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HVDC Transmission System Using 6-Pulse IGBT Converter

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Abstract: - High Voltage Direct Current (HVDC) technology has characteristics which makes it especially attractive in certain transmission applications. The number of HVDC projects committed or under consideration globally has increased in recent years reflecting a renewed interest in this field proven technology. New HVDC converter designs and improvements in conventional HVDC design have contributed to this trend. This paper proposes a simple 6-Pulse HVDC transmission system which can cater to the need of agricultural applications in India. It also provides an overview of the rationale for selection of HVDC technology and describes some of the latest technical developments.

Keywords: - HVDC, Six-pulse rectifiers, SCR, IGBT, GTO, IGCT.

I. INTRODUCTION

High Voltage Direct Current (HVDC) technology has characteristics which makes it especially attractive for certain transmission applications. HVDC transmission is widely recognized as being advantageous for long-distance, bulk power delivery, asynchronous interconnections and long submarine cable crossings. The number of HVDC projects committed or under consideration globally has increased in recent years reflecting a renewed interest in this mature technology. New converter designs have broadened the potential range of HVDC transmission to include applications for underground, offshore, economic replacement of reliability-must-run generation, and voltage stabilization. Developments include higher transmission voltages up to ± 800 kV, capacitor-commutated converters (CCC) for weak system applications and voltage-sourced converters (VSC) with dynamic reactive power control. This broader technology range has increased the potential HVDC applications and contributed to the recent growth of HVDC transmission.

The rationale behind selection of HVDC for transmission is it reduces loss of power. Power does not rely only on voltage, but is equal of voltage times current.

$$P=VI\ldots\ldots\ldots\ldots\ldots. (1)$$

For a given power a low voltage requires a higher current and a higher voltage requires a lower current. However, since metal conducting wires have a certain resistance, some power is wasted, and dissipated as heat. The power losses in a conductor on the other hand are proportional to the square of current and resistance of conductor.

$$P=I^2R\ldots\ldots\ldots\ldots\ldots. (2)$$

Now power is proportional to voltage also, so it can be concluded that higher voltage implies decrease in current level which in turn results in lower power loss. Although power loss can also be reduced by decreasing resistance i.e. either by increasing diameter of conductor or using material with lower resistivity but it in turn results in higher economical costs.

High voltage transmission is used to reduce lost of power, but it cannot be used for lightning system or for supplying to motors. High voltage level has to be adjusted in accordance with the receivers. In AC transformers are used for decreasing or increasing voltage to required level. In DC such possibility does not exist. In case of DC manipulation is possible but in a more complicated way. To change level of voltage electronic devices such as mercury arc valves, semiconductors devices, thyristors, insulated-gate bipolar transistors (IGBTs), high power capable MOSFETs (power metal–oxide–semiconductor field-effect transistors) and gate turn-off thyristors (GTOs).

In AC voltage conversion is simple, and demand little maintenance. Further three-phase generator is superior to DC generator in many aspects. These reasons causes that AC technology is today common in production, transmission and distribution of electrical energy. However alternative current transmission has also drawback which can be compensated in

DC links. So the main reasons why DC technology is chosen instead of AC can be summarized as under:

- Inductive and capacitive elements of lines put limits to the transmission capacity and transmission distance.
- Transmission between two points of different current frequency is not possible.

Therefore electrical engineers have developed a strong research orientation towards developing application of DC technology which doesn't have such limitation.

