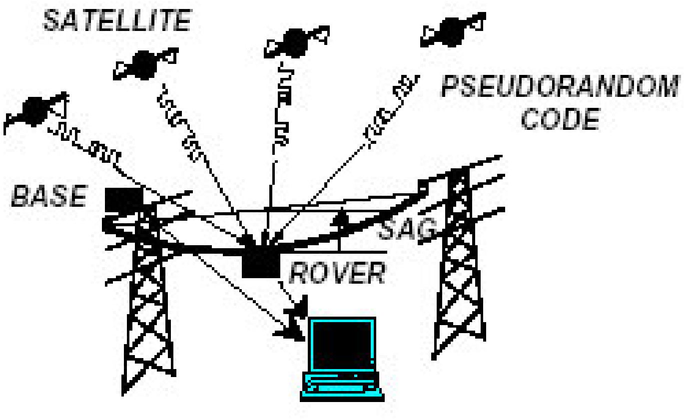


Fig. 7.1 - Basic DGPS configuration for conductor sag measurement [Source [14]]

- ***Video Sagometer:*** Another new technology that may increase the ability to utilize dynamic line ratings is the Video Sagometer. The system uses an imaging system to monitor the location of the conductor, or a target attached to it. The change in vertical position of the conductor in the image is directly related to the change in ground clearance/sag. Recently, EDM International Inc. has developed a commercial product based on this technology, as a result of an EPRI sponsored project developed with the support of the California Energy Commission [12].

The developed sagometer unit is typically mounted on one of the supporting structures for the span being monitored. It is aimed down the span at a target attached to one of the conductors. It uses a "smart" camera technology to capture an image of the target and resolves the x and y coordinates of the target. At user-defined intervals, the target is located by sagometer, its position is determined and then translated into actual ground clearance. This information is immediately transmitted to a datalogger for further processing *[15]. Fig. 7.2* shows the main components of the sagometer developed by EMD International, Inc.

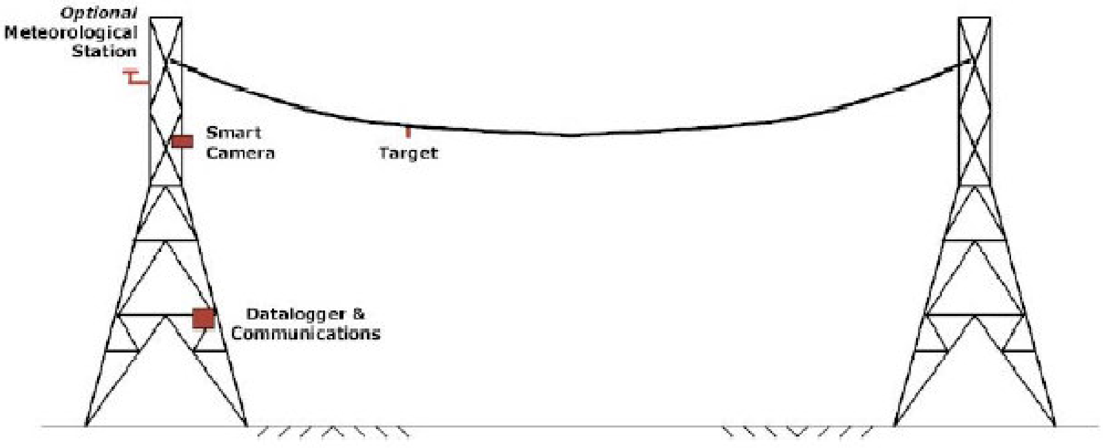


Fig. 7.2 - Components of the sagometer developed by EMD International, Inc. [Source [15]]

There are other methods for dynamic lines rating which do not use measurement of line sag but estimate it by means on real time calculation using weather data as input. In these approaches ambient conditions are measured in real-time, conductor temperature is calculated, and then conductor sag is calculated from conductor temperature. In this case, the ambient conditions are better known in real-time from strategically placed weather stations. However, the ambient conditions at the measuring sites may be different than those experienced by the line as a whole. Also, any errors in sag calculations (such as those for ACSR conductors at elevated temperatures) still exist. Thus these methods can be less accurate than those based on sag measurement [8][12].

f) Application to transformers

Similar to transmission line operation, transformer operation is limited by thermal constraints. However, transformers constraints are localized hot spots on the windings that result in breakdown of insulation. Sophisticated monitoring tools are now commercially available that combine several different temperature and current measurements to dynamically determine temperature hot spots [12].

The Electric Power Research Institute (EPRI), Inc. has developed a dynamic rating program for transformers. This program allows transformers to be operated above their nameplate rating in certain circumstances. Since transformers are one of the most expensive and critical components of an electrical system this dynamic rating allows an increase in power flow at no additional expense but at a risk of loss of life. The program, Power Transformer Loading and Operating Tool (PTLOAD), provides estimates for hot spots and aging parameters to dynamically rate transformers [8].

7.2.4.3 Changes in Operating Philosophies

Two main aspects are directly related with transfer constraints due to adopted system operating philosophies; namely a) uncertainty in calculation of transfer capacity and b) security criteria.

The former is connected with the security margin that is to be adopted to cope with uncertainties on the computation of transfer capacity. If transfer capacity is determined via off line calculations for some reference scenarios, a relatively high security margin must be adopted according to the extent the prevailing operating conditions can differ from the conditions considered in the reference scenarios. It is clear that the greater the uncertainty on the conditions based on which the transfer capacity is evaluated, the larger the security margin that to be considered.

