Weather-Based Dynamic Thermal Rating in WP5 of H2020 Osmose Project: implementation and preliminary results

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Abstract— As already well known, Terna leads the Working Package 5 of The Italian demo of the H2020 Osmose project, which stands for Optimal System-Mix Of flexibility Solutions for European electricity. The main purpose of OSMOSE is developing a novel Energy Management System (EMS), which allows managing distributed Renewable Energy Sources (RES) and grid congestions, by properly coordinating innovative flexibility resources which include Dynamic Thermal Rating (DTR) and Demand Side Response (DSR). In this innovative approach, one of the two DTR investigated methods, which have been both developed by Ensiel, a consortium of Italian universities active in power systems research, is the Weather Based DTR. This technique is based on a thermo-mechanical model of the monitored line and on a detailed weather forecast of the involved area, having as final output the loadability curve of the line. The main features of the Weather Based DTR solution are described in this paper, and the first experimental results obtained on real case studies are presented and discussed in order to prove their effectiveness.

Keywords— dynamic thermal rating, energy management system, congestion resolutions, grid flexibility resources, weather sensors, weather forecasting, weather based, osmose project

I. INTRODUCTION: DYNAMIC THERMAL RATING

Modern power systems are facing several critical issues mainly related to the growing integration of Renewable Energy Sources (RES) and to the load increasing, carrying the transmission lines close to their maximum capacity. Increasing the capacity of existing transmission lines represents a valid alternative to constructing new assets.

The electrical ampacity rating of an overhead Transmission Line is strictly related to the maximum conductor temperature, whose limit is due to the physical characteristics of the line itself, especially to the available phase-to-ground clearance. The conductors temperature depends on the current and on the local weather conditions [1].

Given the mechanical and thermal features of the conductor, the sags and the clearances are substantially dependent on present and predicted conductors temperature.

The Static Thermal Rating (STR) limits, which are very conservative but limitate the full exploitation of the transmission line. On the other side the Dynamic Thermal Rating of an overhead line foresees the estimation of the maximum load current the line can carry during a given period, always respecting all ground clearances, by measuring or estimating the conductor’s temperature along the line route or processing weather and load forecasting [2] [3] [4] [5] [6] [7]. Then DTR represents a flexible tool for dispatching decisions of Transmission System Operators (TSOs), supporting them in case of grid congestions [8].

The first weather-based DTR procedures imposed the same maximum allowable conductor’s temperature (typically, 75°C for traditional ACSR conductors), considering no line mechanical model and sag limits. This approach didn’t consider the relevant fact that the line spans can sensibly differ for both heating exchange conditions and phase-to-ground clearances [9][10].

Within the H2020 Osmose project, in order to have an highly scalable DTR Methodology, the consortium ENSIEL has conceptualized a distributed computing framework for Dynamic Thermal Rating Assessment of OHL, which integrates:

1. A software tool for weather-based Dynamic Loadability Assessment, which predicts the thermal status and the corresponding tensions, sags and clearances, for each line span. Starting from these data, the tool provides the maximum current that can be sustained during the considered time horizon, given as input the predicted evolution of weather forecasted conditions, without exceeding the predefined maximum conductor’s temperature in any span.
2. A Weather Condition-based Optimal Power Flow, which integrates the results of the weather-based dynamic loadability assessment tool in order to reliably improve the components loadability, enhancing the congestion management flexibility, and maximizing the RPGs’ exploitation.

In further Sections the implementation of Weather Based Solution will be described.

One of the great advantages relative to the Weather Based DTR Method is the total lack of installations needed on field, which allows the TSO to save time, resources and to have a vast number of DTR Systems deployed along the Electrical Network.

II. OSMOSE PROJECT OVERVIEW

Osmose is a H2020 project worth 28 M€, includes 33 European partners and it has a time horizon of 4 years (2018-2021). It is subdivided into several Working Packages with different goals.

Terna (the Italian TSO) leads the Working Package 5 (WP5), involving several university departments, research centers, industrial partners and aggregators. The purpose of WP5 is to assess and improve the techno-economic efficiency of flexibility services provision through a smart EMS that will coordinate DTR sensors and algorithms, DSR by large industrial customer and RES generation (wind, even with battery energy storage).

The project started in January 2018 and is currently at the beginning of the testing phase. The demo area is a portion of 150 kV grid in South Italy.

In the following Section III, the description of a new DTR weather-based method, developed for the OSMOSE project by the University of Pisa, within the Ensiel Consortium, is described. In Section IV the implementation of the Weather Forecast part of the DTR technique, performed by RSE, is described; in Section V the ICT automatization of the algorithm is explained, powered by Engineering, and in Section VI the first experimental results are shown.