II. HISTORY

The first transmission of direct current was in 1882, it was 50 km long (distance between Miesbach-Munichbut) and voltage level was only 2 kV. DC transmission was developed by Rene Thury. This scientist created a method, which based on series-connected generator and was put into practice by 1889 in Italy. System based on Thury's idea transmitted 630 kW at 14 kV over distance 120 km. [2] [3]

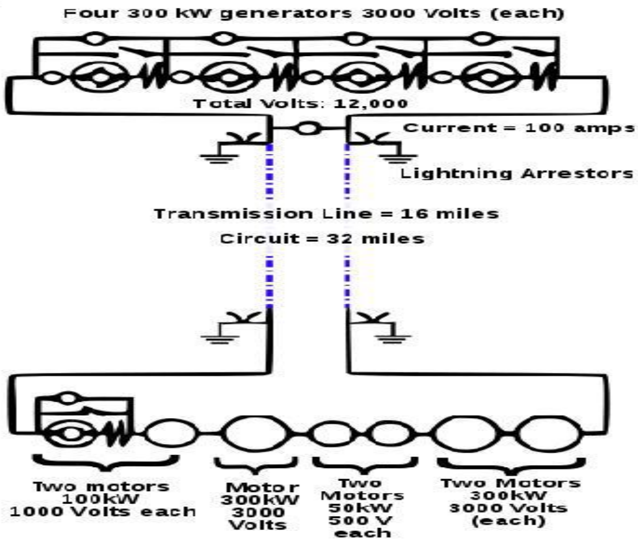

Fig.1. Scheme of Thury's installation from 1889 [1]

The next important project was line Moutiers-Lyon in France which was used from about 1906 until 1936. Moutiers power plant had eight generators which were connected in series. The Moutiers-Lyon system transmitted 8,600 kW of hydroelectric power to a distance of 200 km, including 10 km of underground cable and voltage between two poles was 150 kV. Fifteen Thury's systems were in operation by 1913 [4].Other Thury's systems operating at up to 100 kV DC operated into the 1930s, but the rotating machinery required high maintenance and had high energy loss. So Thury's system was little commercial success.

The next era, was attempts with mercury arc valve. First proposed in 1914 [5], and put into use in 1932 by General Electric, which tested mercury-vapor valves in 12 kV DC line. It could convert current from frequency of 40 Hz to 60 Hz. This installation worked in Mechanicville, New York. In 1941, a 60.0 MW, ±200 kV, 115 km buried cable link was designed for the city of Berlin using mercury arc valves (Elbe-Project), but owing to the collapse of the German government in 1945 the project was never completed. Mercury arc valves were common in systems designed up to 1972.

The replacement of mercury arc valves by solid-state devices in most cases thyristor valves was the next major development. Development of thyristor valves for HVDC had begun in the late 1960's. HVDC using thyristor valves is also known as line-commutated converter (LCC) HVDC [6].

Line-commutated converters have some limitations in their use for HVDC systems, resulting from the inability of the thyristor to turn off current and its need for a period of reverse voltage after turn-off (turn-off time). An attempt to address these limitations is the *Capacitor-Commutated Converter (CCC)* which has been used in a small number of HVDC systems. However, CCC has remained only a niche application because of the advent of voltage-source converters (VSC) which completely eliminate the need for an extinction time [7].

Widely used in motor drives since the 1980s, Voltage-source converters started to appear in HVDC in 1997 with the experimental Hellsjon–Grangesberg project in Sweden. By the end of 2011, this technology had captured a significant proportion of the HVDC market.The development of higher rated insulated gate bipolar transistors (IGBT), gate turn-off thyristors (GTO) and integrated gate-commutated thyristors (IGCTs), has made smaller HVDC systems economical.

With time, voltage-source converter systems will probably replace all installed simple thyristor-based systems, including the highest DC power transmission applications [7].

III. HVDC APPLICATIONS

HVDC transmission applications can be broken down into different basic categories. Although the rationale for selection of HVDC is often economic, there may be other reasons for its selection. HVDC may be the only feasible way to interconnect two asynchronous networks, reduce fault currents, utilize long cable circuits, bypass network congestion, share utility rights-of-way without degradation of reliability and to mitigate environmental concerns. In all of these applications, HVDC nicely complements the AC transmission system.

A. Long Distance Bulk Power Transmission

HVDC transmission systems often provide a more economical alternative to ac transmission for long-distance, bulk-power delivery from remote resources such as hydroelectric developments, or large scale wind farms. Higher power transfers are possible over longer distances using fewer lines with HVDC transmission than with ac transmission. Typical HVDC lines utilize a bipolar configuration with two independent poles.