If system limitations can be calculated for actual conditions rather than off line, the system can be operated closer to actually needed limitations. These calculations require on-line data that provide immediate measurements of actual loading, generation, and transmission system status. On-line dynamic security assessment eliminates all conservative assumptions about future operating conditions because actual data on system operating conditions are used. This on-line assessment can increase the actual transfer capability of a power system [5]. A great deal of investigation have been devoted for many years to on-line security assessment matter, being the most challenging problem the fast and accurate enough calculation of system stability [23][25]. The current state of this technology allows for practical implementation in real power systems. Moreover, commercial products for on line security assessment are available [24].

Transfer constraint derived from security criteria are related to the “Preventive” operating procedures adopted to guarantee secure operation under a set of critical but credible contingency. Thus, preventive operating philosophy means operating the system in such a way so as to avoid instabilities or violating any of the technical limits (thermal and voltage limits) as a result of the occurrence of any of the considered contingencies. Operating in preventive fashion ensures that no action is required in the event of a system contingency other than clearing the fault. When contingencies arise, the system is capable of responding without lines overheating, voltage problems, and instability.

A different security philosophy is “Corrective” operation approach, in which a predefined control actions are executed immediately after a contingency occurs, so the system performance is adequate. Corrective operation can be less reliable than preventive operation, but allows greater power transfers during normal operations. Thus, a level of risk is associated with this operation approach.

A number of corrective actions can be designed and implemented depending upon the characteristics of the system being treated and the level of risk accepted. I Reference [4] reports that Baltic States apply special protection systems on a large scale in order to mitigate load problems.

These protection systems automatically limit the load on the lines in case of a logical combination of events and pre- and post-fault conditions: e.g. a protection scheme can be activated after a particular trip if in the post-fault conditions exceed some predefined values. The action can be load shedding, generation tripping or activation of new stand-by resources. The application of these protection schemes allows increasing the transfer limit under normal operating condition.

Changing the power flows over the system to reduce the loading on the critical line after a contingency occurrence increases the power transfers that can be allocated under normal operating conditions. Alteration of power flow pattern in the post contingency operating state must be fast enough so as temporarily overload can be tolerated. Flexible AC Transmission System, (FACTS) devices fulfil this requirements and can be used to mitigate operating constraints. A FACTS device can be used to reduce the flow on the overloaded line and increase the utilization of alternative electricity corridors.

Novel approaches like stability monitoring, coordinated control and wide are protection open new possibilities for further increase benefits of on-line security assessment and corrective control strategy for transfer capacity improvements [27].

7.2.5 Cost analysis of non-conventional measures

7.2.5.1 Upgrading of Existing Installations

Regarding the use of cables it can be say that in general terms underground cables are more expensive than the equivalent overhead lines serving the same flow of electricity. A meaningful comparison of cost requires a full analysis during the lifetime. The ratio of the cost of underground cable to the equivalent overhead line is usually used in various reports and studies as an indicator for comparisons. This ratio is generally increasing with the kV voltage of the cable/overhead line. However, it is possible to introduce significant variance into the calculated cost ratio depending upon which cost elements are included in the analysis. Thus, truly meaningful cost comparison could therefore only be obtained by undertaking a detailed feasibility study on a particular situation where the required technical solution is clearly defined and scoped. Nonetheless a general comparison on the cost ratios can be conducted bases on actual and planned installation, however this imply to be able to gather the key information from the parties involved such a projects. References [10][11] present a number of examples of cost ratios cables/overhead lines. The Report by ICF Consultants to the European Commission [11] present ratios for different countries, which have been obtained from cost estimation provided by a number of transmission companies, electricity regulators and suppliers in Europe

There are no much information available for the newer cables technologies such ad GIL and HTS as most cases refer to experimental pilot projects and tests. Moreover, in the case of HTS cables at 400kV, technology is still in a prototype state and further research and investment will be required to bring down the cost of the wire before the technology can be used economically on a large scale.

Reference [10] present comparative cost for two projects related to the application of cables for HV transmission. The first refers to a recent development of a 420 m long Gas insulated line at the Geneva airport to replace an existing 220 kV line. It was determined that cost of this achievement of

GIL cable system (including the tunnel) was 12 to 15 times more expensive than that of a new overhead line of the same length. It was also cited that in case that the life-cycle costs of a GIL transmission line of several kilometers in length were compared with the cost of an overhead line, it was concluded that the cost-ratios of below the factor 10 can be achieved.

The other study presented is a project in which three alternative technologies of underground cables were examined, namely Fluid oil insulation cables, XLPE cables and GIL, for the substitution of a section of around 7 Km length (situated in the Western region of Rome in urbanised and natural areas) of 380 KV double circuit overhead transmission line (between the 2,500 MW Torre Valdaliga Nord Power Plant and Aurelia Nord substation, just to the west of Rome). The plan was to replace the existing double circuit overhead line with cables along a number of possible routes (including a direct tunnel, along the roadside and across a turnpike/fields). The oil-filled and XLPE cable solutions (4 circuits/12 cables) had a rated power of 1,000 MVA whilst the GIL solution (2 circuits/6 cables) had a rated power of 2,000 MVA.

The total estimated costs for the three alternatives were [10]:

- Oil-filled $44m; 8,4 million €/km
- XLPE $36m; 6,8 million €/km
- GIL $68m; 12,9 million €/km

Compared to about € 0,4 to 0,5 million /km for overhead line, they give ratios of 1:17, 1:14 and 1:26 respectively [10].

