

Maximizing energy transfer and RES integration using Dynamic Thermal Rating.

Italian TSO experience

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Abstract: The production of electricity from wind and other renewable sources is rapidly increasing all over the world, causing significant changes in the management of electrical systems. The current structural asset is not adequate to manage this growing generation of energy. The hypothesis of construction of new power lines would mean taking into consideration economic, political and social problems. The following paper reports the experience gained by the Italian TSO, Terna S.p.A, on the use of the DTR (Dynamic Thermal Rating), which is able to dynamically calculate the real transport capacity of an overhead power line. The results obtained are encouraging as they show how it is possible to increase, in safety, the energy flows on the lines compared to the static limit evaluations. There are many advantages for electric systems: optimizing energy vectors, reducing congestions, increasing reliability, developing smart grids. In this document, after a brief illustration of the architecture of the DTR system, the authors report the results of two successful applications in the Italian HV electrical system for RES integration: a wind case and a hydroelectric one.

Keywords: DTR, Overhead transmission lines, RES integration.

1. Introduction

The development of renewable sources, especially wind farms, is producing more and more, at certain times of the year, the increase in power flows on transmission lines, causing System Operators to experience some difficulties in managing of electrical systems [1-4]. The Italian TSO, Terna S.p.A., in last years has started an important grid development plan to improve the RES integration building new lines and new substations to gather and transport the big amount of wind production concentrated in specific areas of South Italy and Main Islands. The construction of new assets means taking economic, political and social problems into consideration; therefore, in the meanwhile Terna has for some years been forced to exploit as much as possible the existing energy corridors using specific measures such as heat resistant conductors installation, DTR Systems, etc... [5-15].

The use of DTR systems is one of the adoptable solutions to manage this problem. These systems are very useful to dynamically evaluate the environmental conditions and therefore the actual temperature of the conductors: the knowledge of these parameters therefore allows the system operators to optimize the transport capacity of the overhead lines when the environmental conditions allow it. In the literature the use of DTR or DLR (Dynamic Line Rating) has become widespread in recent years.

In fact, in [16] the dynamic values of the line current (DLR) are evaluated as a function of the variations due to the high penetration of intermittent RES (Renewable Energy Source) in the case

where consistent forecast errors occur. In [17] is proposed an optimal algorithm for the management of congestion on the electric transmission system in real time considering quasi-dynamic thermal rates of transmission lines. In [18] the paper discusses the wide range of real-time line monitoring devices which can be used to determine the DTR of an overhead transmission line in normal or contingency operation. In [19], considering the growth in RES installation, DTR is being investigated as a way to connect the new intermittent generation, expanding the possibility to increase the rating of non-thermally limited lines (long lines). In [20] and [21] some types of commercially available DTR systems are described and also results from the use of DTR systems in an important 220 kV connection has been presented.

This article reports the experience gained by Terna on the application of DTR systems on some strategic lines for the dispatching of energy from RES production.

After a brief description of the devices, algorithms used and of the general architecture of the system, the authors report the results of two specific applications in the Italian HV electrical system: a wind case and a hydroelectric one.

2. DTR System used by Terna

Today the use of DTR systems is one of the most interesting methods to increase the transport capacity of existing power lines. Security, safety and reliability in the transmission of electricity are fundamental elements for the good functioning of the high voltage electrical system and to guarantee a high standard of supply to private and commercial customers. The sag of the high voltage conductor is one of the most important parameters to be monitored as it must always be kept a suitable distance from the ground and / or from other objects. The conductors of high voltage overhead lines are subject to different environmental conditions: the heating caused by joule effect of the passing current, the solar radiation, the ambient temperature, the intensity of the wind and its direction, etc ... These parameters greatly influence the linear thermal elongation of the conductor.

The real-time, reliable and economical measurement of the line temperature (and the calculated sag) under different environmental conditions can lead to a safe increase in the transmissible power on the line. By sure the best approach would be to monitor each span of the line to guarantee the maximum safety of the application, but this would cause unbearable costs in case of long lines. A total opposite approach, uses in some countries, uses a thermal model based on meteorological data without any field measurements to estimate the rating. This method is obviously cheaper and easier to implement but introduces uncertainties, so that appropriate margins on the results should be taken.

For these reasons Terna followed a mixed approach to guarantee a good accuracy of the system and contain the application costs. In last years was developed a thermo-mechanical model which estimates the main conductor parameters (sag, temperature, stress) for each span of the line using detailed meteorological short-term forecasts [22-24] and some monitoring systems have been installed as feedback to model results in the most critical spans in terms of clearance from obstacles.

At the moment, Terna has already installed more than 90 monitoring systems and more than 20 connections are already in operation with DTR, with some more in activation phase. For the future years, Terna considers in its business plan for the years 2019-2021, the installation of circa 30 new monitoring system and more than 10 new connections to be put in operation with DTR.