The controllability of HVDC links offers firm transmission capacity without limitation due to network congestion or loop flow on parallel paths. Therefore, the utilization of HVDC links is usually higher than that for EHV ac transmission lowering the transmission cost per MWh. This controllability can also be very beneficial for the parallel transmission as well since, by eliminating loop flow, it frees up this transmission capacity for its intended purpose of serving intermediate load and providing an outlet for local generation.

B. Cable Transmission

Unlike the case for ac cables, there is no physical restriction limiting the distance or power level for HVDC underground or submarine cables. Underground cables can be used on shared ROW with other utilities without impacting reliability concerns over use of common corridors. For underground or submarine cable systems there is considerable savings in installed cable costs and cost of losses when using HVDC transmission.

The lower cost cable installations made possible by the extruded HVDC cables and prefabricated joints makes long distance underground transmission economically feasible for use in areas with rights-of-way constraints or subject to permitting difficulties or delays with overhead lines.

C. Asynchronous Ties

With HVDC transmission systems, interconnections can be made between asynchronous networks for more economic or reliable system operation. The asynchronous interconnection allows interconnections of mutual benefit while providing a buffer between the two systems. Often these interconnections use back-to-back converters with no transmission line. Asynchronous HVDC links act as an effective “firewall” against propagation of cascading outages in one network from passing to another network.

D. Offshore Transmission

Self-commutation, dynamic voltage control and black-start capability allow compact VSC HVDC transmission to serve isolated loads on islands or offshore production platforms over long distance submarine cables. This capability can eliminate the need for running expensive local generation or provide an outlet for offshore generation such as that from wind. The VSC converters can operate at variable frequency to more efficiently drive large compressor or pumping loads using high voltage motors.

E. Power Delivery to Large Urban Areas

Power supply for large cities depends on local generation and power import capability. Local generation is often older and less efficient than newer units located remotely. Often, however, the older, less-efficient units located near the city enter must be dispatched out-of-merit because they must be run for voltage support or reliability due to inadequate transmission. Air quality regulations may limit the availability of these units. New transmission into large cities is difficult to site due to right of way limitations and land use constraints.

Compact VSC-based underground transmission circuits can be placed on existing dual-use rights-of-way to bring in power as well as to provide voltage support allowing a more economical power supply without compromising reliability. Furthermore, the dynamic voltage support offered by the VSC can often increase the capability of the adjacent ac transmission.

IV. CORE HVDC TECHNOLOGIES

Interconnecting HVDC within an AC system requires conversion from AC to DC and inversion from DC to AC. We refer to the circuits which provide conversion from AC to DC as rectifiers and the circuits which provide conversion from DC to AC as inverters. The term converter is used to generically refer to both rectifiers and inverters. Converter technologies are based on use of switching devices collectively referred to in the HVDC community as valves. Valves may be non-controlled or controlled. A controlled valve comprising usually of thyristors has a similar characteristic to non-controlled valves except that it requires a gate pulse to turn on. Two basic converter technologies are used in modern HVDC transmission systems. These are conventional line- commutated, current source converters (CSC) and self-commutated, voltage-sourced converters (VSC) [8]-[11].

A. Line-Commutated, Current-Sourced Converter

Conventional HVDC transmission employs line-commutated, current-source converters (CSC) with thyristor valves. Such converters require a synchronous voltage source in order to operate. The basic building block used for HVDC conversion is the three-phase, full-wave bridge referred to as a 6-pulse or Graetz bridge. The term 6-pulse is due to six commutations or switching operations per period resulting in a characteristic harmonic ripple of 6 times the fundamental frequency in the dc output voltage. Each 6-pulse bridge is comprised of 6 controlled switching elements or thyristor valves. Each valve is comprised of a suitable number of series-connected thyristors to achieve the desired dc voltage rating. Line-commutated current source converters can only operate with the alternating current lagging the voltage so the conversion process demands reactive power.