XLPE was cheaper than oil-filled due to lower cable costs and HV switchgear. GIL was more expensive due to higher cable costs and accessories, but would have twice the capacity. XLPE was considered to be the cheapest solution and had the lowest maintenance requirement though. Finally the solution based on GIL was adopted, as it deemed important to develop this technology.

It is concluded in reference [10] that these two cases support the view that the use of new innovative technologies cannot reduce significantly the cost-ratio of underground cables in respect to overhead lines. On the other hand, however cable manufacture ABB that the potential of using cables for replacing overhead lines replacement, especially extruded cables, has been increased significantly since XLPE cable systems costs have decreased during the last decade and are likely to fall even further. At the same time, XLPE cable performance has increased enormously [37]. *Fig. 7.3* shows how the cost ratios cable/overhead lines for two voltage levels have been reduced during the last years.

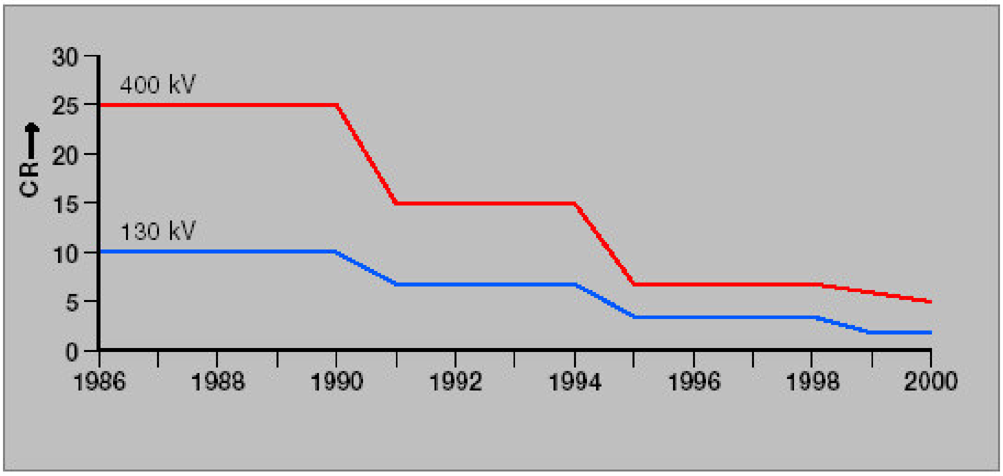


Fig. 7.3 - Comparison of cost ratio (CR) for XLPE cable system and overhead lines transmission lines (Source [37]).

7.2.5.2 FACTS

Gathering meaningful information on typical investment cost of some of the FACTS devices types is not an easy task since the few amount of real installations make them prototype in nature. Moreover, the concept of "typical costs" could not actually be used when referring to investment costs of devices of such kind.

The CIGRE report [16] contains information of cost for FACTS controllers and comparison with their conventional counterparts. Such information has been derived from FACTS installations commissioned prior to 1996, with some information from studies concerning post 1996 projects. The unit cost exposed in the report show in some cases a considerably spread. It is mentioned in that report that the most likely reason for such spread is that the device specific costs have been assembled from the component costs in an incomplete and inconsistent manner, and that another sources of inconsistency in the FACTS controllers cost may arise because of the use of different definitions for controllers ratings. For example, an SVC is assigned a rating possibly the larger but not the sum of the inductive and capacitive outputs. Confusion also seems to arise between the continuous and short-term ratings of FACTS devices.

FCTS technology has evolved greatly since 1996 and a number of FACTS devices have installed worldwide since that time. Thus, costs reported in reference [16] may result no longer valid for cost assessment, nonetheless they could be used for comparison purposes.

We present in this section the updated investment costs (general reference costs) of FACTS devices obtained from different information sources, mainly from manufacturers.

Reference [21] indicates that the investment cost of FACTS devices can be broken down into two categories: a) the device equipment cost and b) the necessary infrastructure cost.

a) Equipment costs: These costs depend not only upon the installation rating but also upon special requirements such as:

- Redundancy of the control and protection
- System main components such as reactors, capacitors or transformers

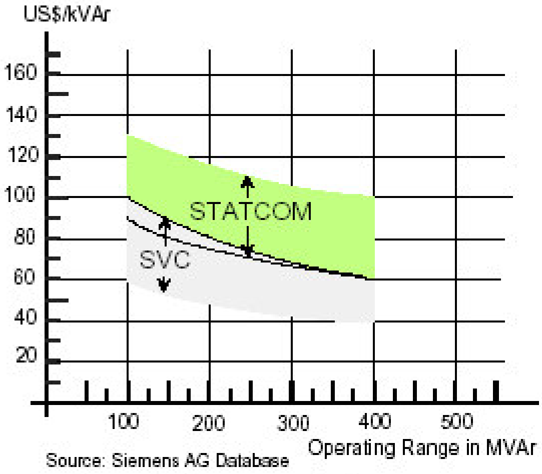
- Seismic conditions
- Ambient conditions (e.g. temperature, pollution level)
- Communication with the Substation Control System or the Regional or National Control Center

b) Infrastructure Costs: Infrastructure costs depend on the substation location, where the FACTS device should be installed. These costs include:

- Land acquisition, if there is insufficient space in the existing substation
- Modifications in the existing substation, e.g. if new HV switchgear is required, construction of a building for the indoor equipment (control, protection, thyristor valves, auxiliaries etc.)
- Yard civil works (grading, drainage, foundations etc.)
- Connection of the existing communication

Fig. 7.4 and *Fig. 7.5* show cost variation range for typical FACTS devices as a function of rating. The lower limit of the cost areas shown in these figures indicates the equipment costs, and the upper limit indicates the total investment costs including the infrastructure costs. For very low ratings, costs can be higher and for very high power ratings costs can be lower than indicated. The total investment costs shown, which are exclusive of taxes and duties, may vary due to the described factors by –10% to +30%.