Before a new DTR implementation, Terna performs a deep analysis on the state of the line and on joints through infrared analysis and, if needed, also with direct resistance measures. These controls are repeated periodically more frequently than on other lines. The feedback in these years of application has confirmed that the ageing of DTR equipped lines is comparable with other lines.

2.1. DTR monitoring systems

After a few market benchmarks and having tested different alternative systems, Terna evaluated pros and cons of each system and decided to use for operation only one type of real-time monitoring system, currently provided by Micca [25] also with the aim to standardize as much as possible the application.

The key points of the monitoring system used are the following:

- Temperature measurement sensor is designed with redundant temperature probes on the conductor and one on the metal casing of the device. With these measures, a compensation algorithm considers the thermal effect induced by the sensor itself, ensuring a good correspondence between the indicated temperature value and the real one of the closest parts of bare conductor;
- Weather station installed on the pylon with WMO (World Meteorology Organization) standard sensors (pyranometer, ultrasonic anemometer, temperature and humidity sensor);
- Sensor on the conductor is feed by an internal battery (no power harvesting from line) and transmits measurements using low power radio waves towards the base-station on the support;
- Power supply of the base-station installed on the pylon is provided by solar panel and battery.
- Unique transmission of information (conductor temperature and meteorological data) to the center via GPRS on a dedicated APN;

The sensor (Fig. 1 and Fig. 2) is mounted on the high voltage conductor with anti-tearing binders; this is equipped with 3 temperature probes for measuring the temperature of the line conductor, plus a reference probe for the aluminum casing of the equipment.

Two measurement areas are used: the first is on the conductor surface with three measure probes Ts1.1, Ts1.2 and Ts1.3 (Fig. 3) that measure the temperature directly on the conductor with a specific validation algorithm. The second area is the body itself of the line sensor (Ts2 sensor) which provides a reference value. With an appropriate algorithm is possible to compensate the influence of the body of the sensor on the measured values and provide more accurate values of the “real” conductor surface temperature unaffected by the presence of the sensor itself. With this approach is possible to guarantee a global accuracy of $\pm 1,5^{\circ}\text{C}$ on a wide range of operation temperatures.

The acquired data are subsequently transmitted to the base-station located on the tower. Prior to be transmitted, data measured by the unit, are validated using their redundancy.

Power is supplied using long-life small form-factor lithium battery, without the need to harvest power by induction from the line. This helps to keep light weight and small dimensions, very useful to facilitate the installation procedure. Terna requires that such kind of sensors must be designed to fit HV and UHV installations (from 60 kV to 380 kV lines), with conductor diameters ranging from 10 mm to 55 mm. Moreover, Terna requires that the sensors must be designed also to be mounted with line in operation, considering also the complexity of managing line outage for critical corridors.



Fig. 1 - Line sensor [25]



Fig. 2 - Line sensor – second view [25]

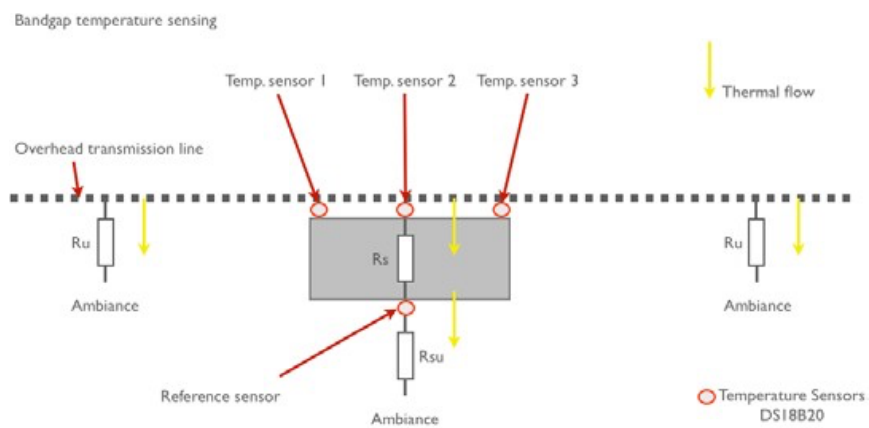


Fig. 3 - Compensation of environmental influences [25]

The base station is mounted on the tower; the maximum range for wireless data transmission between the sensors and the base is around 60 m values. The base station is powered by a rechargeable battery through a solar panel.

The line sensors communicate with the base-station over 868MHz radio link; the measuring and transmission interval can be selected with a minimum interval of one minute. The weather station is connected by wire to the base-station and all acquired data are also stored in the base-station (Datalogger). Inside the base-station a GRPS modem provides to send all the data in an encrypted format to a Terna gateway server using a dedicate private APN. On Terna side a dedicated software is installed to manage and control all base-stations: this software polls data and telemetry (possible errors and faults) information from the field. Data are exported from that platform and stored in a DTR dedicated database.

