Power transmission capacity upgrade of overhead lines

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Abstract. Electric power consumption, has been increasing uninterruptedly, being this increase specially accelerated in the last years. New power generators are been built, the installed power increases each year, thus it is necessary a way to transmit the bulk energy. Nowadays electric lines are saturated, they are reaching critical values of ampacity and sag. Therefore building new lines is necessary to provide the ever increasing consumption.

The difficulty to find corridors to construct new overhead lines is increasing in industrialised countries and in many cases it is simply impossible. It is not easy to obtain the rights of way for new transmission lines. The construction of new overhead electric lines is increasing difficulty, thus there is a need to look at alternatives that increases the power transfer capacity of the existing right of ways. This circumstance is forcing the use of the existing lines, which represents a cheaper solution than making an underground transmission.

Key words

Power upgrading, constraints, overhead line.

1. Introduction

Due to the problems associated with constructing new overhead lines, it is important to examine the possible options for increasing the transmission capacity on present sites and making maximum use of existing transmission systems through upgrades. When feasible, upgrades are an attractive alternative, because the costs and leadtimes are less than those for constructing new lines.

The constraints limit a system's ability to transmit power and lower the use rates of the existing transmission network. The paper describes the constraints on a system's capacity to transmit power from one area to another.

The paper also discusses the upgrade possibilities to increase the transmission capacity of the existing transmission and distribution lines so that additional power can be transmitted reliably from one area of a system to another, or from one entire system to another. Some of the potential remedies for these constraints through upgrades are presented along with a comparison of the power increase that can be achieved on an existing network and of the cost to upgrade compared to the costs for new transmission lines.

2. Power transmission capacity of the lines

There are different constraints that limit the power transmission capacity of the system. The power transmission capacity in permanent regime is defined by:

A. Switchgear characteristics

Certain lines have load capacity limited by some of the switchgear elements associated to them. The element with the smaller rated current in any end of the line is identified.

B. Environmental specifications

The determination of load capacity in high voltage cables must take into account on the one hand the thermal conditions of the conductors work, such as temperature, wind speed, and wind direction, and on the other hand the electric conditions of operation. This is due to respect the minimum safety distances and to maintain the voltage and the network stability within suitable limits.

C. Voltage drops

In the network, lines transmit a great amount of energy from the generating ends to the consuming ones. In these cases, if the receiving zones do not have compensating reactive elements, the voltage can drop below the limit fixed by quality criteria.

In such occasions, it is advisable to limit the transmission of these lines to prevent excessively low voltages in the receiving end as well as to prevent a possible voltage collapse of the transformer regulators because of a performance over their possibilities.

D. System stability

Cases of long interconnection lines between zones with no reactive problems are considered, the voltages maintain in an acceptable limit but there can be situations in which strong interchanges of power demand an excessive angular phase angle between the positions of the generator rotors of each area. It is advisable to limit the transmission of these lines with object to avoid the loss of stability and electric separation between both zones.

Studies of rated capacities of the different elements that take part in the transmission and distribution have been made, with the purpose of indicating the necessities of substitution of those with insufficient capacity and to be able to establish a plan of renovation of equipment

These constraints in the operation of the lines are detected, based on the following information: maximum current foreseeable to transmit by the lines, maximum current of transmission by thermal limit of the lines and maximum permissible current, due to the switchgear of the lines.

3. Transmission capacity upgrading by increasing voltage

Voltage is a measure of the electromotive force necessary to maintain a flow of electricity on a transmission line. Voltage fluctuations can occur due to variations in electricity demand and to failures on transmission or distribution lines. Constraints on the maximum voltage levels are set by the design of the transmission line. If the maximum is exceeded, short circuits, radio interference, and noise may occur, transformers and other equipment at the substations and/or customer facilities may be damaged or destroyed. Minimum voltage constraints also exist based on the power requirements of the customers. Low voltages cause inadequate operation of customer's equipment and may damage motors.