Reference [22] presents costs of shunt-connected devices such as SVC and STATCOM, which have been provided directly by manufacturers (e.g. ABB, SIEMENS). *Tab* 7.4 shows the equipment costs for SVC and STATCOM; these costs do not include installation costs related to civil works. In the case of the STATCOM these values correspond to a GTO-based controller. IGBT-based STATCOMs for distribution system applications are reported to be about 50% more expensive than equivalent SVCs



Source: Siemens AG Database

Fig. 7.4 - Typical investment cost for SVC and STATCOM (Source [21])

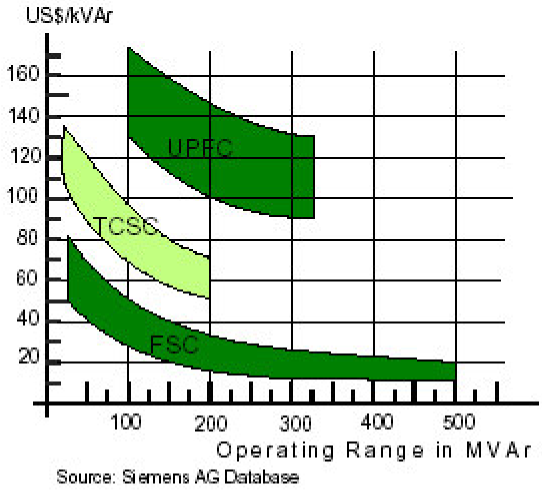


Fig. 7.5 - Typical investment cost for Series devices and UPFC (Source [21]).
Note: FSC: Fixed Series Capacitors; TCSC: Thyristor Controlled Series Capacitors; UPFC: Unified Power Flow Controllers

FACTS Device	Cost (US$/Mvar)
SVC	10,000
STATCOM	50,000-60,000 (for size around 100 Mvar) 35,000-40,000 (for size around 200 Mvar)

Tab 7.4 - FACTS installation costs (Source [22])

Reference [17] reports a study conducted to investigate the potential application and benefits of FACTS devices in the San Diego Gas & Electric (SDG&E). To compare the costs of different alternatives, SDG&E assumed the cost for a **SVC** unit and the series or shunt element of the UPFC to be **$40,000 per MVA.** Such cost assumption was based on information provided by the Electric Power Research Institute (EPRI) and American Electric Power.

Comparing the cost from the three sources considered, namely Ref. [17][22][21], we can be observed that cost are each other consistent, and therefore they can be used for a general cost-benefits analysis. In performing such an assessment for a long period term, it is to be taken into consideration that the cost of individual FACTS devices will be reduced, both through economies of mass production and development of new semiconductor materials. Specifically, ongoing laboratory research involving so called "broad bandgap semiconductors" (such as silicon carbide, diamond, and Group III nitrides) suggests that using these advanced materials in power electronic controllers could eventually reduce the cost of FACTS devices by a factor of two, in part by eliminating the need for coupling transformers [35].

7.2.5.3 Operational solutions

Estimating common general costs of implementing operational solutions to increase transfer capacity is quite a difficult and intricate task, since there is a number of alternatives and combinations of technical solutions that can be to implement to address specific situations.

On the other hand, information on investment and installation costs of systems like dynamic rating (for overhead lines or substations) or wide area measurement and control, is not readily available from open information sources. Besides, equipment manufacturers and suppliers are reluctant to provide estimated general costs, since they can differ to great extent for different application and must be determined on case by case basis. General estimated costs may result meaningfulness even for general comparisons.

Even thought the lack of information make it complex to draw general conclusions about the cost of incorporating this kind of solutions, it is clear that they require a little hardware as compare with alternatives that involve upgrading physical transmission assets like reconductoring lines. So, the cost should be much less, however the increment in transfer capacity gained could be less as well.

The cost-benefit evaluation of incorporating operational solutions should be considered not only the potential increment in transfer capacity but also somehow the broad benefits of this technology (i.e.: high observability of the gird, comprehensive fault analysis, etc.).

7.2.6 Prospective for application of non conventional transmission technologies in the TREN grids

7.2.6.1 General analysis

In this section we illustrate in a general way the possibilities to apply non-standard technologies to increase interconnection transfer capacity, highlighting the main features that make them potential competitive alternatives for transmission system capacity upgrading.

We first present a description of non-standard technologies installation (already implemented or under way projects) in the electric systems of the European countries. The description includes information provided directly by the TSOs in the form of replies to the questionnaire submitted to them. The questionnaire to TSOs addressed the following innovative technologies as well as the reasons on the basis of which TSOs are choosing or are planning to invest in non-conventional solutions:

- undergrounding of EHV cables
- undergrounding of GIL (Gas Insulated Lines)
- Phase Shifter Transformers;
- SVC
- STATCOM
- HVDC thyristor based
- HVDC using VCS (Voltage Source Converter) technology

- Fixed series compensation
- Controllable series compensation
- Other solutions (e.g.: Special Protection Schemes).

The following bar chart depicts in a synthetic way the attitude of the European TSOs to adopt innovative technologies in the power transmission grid.