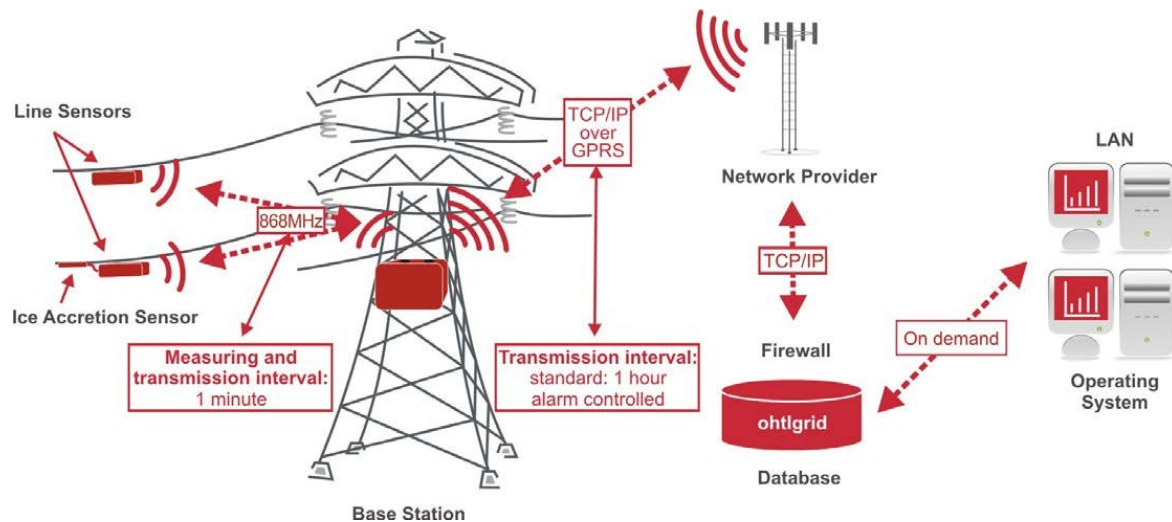


Fig. 4 - Communication scheme [25]

2.2. DTR algorithms

The thermo-mechanical model implemented is an evolution of standard Cigrè Thermal Model [26] applied to each span fed with different environmental data (such as ambient temperature, solar radiation, wind speed and direction) and actual values of the current flowing in the link. The mechanical equations implemented consider the conductor and insulator strings equilibrium and allows to calculate the sag and the stress for each span [22-23]. Moreover, the last version of the model has been updated to simulate properly also the mechanical behavior of HTLS conductors [24].

Considering ambient conditions and actual current flown in last time frames, the algorithm calculates as a first step the initial conditions of each span (temperature and time-constants), then integrates the equations for a fixed time forward and check if any span constraint (maximum temperature and/or maximum sag) is violated. By iteration the maximum admissible current is evaluated.

The algorithm itself has demonstrated during more than 5 years of operation to be quite accurate: the main errors are connected to uncertainties of meteorological data used. For this reason, a new evolution is planned to develop a dedicated nowcasting model based also on the measurements available from meteorological stations installed on the pylons.

2.3. DTR General Architecture

DTR General Architecture is shown in Fig. 5. In red blocks are represented field data inputs, in green ones the calculation blocks, in grey ones configuration parameters. In particular, span constraints are predefined after an elaboration of possible clearance issues starting from a laser scan (LIDAR) of the line.