Voltage on a transmission line tends to "drop" from the sending end to the receiving end. The voltage drop along the AC line is almost directly proportional to reactive power flows and line reactance. The line reactance increases with the length of the line. Capacitors and inductive reactors are installed, as needed, on lines to, partially, control the amount of voltage drop. This is important because voltage levels and current levels determine the power that can be delivered to the customers.

During the last years there have been many efforts to make appropriate modifications to existing overhead lines and to eliminate the old AC transmission lines and substitute them with new compact AC lines.

Both these solutions lead to an increase in the transmitted power by the overhead line increasing the rated voltage. This is possible by utilizing the experience acquired for HVAC lines and permitting reduced safety margins in designing clearances. For compact AC lines, insulated crossarms and a shorter span are also used thereby reducing the line sag so that a substantial increase in *the* power density is achieved.

4. Transmission capacity upgrading by increasing current density

When the flow of electrons goes through the line, produces heat and the conductors temperature increases. It is necessary to make a thermal study to know if the conductor can stand that temperature. The temperature of the conductor is limited by two factors:

1) The limit of the conductors material
2) Conductor – ground distance

Although aluminium conductor was used for overhead transmission since the end of IXX century, its widespread use did not occur until the 1940s, when copper was designated as a vital war material and was no longer available for use by electric utilities. To obtain the desired strength required for transmission lines, the lightweight aluminium was combined with the high tensile strength of steel in the development of aluminium conductor steel reinforced (ACSR). Today, most overhead transmission lines use this conductor construction.

Steel can stand high temperatures, up to 200ºC with no changes in the conductors properties, aluminium on the other hand, mechanical properties when the temperatures is higher than 90ºC. The temperature is a function of the electrical current and the environmental conditions. On a continuous basis, ACSR may be operated at temperatures up to 100ºC and, for limited time emergencies, at temperatures as high as 125°C without any significant change in the physical properties.

Given the many changes in the way the power transmission system is being planned and operated, there is a need to reach higher current densities in existing transmission lines, to increase the thermal rating of existing lines. There are different ways to achieve this increase:

1) Increase the maximum allowable operating temperature to 100°C. For example, if the line is limited to a modest temperature of 50°C to 75°C, and the electrical clearance is sufficient to allow an increase in sag for operation at a higher temperature, then the thermal rating of the line can be increased. If sufficient clearance does not exist in all spans, then conductor attachment points may be raised, conductor tension

increased or other mechanical methods applied to obtain the necessary clearance at the higher temperature.

2) Use dynamic ratings or less-conservative weather conditions relating to wind speed and ambient temperatures. For example, if the existing line is already rated at a temperature near 100°C, and a modest increase of 5% to 15% is desired, then monitors can be installed and the higher ratings used when wind speed is higher than the standard 0.6 m/s and the ambient temperature is lower than 40°C.

3) Replace the conductor with a larger one or with a one capable of continuous operation above 100°C. These solutions would be ideal if the line was already limited to 100°C, and the thermal rating increased by more than 25%. Given the low cost, high conductivity and low density of aluminium, no other high-conductivity material is presently used. Therefore, replacement with a larger conductor will result in an increased load on existing structures because of an increase of wind/ice and tension.

The thermal rating of an existing line can be increased about 50% by using a replacement conductor that has twice the aluminium area of the original conductor. The larger conductor doubles the original strain structure tension loads and increases transverse wind/ice conductor loads on suspension structures by about 40%. Such large load increases typically would require structure reinforcement or replacement. This drawback to the use of a larger conductor may be avoided by using the high-temperature, low-sag (HTLS) conductor, which can be operated at temperatures above 100°C while exhibiting stable tensile strength and creep elongation properties.

Practical temperature limits of up to 200°C have been specified for some conductors. Using the HTLS conductor, which has the same diameter as the original, at 180°C increases the line rating by 50% but without any significant change in structure loads. If the replacement conductor has a lower thermal elongation rate than the original, then the structures will not have to be raised.

Although the use of a larger conductor provides a reduction in losses over the life of the line while operating temperatures remain at a modest level, the use of the HTLS conductor reduces capital investment by avoiding structure modifications. In either case, replacing the existing conductors should improve the reliability of the line because the conductor, connectors and hardware will all be new.