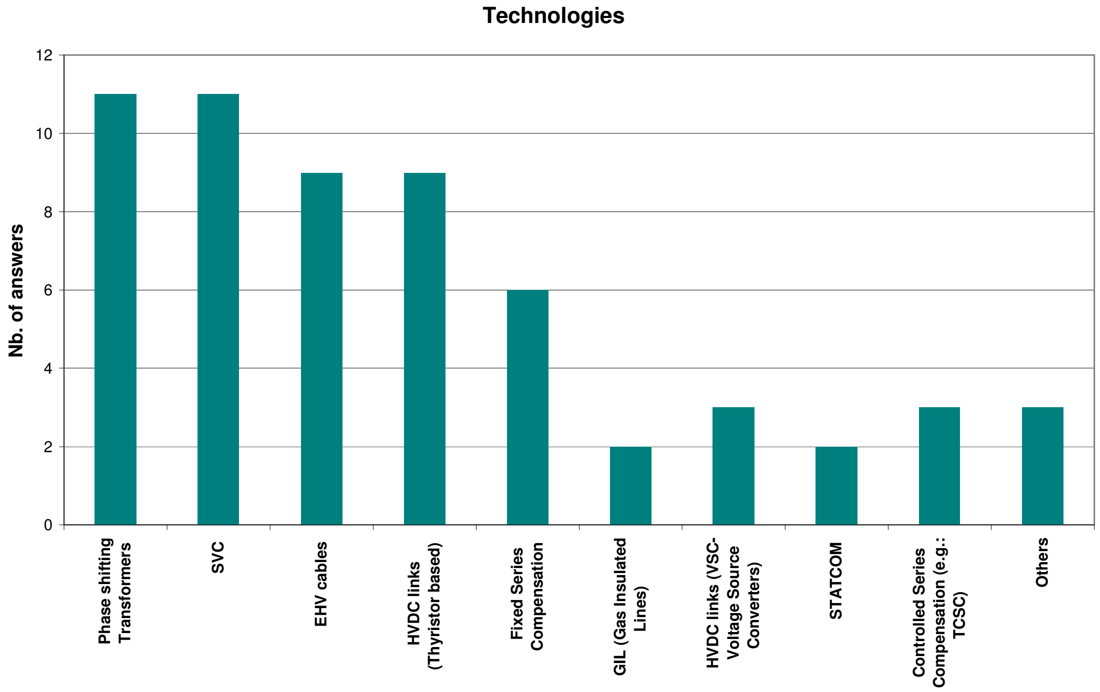


Fig. 7.6 - Attitude of TSOs in investing in non-standard technologies

From the questionnaire replies it can be seen that many utilities in Europe have experience with the undergrounding HV/EHV lines, or have planned to use this technology. It is mainly use in highly populated areas due to the restriction to build overhead transmission lines and also for submarine interconnections. Italy has also experience with more innovative cable technology like Gas Insulated Line (GIL).

It is observed also that the use of SVC is quite common.

There are few systems, however, that use other type of FACTS devices and newer generation of HVDC system. Only GRTN from Italy reported the installation of a HVDC links based on turn-off controlled electronic switches (VSC-Voltage Source Converters).

A dynamic rating system for overhead lines is presently installed in a 400 kV line of the Italy-Switzerland cross-border network. It consists of a system monitoring conductor temperature and predicting the maximum transmission capacity of the overhead line on the basis of the actual and foreseen meteorological conditions [31].

A number of new advance technologies are installed in Sweden's system. Several FACTS devices have been installed to handle dynamic problems and voltage control. Stability problems in the Swedish system is of major concern since it is a longitudinal system with quite long transmission distances between generation and consumption e.g. 800 km long 400 kV lines going from north to the middle of the country.

As for TSCS, an installation in Stöde (Sweden) was commissioned in 1998 in order to obtain the desired level of compensation of a long 400 kV line from the northern part of Sweden down to the central part where the load is located. In its southern part the line is also connected to a large nuclear unit. Without the TCSC there is a risk for SSR (subsynchronous resonance), which would have limited the compensation level of the line below what is desired with respect to system power transfer capability. The installation has a fixed part and a thyristor controlled part. Stöde TCSC uses a local controller using local measured variables such as line currents and capacitor voltage. The controller calculates the thyristor triggering instants and measures the capacitor voltage and thyristor currents in order to operate the TCSC at a stable boost level of 20 %.

There are also several HVDC link thyristor based connecting Sweden with neighboring countries.

The perspective to use FACTS technology in the European system is promising. Particularly, the installation of FACTS devices controlling the active power (Power Flow Controllers: PFC) can provide an interesting alternative to increase transfer capacity in the short term. Moreover PFC can be a temporary alternative to improve the network until the reinforcement measures can be carried out. For rarely changing steady state load-flow control, normally PST transformers are reasonable PFC. However, other series controller devices like SSSC or TCSC can be necessary for fast and frequent power shift requirements.

The need for more flexible grid control is more urgent in case of high penetration of RES, especially wind energy. Great amount of wind energy is at present injected in into the European network and it is foreseen that the supply from wind energy will continue to increase. The use of FACTS devices can be profitable for the dynamic and hardly predictable wind power injections especially from on-shore wind farms.

The installation of PFC can provide an effective alternative to prevent network congestion. Reference [39] presents a qualitative example that exemplifies how the use of power flow controllers can be used to resolve major transmission bottleneck and consequently increase the usable transfer capacity.