III. WEATHER-BASED DTR METHOD

The main idea behind weather-based approaches to DTR is to perform a short-term forecasting of all meteorological quantities and to translate it into a corresponding expected time course of thermal and mechanical parameters of the power line. In fact, it is well known that solar radiation, ambient temperature, wind speed and direction, together with the power flow, drive the dynamic trend of the conductor’s temperature [1], hence mechanical tension and sag at all spans.

In time-evolution applications, also the power flow on the transmission line is forecasted, in order to obtain a prediction of the temperature of the conductor and the corresponding mechanical behaviour of the line for the following few hours. Conversely, when the maximum dynamic rating is searched, only meteorological quantities are forecasted and the aim of the tool is to assess what is the highest step current that can be sustained for a prefixed time period without exceeding the maximum allowed conductor’s temperature and sag at any span, starting from the present thermal conditions. This calculation is usually performed by running several dichotomic loops of the time-evolution algorithm, up to obtain the limit conditions.

In order to address both targets, Ensiel (in particular the University of Pisa) has developed in the last years a novel thermo-mechanical model of a multi-span transmission line, by combining the CIGRE thermal model of conductors [9] and an innovative description of mechanical interactions existing among all the spans placed between two dead-end towers of the line [11][12]. The main features of the weather-based DTR tool developed within the OSMOSE project, already described and discussed in [22], can be summarized as follows:

- in time evolution mode, the thermal behaviour of the conductor is evaluated, separately span by span, by applying a sample-and-hold procedure to the time course of inputs (line current and weather parameters) and then calculating the dynamic evolution of the conductor temperature as a sequence of first-order step responses. The calculation granularity of this first “thermal problem” is usually 60 seconds, while step variations of inputs can occur no more frequently than each 5 minutes;
- the temperatures obtained along the line are then used, separately at each time step, to solve an algebraic multi-span mechanical problem that provides tensions, sags and clearances at each span of the line;
- although the maximum allowed temperature of the conductor is a constant parameter, this check is performed span by span, since solar radiation and expressly wind speed and its relative direction can vary all along the line; the same applies for sags and obviously for ground-to-ground clearances, possibly diversified span by span also in Every Day Stress conditions;
- the mechanical model developed to calculate sags and tensions takes into proper account the interaction between adjacent spans and the corresponding possible rotation of insulator strings; this means considering both vertical and horizontal components of mechanical tension of conductors, which represents a significant improvement in the analysis of multi-span lines with respect to the conventional simplified “equivalent ruling-span” technique [13].

The tool has been widely validated in previous works and compared with the state-of-the-art procedures [11][12][21][26]. This model has been implemented on two 150-kV sub-transmission lines located in Southern Italy. The following structural data have been gathered to be enclosed into the weather-based DTR model: position and height above sea level of all towers; features of insulator chains; electrical, geometrical, thermal and mechanical characteristics of ACSR conductors; Every Day Stress of the line; maximum temperature and sag allowed at each span [12]. The section monitored in one of the lines, equipped with standard ACSR conductors with a diameter of 31.5 mm, is composed by 20 spans placed between two dead-end towers. Conversely, the section under test on the other line, equipped with standard ACSR conductors with a diameter of 22.8 mm, is composed by 30 spans.

Each quarter of an hour, the weather conditions expected for the following 3 hours along the line path are forecasted, as described in paragraph IV. Starting from the present conductor’s temperature, estimated span by span based on recent weather and loading conditions, the limit current that can be sustained for the next \( \alpha \) minutes is then calculated, according to the maximum dynamic rating mode. The maximum allowed temperature of conductors is 55°C and the parameter \( \alpha \) varies iteratively from 15 minutes to 3 hours,
with steps of 15 minutes. This procedure allows calculating, every 15 minutes, an overloading curve that is provided to the TSO optimum power flow. All the different rolling-horizon routines are automatized and interfaced as further described in paragraph V.

IV. METEO FORECAST

The Weather Based DTR method needs the 3-hours-ahead forecasts of some meteorological variables, such as wind intensity and direction at 10 m agl, air temperature and relative humidity at 2 m agl, and the global surface irradiation. These variables are provided by two different numerical weather prediction models: the Weather Research and Forecasting Model (WRF) [23] and the Regional Atmospheric Modeling System (RAMS) [24]. These local area models are driven with initial and boundary conditions provided by two different global models: the Integrated Forecast System (IFS), developed by the European Centre for Medium Range Weather Forecasts, UK (ECMWF), and the Global Forecast System (GFS), developed by the National Oceanic and Atmospheric Administration, USA (NOAA). In this way, four distinct models are available, which can also differ greatly from each other especially during perturbed conditions.