A. Increasing the transmission capacity of overhead lines using HTLS conductors

Replacing original ACSR conductors with HTLS conductors with approximately the same diameter is one method of increasing transmission line thermal rating. HTLS conductors are effective because they are capable of:

1) High-temperature, continuous operation above 100°C without loss of tensile strength or permanent sag-increase so that line current can be increased.

2) Low sag at high temperature so that ground and underbuild clearances can still be met without raising or rebuilding structures.

The original conductor's “initial installed sag” increases to a final “everyday sag”, typically at 16°C with no ice or wind, as a result of both occasional wind/ice loading and the normal aluminium strand creep elongation that is a result of tension over time. This final sag may increase occasionally because of ice/wind loading or high electrical loads, but these effects are reversible.

For most transmission lines, maximum final sag is the result of electrical rather than mechanical loads. It is important that any replacement conductor is installed so its final sag under maximum electrical or mechanical load does not exceed the original conductor's final sag and the existing structures need not be raised or new structures added. Under these circumstances, where structure reinforcement or replacement is to be avoided, HTLS conductors are used to advantage.

New construction, long-span crossings can be achieved with shorter towers. These can be accomplished using the existing right-of-ways and using all the existing tower infrastructure, thereby avoiding extensive rebuilding, avoiding difficult and lengthy permitting, and reduced outage times.

B. Types of HTLS Conductors

Conductors are constructed from helically stranded combinations of individual wires where galvanized steel wires are used for mechanical reinforcement, aluminium wires for the conduction of electricity, and hard-drawn aluminium for both mechanical and electrical purposes.

Desirable properties for reinforcing core-wire material include a high elastic modulus, a high ratio of tensile strength to weight, the retention of tensile strength at high temperatures, a low plastic and thermal elongation, a low corrosion rate in the presence of aluminium and a relatively high electrical conductivity. The material must be easy to fabricate into wire for stranding.

Among the choices available for HTLS conductors are:

1) ACSS and ACSS/TW (Aluminium Conductor Steel Supported) Annealed aluminium strands over a conventional steel stranded core. Operation to 200°C.

2) ZTACIR (Zirconium alloy Aluminium Conductor Invar steel Reinforced) High-temperature aluminium strands over a low-thermal elongation steel core. Operation to 150ºC (TAI) and 210°C (ZTAl).

3) GTACSR (Gap Type heat resistant Aluminium alloy Conductor Steel Reinforced) High-

temperature aluminium, grease-filled gap between core/inner layer. Operation to 150°C. GZTACSR (Gap Type super heat resistant Aluminium alloy Conductor Steel Reinforced).

4) ACCR (Aluminium Conductor Composite Reinforced) High-temperature alloy aluminium over a composite core made from alumina fibres embedded in a matrix of pure aluminium. Operation to 210°C.

5) CRAC (Composite Reinforced Aluminium Conductor) Annealed aluminium over fibreglass/thermoplastic composite segmented core. Probable operation to 150°C.

6) ACCFR (Aluminium Conductor Composite Carbon Fibre Reinforced) Annealed or high-temperature aluminium alloy over a core of strands with carbon fibre material in a matrix of aluminium. Probable operation to 210°C.