Fig. 7.7 depicts a system arrangement (taken from a practical example related to the German grid) prone to congestion problems when a relatively large amount of power is injected. In this example an offshore wind power injection of Ptrans = 2500 MW at a strong node in the northern part of the grid is considered. In the uncontrolled scenario, one transmission line exceeds its maximum permissible loading. The use of one PFC is able to unload the bottleneck in the base case scenario. Therefore, the scenario is feasible with one PFC. The evaluation of contingency cases leads to a demand of two additional PFC to fulfil the (n-1) criterion for all lines and generators in the power system area.

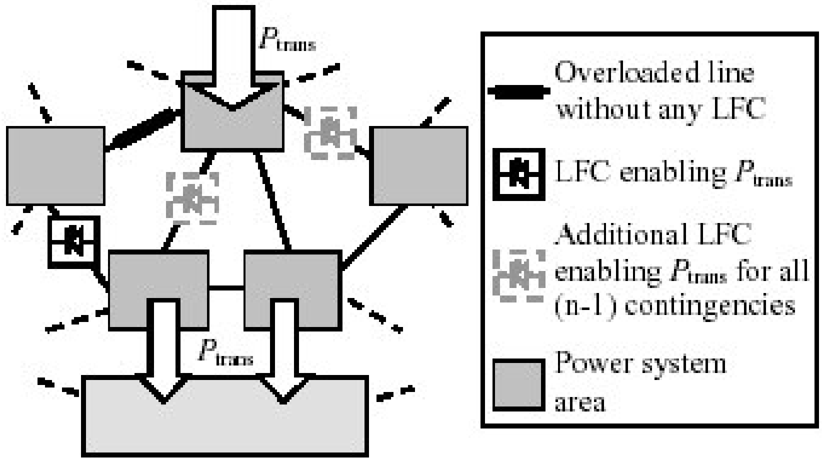


Fig. 7.7 - PFC demands for a transit scenario in the UCTE (Source [39])

Without outages, the transfer capacity in addition to the evaluated transit power Ptrans is about 50 MW. If an additional PFC is used, it can be further increased by about 720 MW. A second additional PFC leads only to an increase about 90 MW. Because a further power shift from the resulting bottleneck is not possible, the maximum capacity utilization of the power system is, therefore, reached for this transit scenario with three PFC and a total transfer capacity of about 3360 MW. Nevertheless, a practical installation of PFC requires an evaluation of various power system utilization scenarios with an assessment of alternative solutions to increase the power transfer capability [39]

The amount of transfer capacity increment that could be achieve by incorporating power flow controllers will depends on the extent power flows shifts can resolve the bottlenecks. Example of this is the phase shifting transformer in Pragnères (interconnection between France and Spain) that prevents the central 220 kV corridor from being overload as a consequence of failure on one of the 400 kV interconnection lines, thus allowing to rise the transfer capacity of the interconnection. In that case however, due to the topological configuration and the usual power flow patterns, the use of a more flexible device (fast control FACTS) would not increase further the usable transmission capacity.

7.2.7 Concluding remarks on non-conventional technologies in the electricity sector

From the above analyses, the following conclusions can be drawn:

- there is a number of alternative technologies that can be implemented to enhance the utilization of existing transmission facilities, thus allowing increasing the transfer capacity to some extent without the need of new construct new transmission lines. The more attractive non-conventional solutions are based on the installations of high voltage extruded polyethylene cables, connections in high voltage direct current and phase shifter transformers
- The extent the cross border capacity can be increased by the use of non-standard technologies is highly dependent upon the specific transmission system and the convenience to use them is to be evaluated in case-by-case basis

- The benefits of using FACTS devices can be drastically improved if they are implemented along with a coordinated control system using wide area measurement technology. Combining FACTS devices with appropriate communication systems makes feasible the adoption of security criteria based on a corrective control mode. FACTS devices may assist in post-fault recovering of the transmission system power flows, allowing the system being operated with higher limits without jeopardizing the level of system security.
- The implementation of inter-area coordinated control would require considerable changes in the operation of power system, which in the case of the TREN would imply appropriate changes or adaptation of present regulation. In other words, to justify migration to a more sophisticated form of power system organization and management implied by the widespread use of FACTS, it would be essential to clearly identify both the economic and technical benefits of this technology [28].
- In Europe, many solutions based on innovative technologies are already installed and several studies are being conducted to assess the feasibility of the use of these technologies in the future.

7.3 Non-conventional technologies in the gas sector

7.3.1 A mature gas industry, but still with technological development

Natural gas transmission is becoming a mature industry; however, there have been a number of significant developments during the last decade and it is possible that also new technologies will be implemented during the coming years.

Due to the international nature of gas transmission a break-through in a new technology will rapidly move around the world and be implemented rapidly.

The most important break-through in new technologies during the last decade has been without doubt the use of offshore pipeline for very deep water (more than 2000 m).

During the next decade, the widespread use of LNG and small-scale LNG and the application of high-pressure pipeline for onshore transmission system might change the way gas transmission systems are operated.

7.3.2 Hardware non-conventional technologies in the gas sector

7.3.2.1 Deep water offshore pipelines – more than 2000 m

The Blue-stream pipelines between Russia and Turkey changed the gas transmission map of Europe. Instead of gas transit through Ukraine, Moldova, Romania and Bulgaria, it now became possible to transport gas directly from Russia to the destination in Turkey.

The water depth for the Blue Stream pipeline is approx. 1800 m, while the Trans-Mediterranean pipeline installed in 1980 between Tunisia and Italy only lays at approx. 700 m.