In this project, both WRF and RAMS run once a day, with start at 12 UTC. The temporal horizon of the data is 60 hours ahead, in order to provide two full days ahead, although the second forecast day is only used if the fresher forecast is delayed or missing for some reason. The temporal resolution of the NWP outputs is 15 minutes, and the spatial resolution of about 4 km for both NWPs. Finally, the outputs are spatially interpolated on the considered transmission lines.

These data are the inputs of the PREVDTR forecast chain.

The PREVDTR system consists of two steps, aimed at reducing the systematic error and bias of NWP models:

- A Short-Term forecast (ST). A Random Forest (RF) algorithm is applied for each weather variable. The training dataset is 60 days long and consists of the four distinct forecasts and the on-site measurements. In this way, a new forecast is produced for the next two days. This step is necessary to better describe the behaviour of the real-time series, especially for those variables that experience fast fluctuations, such as wind (intensity and direction) and relative humidity. The use of the four model outputs, instead of an average or a single model, as input to RF algorithm improves greatly its performance.

- A Very Short-Term (VST). Two different approaches have been considered and are still being evaluated: an Auto-Regressive Integrated Moving Average Model with eXogenous input (ARIMAX), and the Analog Ensemble method [25] (AnEn). The AnEn is a statistical technique that uses predictors from weather forecasts to select past events that are most similar to the current forecast. Once the times in which similar weather forecasts have occurred have been identified, a distribution of the forecast variable is created using past measurements of that variable recorded at those past times. The similarity is established by means of a metric that considers the forecast and the measures at leadtime 0 and at two adjacent leadtimes [25]. Both methods use ST forecast as predictor, and the training period is 21 days for ARIMAX and 30 days for AnEn.

One of the main problems tackled in the VST forecasts is related to the continuous availability of measurements. In the operational context, this availability is not always ensured in time, so ST provides a way to adjust the raw NWP forecast considering the measurements occurred in the last two months, while VST merges the freshest measurements (up to 15 minutes before the nominal time) into the ST forecast, in order to reduce the bias of the numerical forecast.

V. AUTOMATIZATION ALGORITHM OF THE WEATHER BASED DTR

The outcome of the Weather Based DTR method is one of the relevant inputs of the Zonal EMS, the novel EMS developed in the context of the OSMOSE project. In particular, the Italian demo relies on an ICT infrastructure that was developed for the sake of the project. The development of an automatization algorithm of the Weather Based stems from the need to properly integrate and exploit the Weather Based DTR solution into the ICT infrastructure of the Italian demo. In order to address the functional and not functional requirements directly coming from the demo, Engineering (ENG) has developed a software tool, namely “Wrapper DTR” which implements the needed business logic for allowing the proper execution of DTR weather-based software algorithm and managing both input and output files.

The automatization algorithm implemented by the Wrapper DTR is based on a scheduling process that checks the availability of input data, the output of the PREVDTR forecast chain, on a frequent basis. The schedule frequency defines the frequency at which a schedule has to be repeated at the specific time and interval; it is defined as a configurable parameter of the Wrapper DTR in order to have a strict control and an efficient management of the automatization process. Therefore, the Wrapper DTR is set up as a flexible component by facilitating both the installation and the testing phase. In the demo the schedule frequency is set to a proper value which optimises the process of data retrieving so that the DTR Weather Based can start its execution as soon as the input data is available. In this way, the overall time needed for the production of the readability curve is speeded up and the Zonal EMS can run its algorithm properly. The main steps of the Wrapper DTR automatization algorithm can be summarized as follows: input data reading and reconciliation, start the executable file of DTR Weather Based method, output data writing and reconciliation. The reconciliation phase is needed in order to convert both input and output files in a format compliant with the Weather Based method and the Zonal EMS, respectively. Moreover, the Wrapper DTR supports the input/output data storage functions: the file containing the forecasted weather conditions, output of the PREVDTR forecast chain, and the file related to loadability curve of the line, output of Weather Based DTR, are stored in an archive available on the server where both Wrapper DTR and Weather Based DTR are deployed. This functionality is the prerequisite for allowing the further phase of KPIs’ computation related to the DTR Weather Based. Moreover, the monitoring and debugging phase of the overall process is made easier since the analysis of input and output files together with the log file allows having a clear understanding of the DTR Weather Based behaviour for each running of execution. Indeed, the Wrapper DTR implements features of Log Management and also of Failure Recovery Mechanism assuring the provision of loadability curve to the Zonal EMS and minimizing the failure rate.
VI. FIRST RESULTS

The following figures report the very preliminary results obtained in a first test campaign carried out between February and April 2021. The main KPIs addressed by this analysis regard the comparison between Static and Dynamic Thermal Rating. STR has been assumed equal to 560 A and 370 A, respectively for the 31.5-mm and the 22.8-mm conductor, according to Terna operational procedures. Only the thermal limit of the conductor (55°C) was considered, while mechanical constraints like maximum sags or minimum clearance-to-ground were not activated.