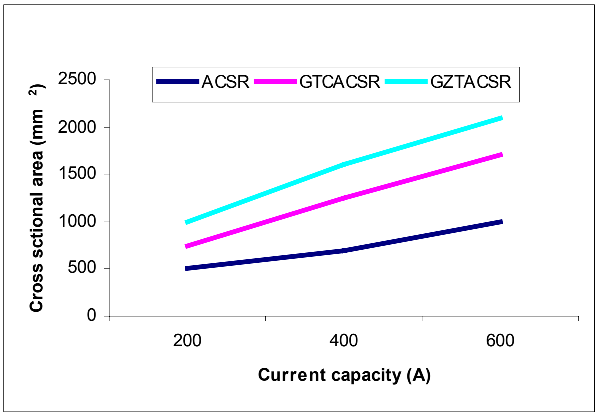

Fig. 1. Current capacity in function of the cross sectional area

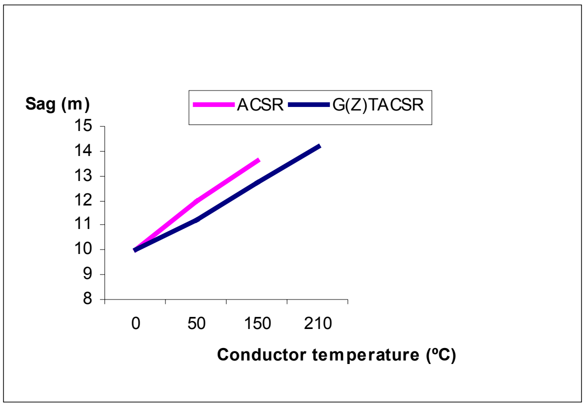

Fig. 2. Sag in function of the conductor temperature for a span length of 400m

5. Transmission capacity upgrading by using AC lines to transmit DC power

The fast development of power electronics based on new and powerful semiconductor devices has led to innovative technologies, such as HVDC, which can be applied to transmission and distribution systems. The technical and economical benefits of this technology represent an alternative to the application in AC systems. Some aspects, such as deregulation in the power industry, opening of the market for delivery of cheaper energy to customers and increasing the capacity of transmission and distribution of the existing lines are creating additional requirements for the operation of power systems. HVDC offer major advantages in meeting these requirements.

The HVDC transmission systems are point-to-point configurations where a large amount of energy is transmitted between two regions. The traditional HVDC system is built with line commutated current source converters, based on thyristor valves. The operation of this converter requires a voltage source like synchronous generators or synchronous condensers in the AC network at both ends. The current commutated converters can not supply power to an AC system which has no local generation. The control of this system requires fast communication channels between the two stations.

A. Feasibility of HVDC transmission

A HVDC system can be 'monopolar' or 'bipolar'. The monopolar system uses one high voltage conductor and ground return. This is advantageous from an economic point of view, but is prohibited in some countries because the ground current causes corrosion of pipe lines and other buried metal objects. However, in Europe, monopolar systems are in operation. Most of them are used for submarine crossings.

The bipolar system uses two conductors, one with plus and one with minus polarity. The mid point is grounded. In normal operation, the current circulates through the two high voltage conductors without ground current. However, in case of conductor failure, the system can transmit half of the power in monopolar mode. Besides, this operation can be maintained for a limited time only.

Recently, ABB and Siemens started to build HVDC systems using semiconductor switches (IGBT or MOSFET) and pulse width modulation (PWM). The capacity of a HVDC system with VSCs is around 30-300 MW. Operating experience is limited but many new systems are being built worldwide. The PWM controlled inverters and rectifiers, with IGBT or MOSFET switches, operate close to unity power factor and do not generate significant current harmonics in the AC supply. Also the PWM drive can be controlled very accurately. Typical losses claimed by ABB for two converters is 5%.

6. DC versus AC

The vast majority of electric power transmissions use three-phase alternating current. The reasons behind a choice of HVDC instead of AC to transmit power in a specific case are often numerous and complex. Each individual transmission project will display its own set of reasons justifying the choice.

A. General characteristics

The most common arguments favouring HVDC are:

1) Investment cost. A HVDC transmission line costs less than an AC line for the same transmission capacity. However, the terminal stations are more expensive in the HVDC case due to the fact that the7y must perform the conversion from AC to DC and vice versa. On the other hand, the costs of transmission medium (overhead lines and cables), land acquisition/right-of-way costs are lower in the HVDC case. Moreover, the operation and maintenance costs are lower in the HVDC case. Initial loss levels are higher in the HVDC system, but they do not vary with distance. In contrast, loss levels increase with distance in a high voltage AC system

   Above a certain distance, the so called "break-even distance", the HVDC alternative will always give the lowest cost. The break-even-distance is much smaller for submarine cables (typically about 50 km) than for an overhead line transmission. The distance depends on several factors, as transmission medium, different local aspects (permits, cost of local labour etc.) and an analysis must be made for each individual case (Fig. 3).