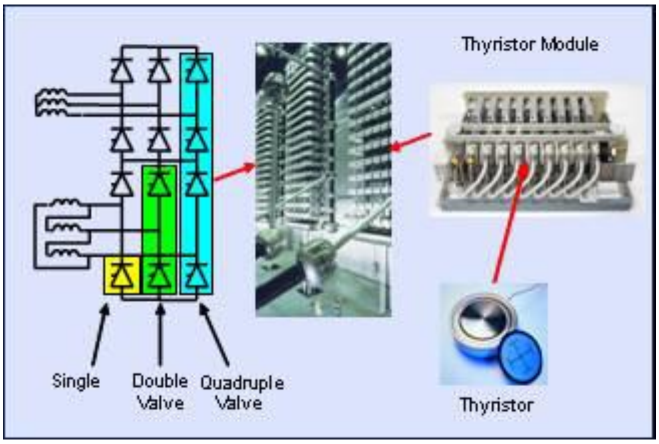

Fig. 2. HVDC thyristor valve arrangement

B. Self-Commutated Voltage-Sourced Converter

HVDC transmission with VSC converters can be beneficial to overall system performance. VSC converter technology can rapidly control both active and reactive power independently of one another. Reactive power can also be controlled at each terminal independent of the dc transmission voltage level. This control capability gives total flexibility to place converters anywhere in the AC network since there is no restriction on minimum network short circuit capacity. Self commutation with VSC even permits black start, i.e., the converter can be used to synthesize a balanced set of three phase voltages like a virtual synchronous generator. The dynamic support of the ac voltage at each converter terminal improves the voltage stability and can increase the transfer capability of the sending and receiving end AC systems thereby leveraging the transfer capability of the DC link.

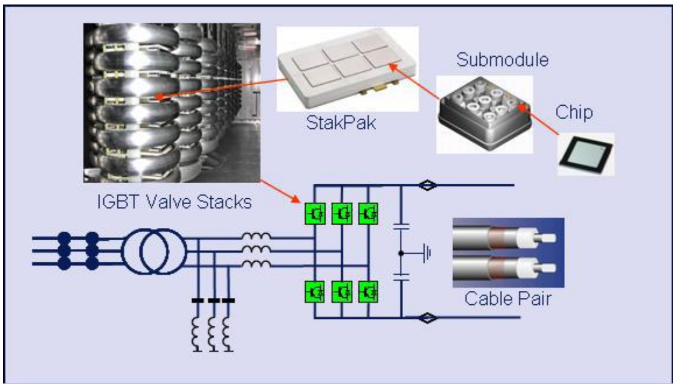

Fig. 3. HVDC IGBT valve arrangement

V. HVDC CONTROL & OPERATING PRINCIPLES

A. Conventional HVDC

For conventional HVDC transmission one terminal sets the dc voltage level while the other terminal(s) regulates the (its) dc current by controlling its output voltage relative to that maintained by the voltage setting terminal. Since the dc line resistance is low, large changes in current and hence power can be made with relatively small changes in firing angle, alpha. Two independent methods exist for controlling the converter dc output voltage. These are 1) by changing the ratio between the direct voltage and the ac voltage by varying the delay angle or 2) by changing the converter ac voltage via load tap changers (LTC) on the converter transformer. The former method is rapid whereas the latter method is slow due to the limited speed of response of the LTC.