In terms of dynamic rating, the 15-min DTR and the 180-min DTR, i.e. the two extremes of the loadability curve, have been analyzed. In fact, DTR is usually higher than STR due to main reasons:

1. STR assumes extreme and very conservative weather conditions that stress the temperature of conductors: high ambient temperature, maximum solar radiation and absence of wind; conversely, DTR is based on weather short-forecasting, which means on realistic ambient, solar and wind conditions that usually correspond to higher conductor cooling than supposed in STR;

2. DTR properly captures the real thermal behavior of the conductor, which basically corresponds to a 1st-order dynamic system; this means that the response to a step of current do not correspond to a step of conductor’s temperature, rather to an exponential function that reaches its steady-state conditions in 4-5 time constants, where τ is around 7-10 minutes [10]; this is why 15-min DTR is higher than 30-min DTR, while all the time horizons beyond 45 minutes can be considered already corresponding to the same steady-state conditions.

It is important to notice that comparing 180-min DTR and STR provides information regarding the first phenomenon (i.e. realistic weather instead of conservative meteorological conditions), while 15-min DTR gives evidence to the effect of thermal transients. As discussed in [12], the impact of transient effects depends on the $\alpha/\tau$ ratio, on the difference between the two steady-state conductor’s temperatures (for $t=0$ and $t=\infty$), and on the temperature of the conductor itself (the higher the temperature, the lower $\tau$, due to non-linearities of the thermal model).

Fig.1 and Fig.2 show the time course and the duration curve of the comparison between 180-min DTR and STR, for the line n.1, the one with the larger conductor ($\phi$ 31.5 mm).

These figures clearly show that weather short-forecasting, instead of using conservative meteorological parameters, already increases the rating of the line up to a peak of +300%. This peak value must not surprise: according to the CIGRE thermal model of a 31.5-mm conductor [9], in case of 8-m/s wind, no solar radiation (night) and 10°C of ambient temperature the steady state temperature of the conductor reaches its limit of 55°C only with a current of around 2400 A (4 times STR). Most interesting is the observation that, for approximately 40% of the winter testing campaign, DTR at least doubles the steady-state thermal rating. This is of course a preliminary result due to the fact that during the monitored days the line experienced very windy weather conditions, which maximizes the conductor’s cooling, hence the added value of DTR with respect to STR.

Fig.3 and Fig.4 show the time course and the duration curve of the comparison between 15-min DTR and STR, for the same line. As evident, in short time horizons the thermal transient phenomena enhance the added value of DTR with respect to STR, by a markup that varies from +15% (in working points where 180-min DTR was already at its maximum performance) to around +40% (when 180-min DTR was only slightly over-performing STR). For approximately 90% of the considered quarters of an hour, 15-min DTR at least doubles STR.

Fig. 1. Time course of 180-min DTR VS STR. Line #1.

Fig. 2. Duration curve of 180-min DTR VS STR. Line #1.

Fig. 3. Time course of 15-min DTR VS STR. Line #1.
Very similar results have been obtained for the second line, the one with the smaller conductor (φ= 22.8 mm), as reported in figures 5 and 6.

Due to the thinner conductor, in this second line the time constant of thermal heating is slightly lower (around 7 minutes instead of 10). This implies that the transient thermal phenomena have a smaller impact than in the first line, because at the end of the first 15 minutes the conductor has already experienced almost 2 time constants. The added value of 15-min DTR with respect to 180-min DTR, assuming STR as the base reference, consequently slightly decreases to the range [+10; +30%].

VII. CONCLUSIONS

The first test campaign performed between February and April 2021 clearly shows the effective operation of the weather-based tool developed within the Osmose project and implemented on two 150-kV sub-transmission lines in Southern Italy.

The excellent performance so far obtained for the dynamic thermal rating compared to the traditional static ampacity is certainly related to the fresh and extremely windy weather conditions experienced all along the monitored lines during the campaign. Indeed, this has significantly boosted conductor’s cooling with respect to the conservative meteorological conditions assumed by STR. It is also worth observing that this aspect resulted much more effective than the transient thermal aspects that are properly captured by DTR procedures when the overloading window is shorter than 4-5 thermal time constants of the conductor.

Tests in summer hot days are presently ongoing. Very preliminary results suggest that the markup of DTR with respect to STR remains substantial, but compared with winter windy conditions is roughly halved. Final results will be available in the next few months. Scalability and replicability evaluations are also ongoing within the Osmose project, also based on cost assessment and comparison with sensor-based approaches.

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