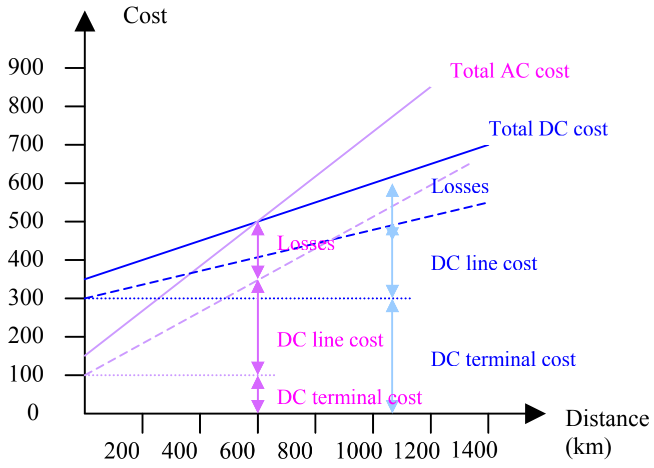

Fig. 3. HVAC-HVDC cost

2) Long distance water crossing. In a long AC cable transmission, the reactive power flow due to the large cable capacitance will limit the maximum transmission distance. With HVDC there is no such limitation, why, for long cable links, HVDC is the only viable technical alternative.

3) Lower losses. An optimized HVDC transmission line has lower losses than AC lines for the same power capacity. The losses in the converter stations have of course to be added, but since they are only about 0.6 % of the transmitted power in each station, the total HVDC transmission losses come out lower than the AC losses in practically all cases. HVDC cables also have lower losses than AC cables.

4) Asynchronous connection. It is sometimes difficult or impossible to connect two AC networks due to stability reasons. In such cases HVDC is the only way to make an exchange of power between the two networks possible. There are also HVDC links between networks with different nominal frequencies (50 and 60 Hz) in Japan and South America.

5) Controllability. One of the fundamental advantages with HVDC is that it is very easy to control the active power in the link

6) Limit short circuit currents. A HVDC transmission does not contribute to the short circuit current of the interconnected AC system**.**

7) Environment. Improved energy transmission possibilities contribute to a more efficient utilization of existing power plants. The land coverage and the associated right-of-way cost for a HVDC overhead transmission line is not as high as for an AC line. This reduces the visual impact. It is also possible to increase the power transmission capacity for existing rights of way. There are, however, some environmental issues which must be considered for the converter stations, such as: audible noise, visual impact, electromagnetic compatibility and use of ground or sea return path in monopolar operation.

   In general, it can be said that a HVDC system is highly compatible with any environment and can be integrated into it without the need to compromise on any environmentally important issues of today.

B. Power carrying capability of AC and DC lines

It is difficult to compare transmission capacity of AC lines and DC lines. For AC the actual transmission capacity is a function of reactive power requirements and security of operation (stability). For DC it depends mainly on the thermal constraints of the line.

If for a given insulation length, the ratio of continuous-working withstand voltage is as indicated in equation (1).

$$k = \frac{DC \cdot withs \tan d \cdot voltage}{AC \cdot withs \tan d \cdot voltage(rms)} \quad (1)$$

Various experiments on outdoor DC overhead-line insulators have demonstrated that due to unfavourable effects there is some precipitation of pollution on one end of the insulators and a safe factor under such conditions is k=1. However if an overhead line is passing through a reasonably clean area, k may be as high as √2, corresponding to the peak value of rms alternating voltage. For cables however k equals at last 2.