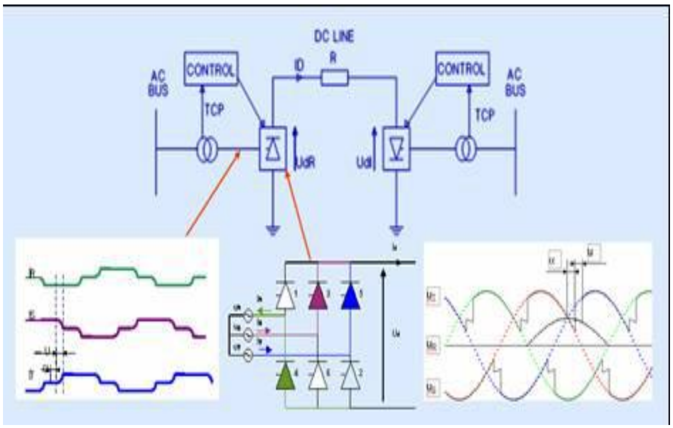

Fig. 4. Control of conventional HVDC transmission

B. VSC-Based HVDC

Power can be controlled by changing the phase angle of the converter ac voltage with respect to the filter bus voltage, whereas the reactive power can be controlled by changing the magnitude of the fundamental component of the converter ac voltage with respect to the filter bus voltage. By controlling these two aspects of the converter voltage, operation in all four quadrants is possible. This means that the converter can be operated in the middle of its reactive power range near unity power factor to maintain dynamic reactive power reserve for contingency voltage support similar to a static var compensator. It also means that the real power transfer can be changed rapidly without altering the reactive power exchange with the ac network or waiting for switching of shunt compensation.

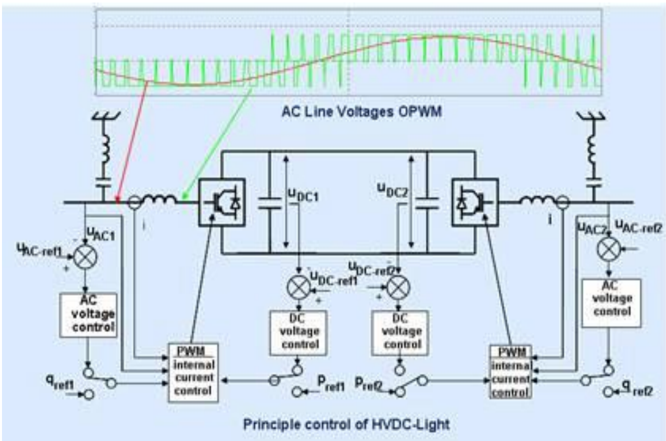

Fig. 5. Control of VSC-based HVDC transmission

VI. PROPOSED 6-PULSE HVDC TRANSMISSION SYSTEM MODEL

In the proposed model a 500 MW (250 kV, 2 kA) DC interconnection is used to transmit power from a 315 kV, 5000 MVA AC network. The network is simulated by a LLR damped equivalent (impedance angle of 80 degrees at 60 Hz and 3rd harmonic). The converter transformer and the rectifier are modeled respectively with the Universal Transformer and Universal Bridge blocks The converter used is a 6-pulse rectifier. It is connected to a 300 km distributed parameter line through a 0.5 H smoothing reactor LsR. The inverter is simulated by a simple DC voltage source in series with a diode (to force unidirectional conduction) and smoothing reactor LsI. The reactive power required by the converter is provided by a set of filters (C bank plus 5th, 7th and high pass filters; total 320 Mvar). The filter toplogy is depicted in Fig.6. The usage of a circuit breaker allows to application of DC line fault on the rectifier side.

The control system uses two main blocks: the Synchronized 6-pulse generator and a PI Current Regulator. Voltages sent to the synchronization system are filtered by 2nd order band pass filters. The whole control system is discretized (Sampling interval = 1/360/64 = 43.4 µsec). The DC line current at the output of the rectifier is compared with a reference. The PI regulator tries to keep the error at zero and outputs the alpha firing angle required by the synchronizing unit to maintain minimum error. Inputs of the current regulator allow to bypass the regulator action and to impose the alpha firing angle.