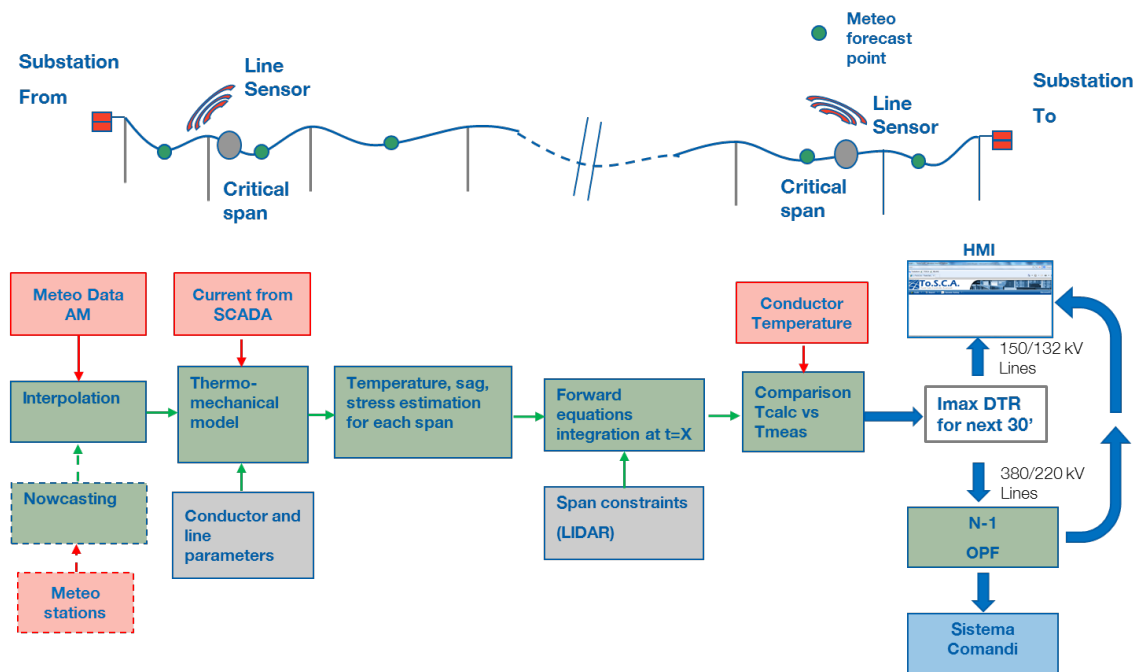


Fig. 5 - DTR – System architecture

The results in terms of Dynamic ampacity are displayed in a dedicated web platform to operators in Control Rooms. Moreover, for applications to 380/220 kV lines, the dynamic limits fed the EMS: they are used in N-1 calculation tool and in Optimal Power Flow system. In this way both manual and automated redispatch (OPF) take in consideration the ampacity margins provided by DTR system. The application is designed for very short-term application in order to contain as much as possible errors linked to environmental conditions forecasts.. The ampacity limit is evaluated considering the max current affordable for 30' guaranteeing the respect of all thermal and mechanical constraints. The selected time frame is coherent with the redispatch/ RES curtailments timing.

3 Terna experiences

At the moment Terna has implemented DTR for two main types applications:

- N-1 congestion relief application for 380/220 kV lines
- Application for managing local congestion due to high RES production

It's very important to notice that for 380/220 kV lines, the increased DTR limit is used only for N-1 application, while in N condition the usual static limit is maintained. The conductor temperature is always lower than the permanent limit. The conductor could be used close to its thermal limit only in case of contingency during re-dispatching time (few minutes).

Vice versa in RES applications the ampacity limit evaluated by DTR algorithm is usually higher than the cap limit given by substation elements, so the actual line temperature is also in this case lower than permanent limit.

In the following the two different examples related to the second type of application are described.

3.1 Wind case

Several 150 kV lines of the areas with high wind plants concentration between Campania and Puglia, in some cases subject to local congestion in high wind conditions, have been equipped with DTR systems.

Before using the DTR, managing the power lines with the standard seasonal current limits (winter and summer), it was sometimes necessary to limit the transit in these areas, apply some radial configurations and/or limiting the production of wind farms, with significant economic and environmental impacts: charges associated to the “Mancata Produzione Eolica – MPE” (Wind Power Curtailment Indicator) and increase in the CO₂ produced.

The lines of the application cross areas with little load, therefore almost all the wind generation collected from the various wind farms is transported on these lines to the 380 kV reference stations and then be transmitted on the UHV grid. These lines are generally lightly loaded in low wind conditions, while they are heavily loaded in conditions of high wind production.

The application of the DTR on these connections is very effective because in conditions of high wind generation infeed and consequently of high transits on these lines, the strong wind guarantees an excellent cooling effect on the conductor.

3.2 Application results - Wind case

As an example of the application for wind case, the probability density (right y-axis) and cumulated probability (left y-axis) of the DTR ampacity (x-axis) calculated on a 150 kV line of the area are compared with the seasonal static limits in Fig. 6 and Fig. 7.