A line has to be insulated for overvoltages expected during faults, switching operations, etc. AC transmission lines are normally insulated against overvoltages of more than 4 times the normal rms voltage; this insulation requirement can be met by insulation corresponding to an AC voltage of 2.5 to 3 times the normal rated voltage.

$$k_1 = \frac{AC \cdot insulation \cdot level}{rated \cdot AC \cdot voltage(E_p)} = 2.5 \quad (2)$$

On the other hand with suitable conversor control the corresponding HVDC transmission ratio is shown in equation (3).

$$k_2 = \frac{DC \cdot insulation \cdot level}{rated \cdot DC \cdot voltage(V_p)} = 1.7 \quad (3)$$

Thus for a DC pole to earth voltage V_d and AC phase to earth voltage E_p the relations (4) exist.

$$Insulation \cdot ratio = \frac{insulation \cdot length \cdot required \cdot for \cdot each \cdot AC \cdot phase}{insulation \cdot length \cdot required \cdot for \cdot each \cdot DC \cdot pole} \quad (4)$$

and substituting (1), (2) and (3) equations, we obtain equation (5) for the insulation ratio.

$$Insulation \cdot ratio = \left(k \frac{k_1}{k_2} \right) \frac{E_p}{V_d} \quad (5)$$

DC transmission capacity of an existing three-phase double circuit AC line: the AC line can be converted to three DC circuits, each having two conductors at ± V_d to earth respectively.

Power transmitted by AC:

$$P_a = 6 E_p I_L \quad (6)$$

Power transmitted by DC:

$$P_d = 6 V_d I_d \quad (7)$$

On the basis of equal current and insulation

$$I_L = I_d \quad (8)$$

$$V_d = \left(k \frac{k_1}{k_2} \right) E_p \quad (9)$$

The following relation shows the power ratio.

$$\frac{P_d}{P_a} = \frac{V_d}{E_p} \left(k \frac{k_1}{k_2} \right) \quad (10)$$

For the same values of *k*, k_1 and k_2 as above, the power transmitted by overhead lines can be increased to 147%, with the percentage line losses reduced to 68% and corresponding figures for cables are 294 % and 34% respectively.

Besides, if the AC line is converted, a more substantial power upgrading is possible. There are several conversions of AC lines to DC lines proposals [2], these conversions are carried out as a simple reconstruction. The most feasible of them is Double Circuit AC Conversion to Bipolar DC, it implies tower modifications that maintain all the conductors at a height above ground of 1 to 2 meters below the original position of the lowest conductor during the whole construction phase. Two new crossarms are inserted at the level of the old intermediate crossarm.

No change is made to the conductors, the total rated current remains the same, which means that the transmitted power increases proportionally to the adopted new DC line-to-ground voltage. The conversion of lines where an increase of phase to ground voltage can be higher than 3, is possible when all the conductors of one AC circuit are concentrated in one DC pole.

The line to line (LL) AC voltage is doubled for use with DC, thus the transmitted power will increase by 3.5 times.

7. Conclusions

Given the many changes in the way the power transmission system is being planned and operated, there is a need to reach higher current densities in existing transmission lines.

The different types of constraints that limit the power transfer capability of the transmission system are discussed for analyzing the upgrade possibilities to increase the transmission capacity.

Replacing original ACSR conductors with HTLS conductors with approximately the same diameter is one method of increasing transmission line thermal rating. HTLS conductors can carry 1.6 to 2 times higher current than ACSR conductors. With the new HTLS conductors that are been designed together with a voltage increase, power increases in the 200-500% range can be obtained.

Using AC lines to transmit DC power not only increases substantially the transmission capacity, but it has more added values, such as stability, controlled emergency support and no contribution to short circuit level. The transmitted power can be increased by 3.5 times.

References

[1] J. Makens "Upgrading Transmission capacity for wholesale electric power trade", EIA, March 2002

[2] A. Clerici, L. Paris, P. Danfors, "HVDC conversion of HVAC lines to provide substantial power upgrading", IEEE Transactions on Power Delivery, Vol. 6, No.1 January 1991.

[3] D.M. Larruskain, I. Zamora, A.J. Mazón, O. Abarrategui, J. Monasterio, "Transmission and Distribution Networks: AC versus DC", 9CHLIE Marbella 2005

[4] A.J. Mazón, I. Zamora, P. Eguia, E. Torre, S. Miguelez, R. Medina, J.R. Saenz "Analysis of traditional suspension strings with GTACSR conductors" IEEE Transactions on Power Delivery, Vol.19, July 2004.