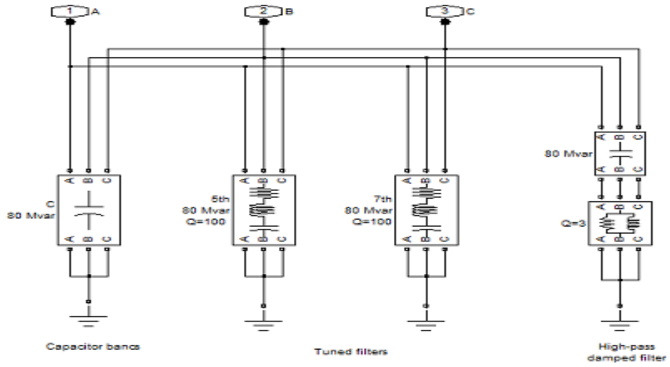

Fig. 6. AC filter topology (320 Mvar) HVDC

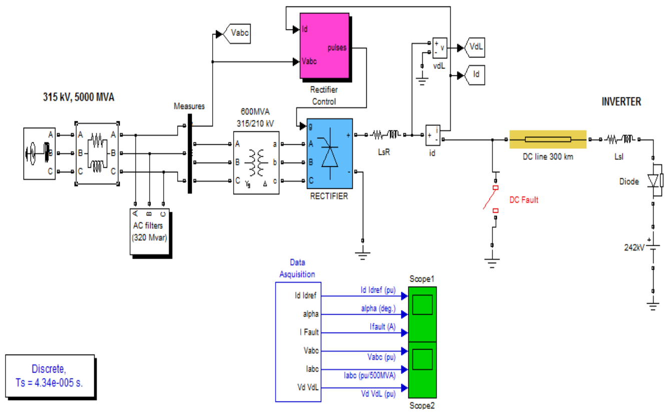

Fig. 7. Proposed model of HVDC Transmission system

VII. SIMULATION RESULTS AND DISCUSSION

The proposed model was simulated using MATLAB version 7.9.0.2601 (R2009b). The system is programmed to start and reach a steady state. Then, a step is applied on the reference current to observe the dynamic response of the regulator. Finally a DC fault is applied on the line. The simulation results are shown in Fig.7.In the figure Trace 1 shows the reference current I_{dref} (magenta) and the variation in measured current I_d (yellow) in per units (pu). Trace 2 shows the alpha firing angle in degree (deg.) required to reach the reference current. Finally Trace 3 depicts fault current I_{fault} variation in amperes (A).

For our simulation reference current I_{dref} is initially set to 0.5 pu (1kA).On starting simulation the direct current I_d starts from zero and reaches a steady-state in 0.1 s as depicted in trace 1. Trace 2 shows the alpha firing angle required to obtain 0.5 pu of reference current is 30 degrees.

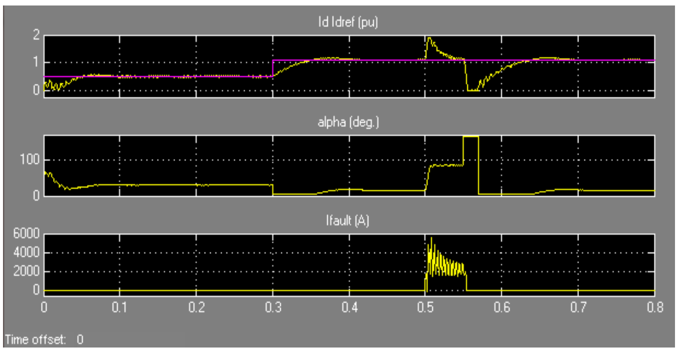

Fig. 8. Simulation result of proposed model

Further at t = 0.3 s, the reference current was increased from 0.5 pu (1 kA) to the nominal current 1pu (2 kA). The current regulator responds in approximately 0.1 s and tries to reach new steady state value. In the mean time the alpha angle decreases from 30 degrees to 15 degrees. So we can conclude that the model has a very low response time and the controller starts transition as soon as the reference current is altered.