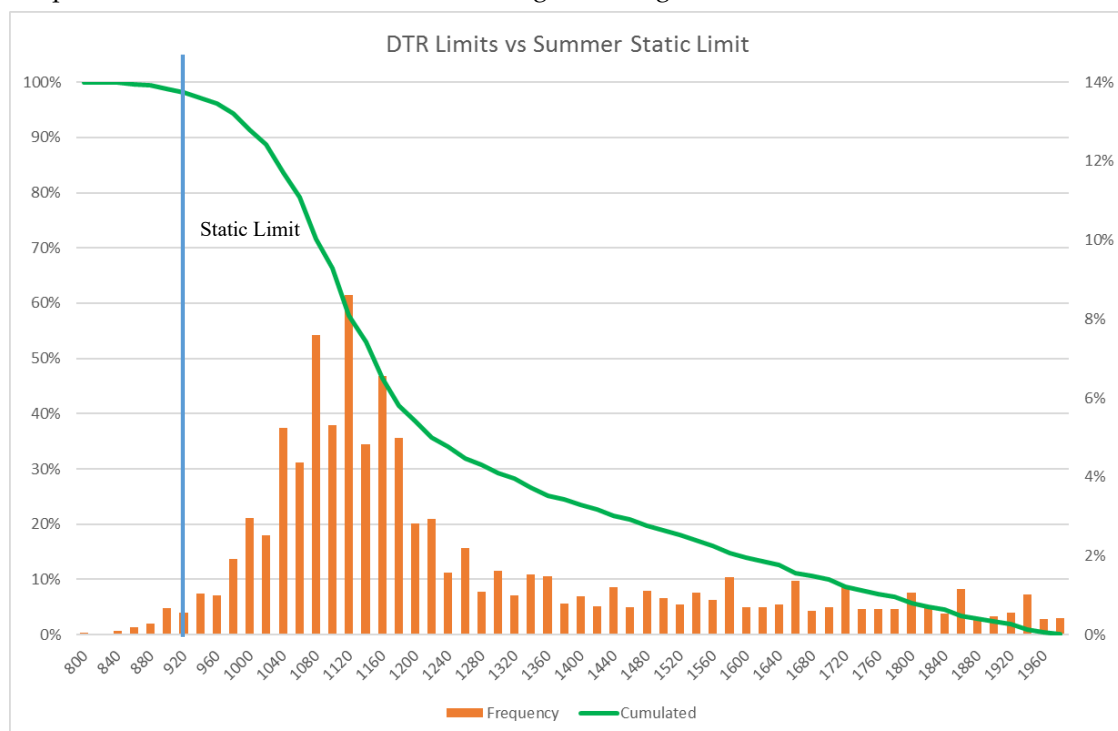


Fig. 6 - DTR limits Vs Summer static limit (wind case)

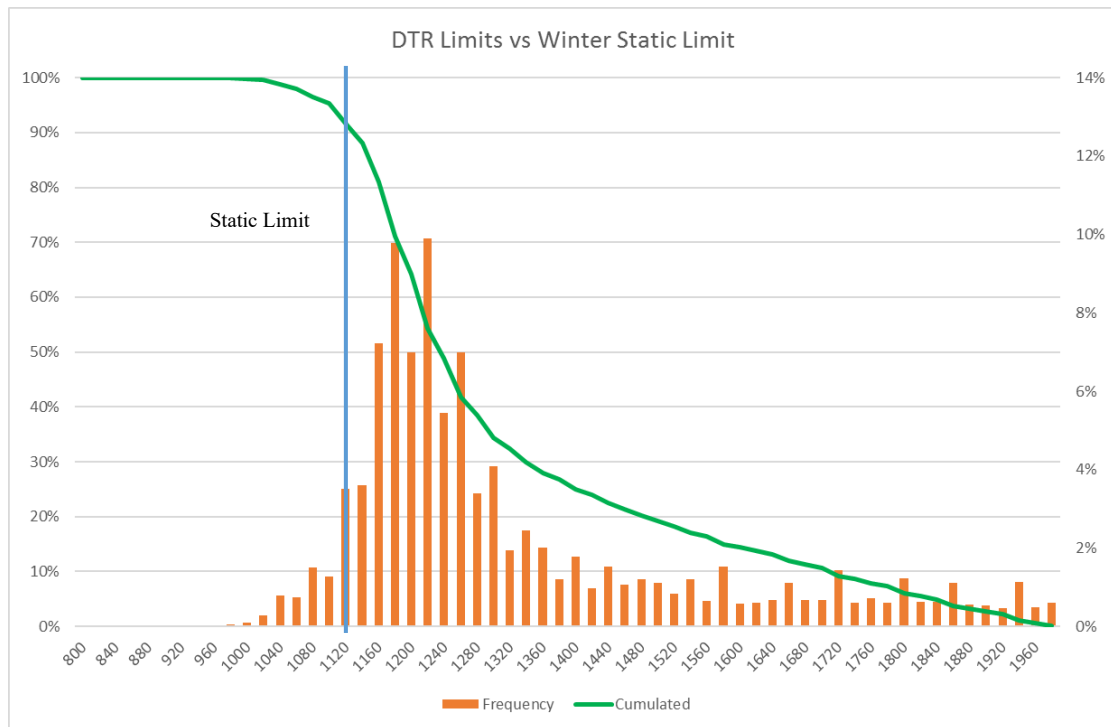


Fig. 7 - DTR limit Vs winter static limit (wind case)

Calculated dynamic limits are almost always higher than seasonal static ones (represented with the blue lines in Fig. 6 and Fig.7): about 98% of cases in summer, 92% of cases in winter). Moreover, the few cases in which the dynamic limit is lower are not relevant for operation because they almost always occur in concomitance with low wind conditions and consequently of low transits on the line.

It can be noticed that the limits calculated for the conductor (ACSR – 31,5 mm diameter, 585 mm² section) are noticeably higher than the static ones (up to 1900 A in particularly favorable conditions). To ensure compliance with end stations equipment's limits and to avoid possible problems of accelerated aging of the conductor and above all joints and clamps, where hotspots could arise, a prudential approach was followed by setting a higher cap (1250 A) to the limit provided by the DTR algorithm.