Deep-water pipelines are as such a well-known technology, which were studied intensively during the 1970´s. However, it was the modification of large trench barges, which made it possible to install the pipeline. Also, new developments in welding technology, non-destructive testing, pipe materials, seabed survey technology contributed to the development.

The difference between deep water and shallow water pipeline can be explained by the determining factor concerning the wall thickness of the pipeline. For onshore pipelines and shallow water pipelines, it is mainly the internal gas pressure, which determines the wall thickness. For deep-water pipelines it is the external hydrostatic pressure, which determines the wall thickness to avoid buckling. As a consequence, the deep-water pipelines will typically have a smaller diameter than shallow water pipeline, as there are practical limits of weight and welding which sets the limit for wall thickness.

The big advantage of deep-water pipelines is that the technology opens for short cuts and more direct delivery of gas between producer and consumer. At present, a number of major projects for delivery of gas for Europe are based on deep-water technology:

- Medgaz (Algeria-Spain)
- Galsi (Algeria – Sardinia – Italy Mainland)

- Libya – Italy

The advantage of these pipelines is that transit through respectively Morocco and Tunisia are avoided. Such transit countries have typically received more than 5 percent of the gas in payment for access to their soil. The losers of the deep-water pipeline technology are therefore the transit countries.

Since the main benefits of deep-water pipelines in some cases are political – to avoid transit countries-, the actual projects to show up during the next decades will depend on the political development in transit countries. One could consider the following projects apart the one mentioned above:

- Algeria-France
- Egypt-Greece
- Georgia-Ukraine with Azerbaijan or Iranian gas
- Georgia- Romania.

7.3.2.2 High pressure pipelines onshore

As shown in previous chapters, there are wide differences in the definition of design pressure for gas transmission systems. Overall the upper pressure limit in Western Europe has been 70 – 80 bar, while the limit in most Eastern European countries have been 55 bar. Some new pipelines have been designed for 100 bar, but are often operated at lower pressure.

Opposite to this, the offshore pipelines are often designed for pressure up to around 200 bar depending on water depth. The reasons for using lower pressure onshore has been a combination of different issues like:

i) safety,
ii) interoperability with other pipelines,
iii) cost,
iv) technical difficulties in construction and most important
v) tradition.

Only in few cases there are legal restrictions, which determine the upper pressure level.

If high-pressure pipelines were used, it would be possible to have much longer distances between compressor stations, and smaller diameter pipelines could be used. Hence, one could consider such high-pressure pipelines as a new layer of transmission system above the existing grids in the same way as high speed trains is a new dimension in railway systems.

The present regulation of the EU gas transmission is based on national transmission system operators with regulated tariffs. There is, hence, no pipe-to-pipe competition, but only modest TSO-to-TSO competition in a few cases. Hereby there is little incentive to optimize the gas transmission and reduce cost.

If one of more major sources for European gas supply dries out, it could be considered to change the rules of the game and allow for pipe-to-pipe competition based on new technology and independent from existing TSO´s.

7.3.2.3 Electrical driven compressor

The increase in capacity of the UK-Belgium interconnector from Belgium to the UK is based on electrically driven compressors. So are the compressors in Norway for gas transmission to the Continent. However, most compressor units on the main transmission grid are based on gas turbine driven compressors.

One main reason for using electrical driven compressors is the local environmental benefits as there are no local emissions as NOx, which in other locations have show to be a major problem. The disadvantage from a system point of view is that the use of electrical driven compressors will create a linkage between the gas and power system, which could eventually result in power black outs spreading into the gas system and, hence, to a wider European energy supply crises.

The use of electrical driven compressors opens for an optimized expansion of the transmission grids, as there will be fewer restrictions in location of compressor stations.

7.3.2.4 Plastic or composite materials for pipelines

Plastic and composite materials for pipelines are being developed for higher pressure. In particular the recent increase in steel prices shows the importance of alternatives.

7.3.2.5 Trench less technology and other new construction methods

Right of way is a major obstacle for construction of new pipelines because the traditional construction methods require a broad working belt of approx. 40 meters. In particular, at crossings of nature reserves, rivers, woods etc. the construction work may cause unacceptable damage.

Trench less technology by using horizontal directional drilling or mini tunnelling are alternatives, which has declined sharply in prices. Whereas such method was originally mostly used for crossing of rivers and other obstacles, it can be adapted to longer sections of pipelines in open terrain at marginally higher cost than normal construction methods.

Automatic welding techniques have been used for offshore pipelines for many years. Such technology can also be adapted to onshore pipelines and hereby secure higher quality and less manpower resources. To this purpose, it's worth noting that certificated welders are difficult to find.

7.3.2.6 LNG technology – small scale LNG and CNG

About LNG technology, significant cost reductions have occurred, which also have made it possible to increase the use of LNG. The historic fall in the capital costs is expected to continue, but at a lower speed than what has been experienced (see *Fig. 7.8*).