Now to depict fault management of the model at t = 0.5 s, a DC fault is applied on the line. The fault current I_{fault} in trace 3 increases to 5 kA and the I_d current increases to 2 pu (4 kA) in 10 ms. Then, the fast regulator action lowers the current back to its reference value of 1 pu. At approximately t = 0.55 s, the alpha angle is forced by the protection to reach 165 degrees thereby making the Forced_alpha input of the current regulator high. The rectifier thus passes in inverter mode and sends the energy stored in the line back to the 345 kV network. As a result, the arc current producing the fault rapidly decreases. The fault is cleared at t = 0.555 s when the fault current zero crossing is reached. At t = 0.57 s, the regulator is released from inverter mode, it goes back into rectifier mode and it starts to regulate the DC current again. The steady-state 1 pu current is finally reached at t = 0.75 s.

The harmonics present on the AC system are (6k±1). Thus the AC harmonic filters are tuned to the 5th, 7th, 11th, and 13th harmonics to reduce the harmonic content in the voltages and currents in the AC network to acceptable levels. Higher harmonics thus would not penetrate very far into the system. The harmonics are mainly present in the AC current as the AC voltage is heavily dependent on the system itself. The Harmonics present on the DC side are mainly on output voltage. These are in multiples of 6 as the waveform repeats itself 6 times. The DC is smoothed by the smoothing reactors.

VIII. ADVANTAGES AND DRAWBACKS

The advantages HVDC transmissions have can be enumerated as:

- More power can be transmitted per conductor per circuit.
- Use of Ground Return Possible.
- Smaller Tower Size.
- Higher Capacity available for cables.
- No skin effect.
- Less corona and radio interference.
- No Stability Problem.
- Asynchronous interconnection possible.
- Lower short circuit fault levels.

The inherent problems associated with HVDC are summarized hereunder:

- Expensive convertors.
- Reactive power requirement.
- Generation of harmonics.
- Difficulty of circuit breaking.
- Difficulty of voltage transformation.
- Difficulty of high power generation.

IX. ECONOMIC COMPARISIONS

The HVDC system has a lower line cost per unit length as compared to an equally reliable AC system due to the lesser number of conductors and smaller tower size. However, the DC system needs two expensive convertor stations which may cost around two to three times the corresponding AC transformer stations. Thus HVDC transmission is not generally economical for short distances, unless other factors dictate otherwise. Economic considerations call for a certain minimum transmission distance (break-even distance) before HVDC can be considered competitive purely on cost. Estimates for the break even distance of overhead lines are around 500 km with a wide variation about this value depending on the magnitude of power transfer and the range of costs of lines and equipment. The breakeven distances are reducing with the progress made in the development of converting devices.

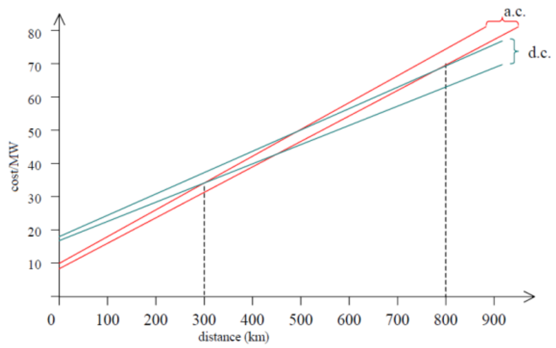

Fig. 9. Break-even distance for DC transmission

Figure 9 shows the comparative costs of DC and AC links with distance, assuming a cost variation of ± 5% for the AC. link and a variation of ± 10% for the DC link. For cables, the break-even distance is much smaller than for overhead lines and is of the order of 25 km for submarine cables and 50 km for underground cables.

X. CONCLUSION

Today HVDC is very important issue in transmission energy. In near future this technology probably will be developed very intensively. Influence on future may have intensive spread of renewable energy source, also wind farm which need undersea connections. Also problem of cascade blackout can be reduced by application of HVDC. To implement the grid that is required for the future, collaborative planning is needed using a long term, system perspective.

In order to capture the full scale of benefits that high capacity technologies such as 765-kV and HVDC provide, the system must be examined on an interregional scale that matches the reach of those benefits. Some keys to success include: adoption of interconnection wide planning criteria and assumptions focusing on broad system solutions.

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