As an example, in Fig. 8 the trends of a year (with sampling at quarter of an hour) of the transit current and of the dynamic limit are shown.

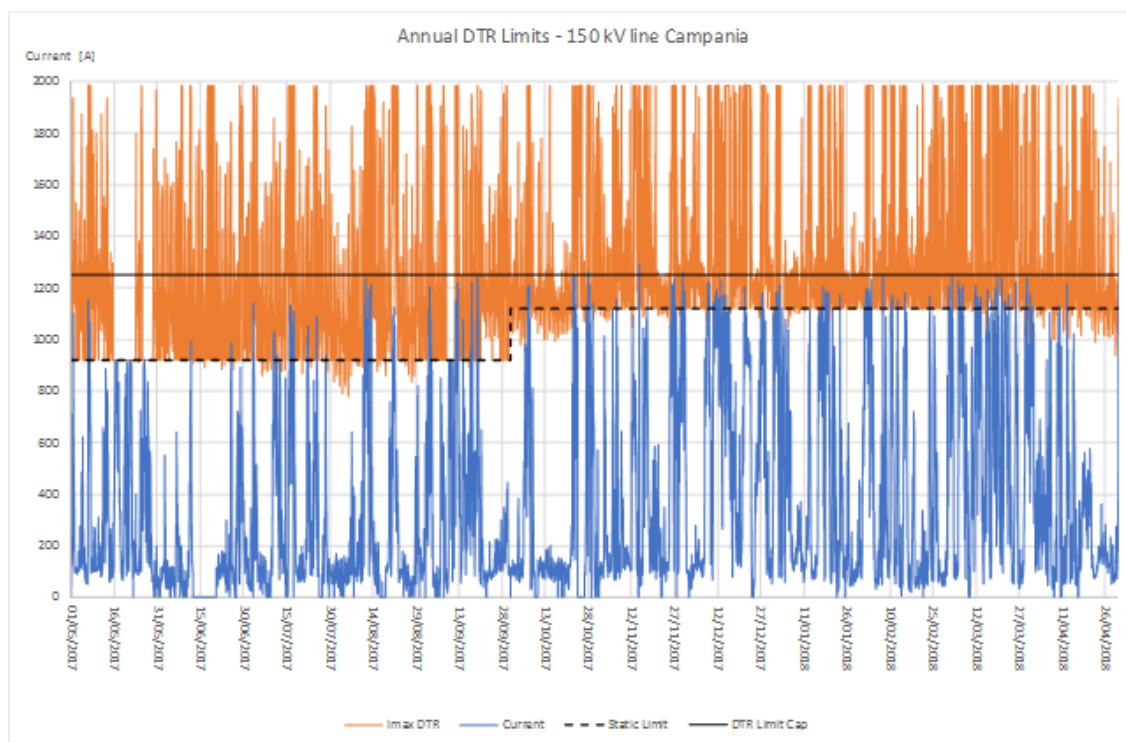


Fig. 8 - Yearly DTR limits on a 150 kV line (wind case)

Fig. 8 shows a benefit in correspondence with all those samples in which the actual current was higher than the dotted line representing the seasonal static limit value (for a total of about 250 h) without or with reduced RES production curtailments.

The effectiveness of DTR application on wind curtailments is highlighted in Fig. 9. DTR has been implemented on two similar lines subjected to local congestions caused by high wind power injection. It's evident after the DTR commissioning (end of 2012 for line A, end of 2013 for line B) a relevant curtailment reduction for both lines. This benefit has been confirmed also in following years and DTR helps to keep the curtailments to a low level also after the increase of installed capacity related to line B.