The current LNG regasification plants are expected to have a cost of 86 MUSD per bcm yearly, falling to 77 MUSD per bcm yearly in 2010 and further to 65 MUSD per bcm yearly in 2030.1

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[1] IEA, World Energy Investment Outlook 2003

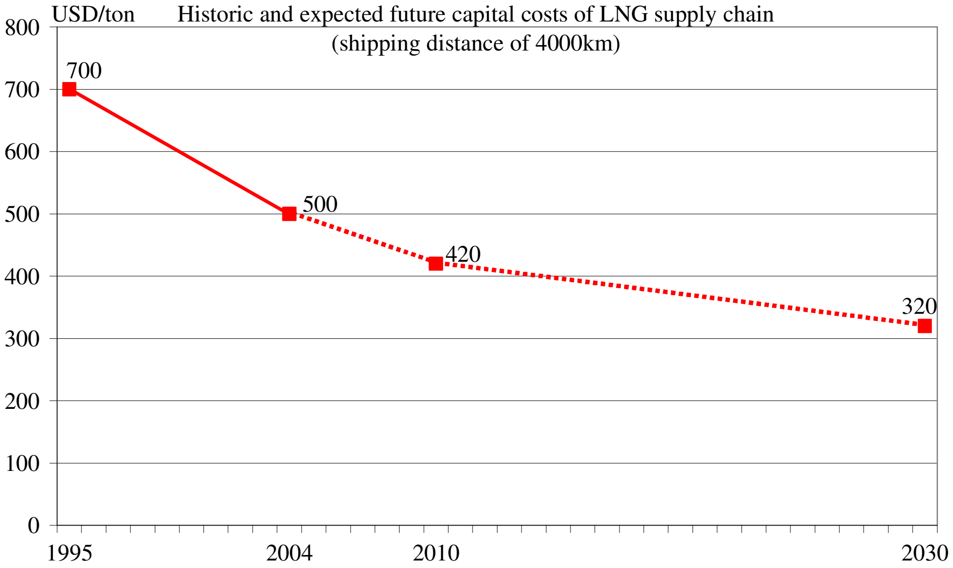

Fig. 7.8 - Historic and expected future capital costs of LNG supply chains (Based on data from IEA)

Generally, pipelines are more competitive for short distances and LNG more competitive for long distances. The figure below tries to summarise which method of transportation is the most economical, and where the breakeven distances are. The figure shows that compared to LNG, offshore gas pipelines are competitive to around 1250 miles (2000 km) while the onshore pipeline (42-inches) is competitive to above 3000 miles (5000 km).

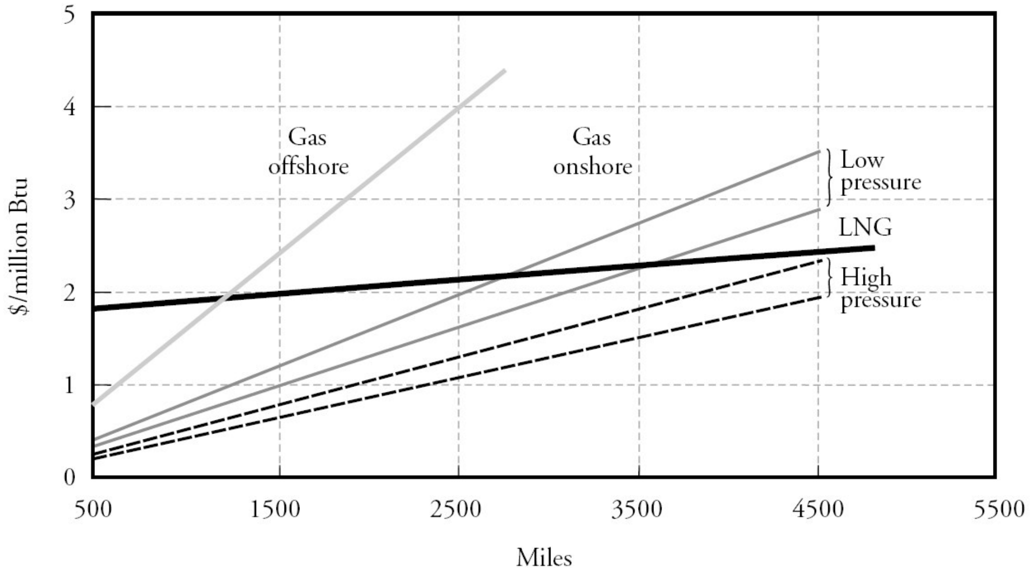

Fig. 7.9 - Pipelines and LNG competition for 30 bcm yearly capacity (from IEA, based on ENI)

High-pressure pipelines are competitive for large quantities of around 30 bcm yearly. The figure shows that for the large gas quantity high-pressure pipelines are competitive beyond 4500 miles (over 7000 km). When the gas capacity is reduced to 10 bcm yearly, LNG is more competitive compared to high pressure pipelines for long distances.

Small scale LNG is being developed for transportation of gas to islands and other markets that cannot be easily connected to the gas transmission pipelines. Also, smaller volumes of LNG can be transported on lorries or rail cars.

Compressed natural gas (CNG or PNG) can be used for transmission of smaller volumes of natural gas. New ships are being developed that can also be used to loading gas from small gas fields, which can not be economically connected to the pipeline systems.

7.3.3 Software non-conventional technologies in the gas sector

7.3.3.1 New meters and satellite communications

The liberalization of the EU gas market requires collection of large amounts of reliable data on gas transmission. A number of new meters for metering of volumes and gas quality have and will be installed.

Communication over long distances as part of the SCADA system is changing from ordinary telephone systems and radio links to advanced IP systems and satellite communications.

7.3.3.2 Satellite imaging and other IT based design methods

Design of pipelines can be eased by use of satellite three-dimensional charts showing topography, environmental constraints etc. Hereby, it is possible to optimize the design work and shorten the time for implementation of new projects. Such technology is in particular important for new import pipelines in difficult terrain as the Nabucco pipeline and the Trans-Saharan pipeline.

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