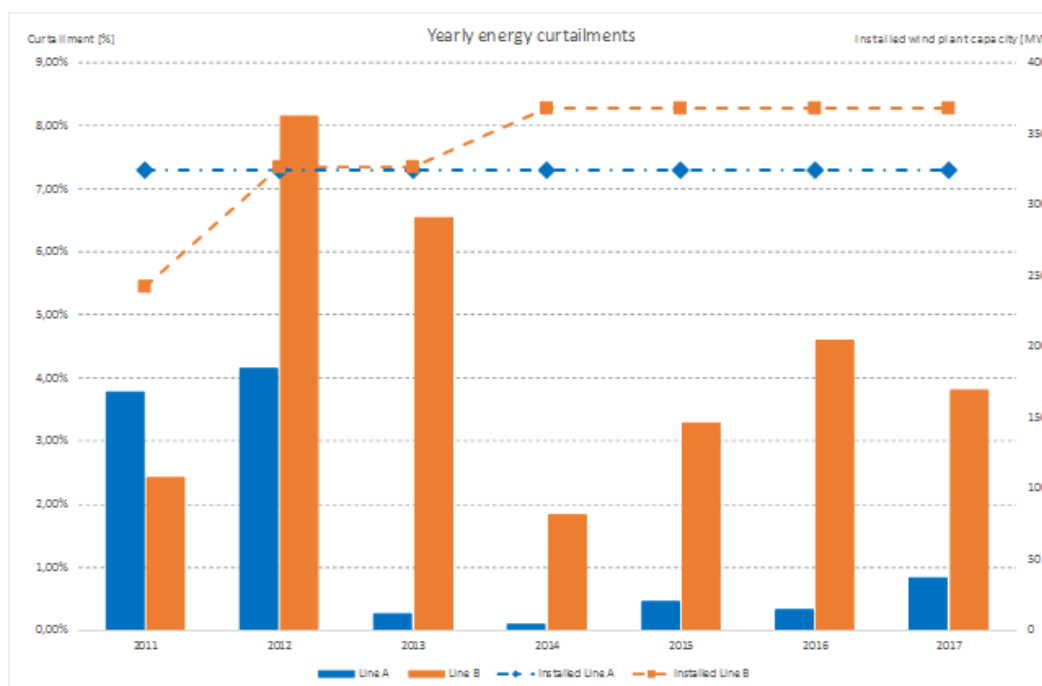


Fig. 9 - Yearly energy curtailments for two line applications from 2011 to 2017 (wind case)

3.3 Hydroelectric case

This application has been implemented on 132kV lines of the mountain area of Trentino Alto Adige characterized by high hydroelectric production, which often cause grid congestions in summer.

The network between the provinces of Bolzano and Belluno is characterized by a strong presence of hydroelectric production and more generally by renewable sources. The presence of a limited load in the region and the increase in distributed generation (hydroelectric and photovoltaic) connected in MV and LV networks, often lead to an inversion of power flow from the MV distribution networks towards HV ones. In summer period (May - September), with lower seasonal current limits and the high values of hydroelectric generation, grid congestions are sometimes recorded. Their containment is only possible adopting radial configurations of the grid and/or through limitation of the Production Units (Hydroelectric plants) with consequent economic impacts in terms of dispatching and / or increased risk of Energy Not Supplied and Non-Withdrawal Energy from the System Operator.

Considering orographic characteristics of the area, which are problematic for new lines construction due to the high investment costs needed and environmental impacts, the installation of DTR on the bottle-neck lines of the main transit routes that descend from the northern valleys of South Tyrol towards the Veneto plain, represents an ideal temporary solution to avoid overload problems during periods of high hydraulicity.

The application of the DTR guarantees good results in terms of increased transport capacity, despite the limited section conductor used in those lines, as it can take advantage from environmental

conditions typical of mountain areas (the pylons are all above 1000 meter of altitude) with ambient temperatures more favorable than the standard conservative ones used in the calculation of static limits.

3.4 Application results - Hydroelectric case

Fig. 10 shows the trend of the current in one of the lines of that area, and of the calculated dynamic limit during the summer period in which the congestions, due to high hydraulicity, are more probable.

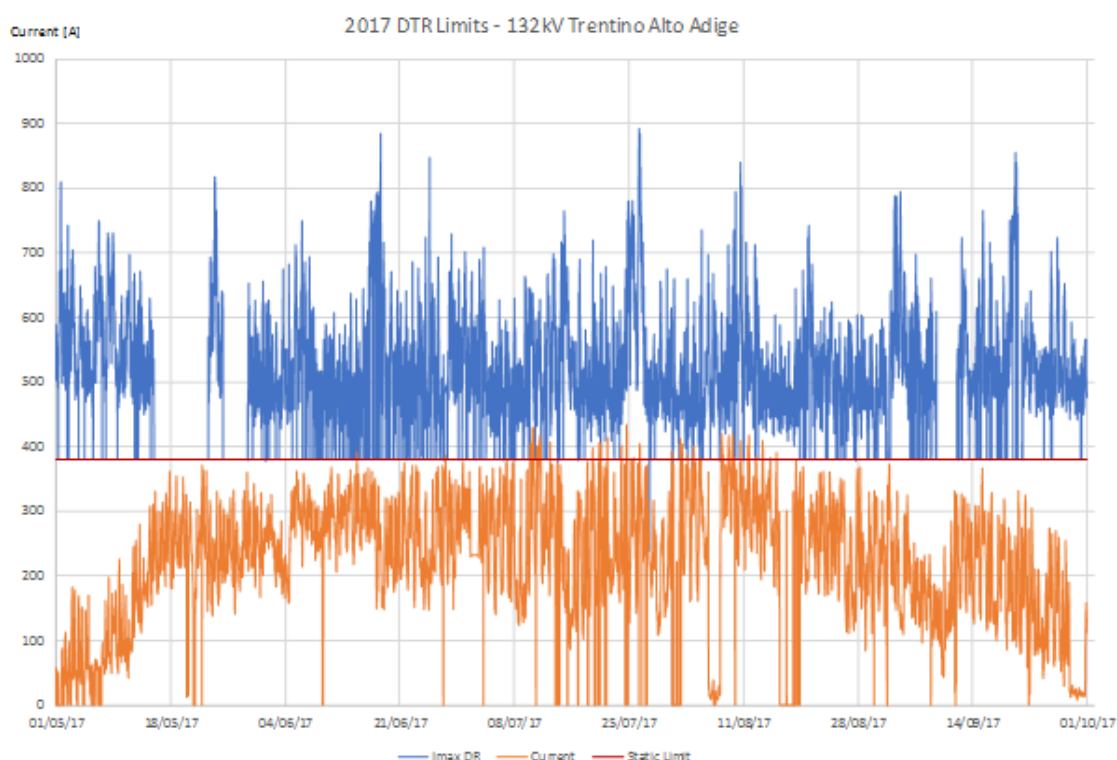


Fig. 10 - DTR limits on a 132 kV line (hydroelectric case)

Thanks to the environmental characteristics of the territory crossed by the line, the dynamic limits are significantly higher than the static ones, allowing an average current transit of around 500 A. The current samples exceeding the static limit of the conductor (about 30h overall) represent the actual benefit of the DTR system, as it was possible to manage such transits without any reduction in production from RES.

In order to assess the potential future benefits of this application, it should be considered that this benefit could be much more relevant in years characterized by particularly high levels of hydraulicity as happened in 2014. Under these conditions, to ensure compliance with the static limit of the lines, some radial configurations in the surrounding network were applied and noticeable amount of power plants were redispatched. If the DTR system had been available, such costly actions in terms of cost-effectiveness and safety of the system would not have been necessary.

4. Benefits of the application of the Dynamic Thermal Rating

The use of the DTR can generate economic safety and security benefits. From a security point of view, the use of the DTR on transmission network subjected to overloads allows to avoid radial configurations with a reduction of the risk of outage and disconnection of users. From a safety point of view the models/direct measurements allow the TSO to monitor the actual status of the asset: usually DTR application provides limits higher than the static seasonal ones (more than 95% of calculated values in Terna experience) but it is possible to detect also cases of lower rating due to very unfavorable environmental conditions: in a static management of limits these cases could remain hidden.

In order to evaluate the benefits in economic terms, with reference to the wind case, it is necessary to consider how, in case of limitation of production, the wind farms receive a compensation for the difference between the energy that would have been produced (estimation based on the wind data) and the one actually injected: not-produced wind energy (Mancata Produzione Eolica - MPE) is valued at the price of the energy market (average prices of 50-70 € / MWh). The reduction in the power input must be balanced by other conventional generation plants on the Ancillary Services Market (Mercato dei Servizi di Dispacciamento - MSD) causing an additional cost for the system equal to the upward price offered by the Production Units on this Market (average prices very variable from 70-150 € / MWh).

In the proposed hydroelectric case, it must be considered that the Production Units already have a production program from outcomes of Energy Markets valued according to the closing price of these markets. Following a real-time reduction order requested by Terna, the reduced energy volumes are valued with the downward prices offered by the producer on the MSD market, which have to return this amount to the market system. These prices are almost always lower than the Energy Market price so the producers can retain the difference. To this charge for the system is added, in analogy to the wind farm, the costs incurred to balance the reduction by increasing production on other generation plants valued with upward MSD price.

The monitoring approach chosen by Terna guarantees at the same time good accuracy and reliability and contains the investments costs: basing on current experiences payback periods vary between some months to maximum 2 years.

In best cases such the wind case described in Paragraph 3.1, the savings in the period 2013-2017 in terms of curtailment costs paid by the system (normalized on 2012 production profiles) amount to circa 1 M€/year for each line

5. Conclusions

In Italy, in recent years, the Electric system operators (TSO and DSO) have been investing in Dynamic Thermal Rating systems in order to optimize the existing energy corridors.

This solution represents an important evolution of the HV network towards an intelligent system. The possibility to continuously check some fundamental parameters of the system, such as the temperature and the tension of the conductors, allows a more flexible operation of the rating of the overhead power lines.

The DTR systems are installed for various reasons: to favor the integration of renewable sources (especially wind and hydroelectric power), to guarantee the N-1 safety of the system, etc .., without the need to re-dispatch and therefore containing the operational costs.

This paper reports the experience gained by Terna on the application of DTR systems on some important connections for the dispatching of energy from RES production. After a brief description of the devices and of the architecture of the system, the authors report the results of two applications in the Italian HV electrical system: a wind case and a hydroelectric one.

In both cases the advantage of the installation of these devices is demonstrated from an economic, security and environmental point of view.

In particular, in the case of wind generation analyzed, it was shown that, in only one year, it has been possible to use the asset over the static limits for 250 hours; this result allows an important economic saving for the system, a reduction of the curtailments of RES and therefore also an important environmental benefit.

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