Experimental Assessment of Cooperative Sensors Network-based Dynamical Thermal Rating: the first evidences from the H2020 OSMSOSE Project

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***Abstract*—The main purpose of the Working Package 5 of the H2020 Optimal System-Mix of flexibility Solutions for European electricity (Osmose) project is to develop an advanced Energy Management System (EMS), which allows the Transmission System Operators (TSOs) to reliably manage 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 context, Ensiel, a consortium of Italian universities active in power systems research, developed a new DTR solution, which is based on a self-organizing sensor network composed by cooperative smart nodes deployed along the line route, having as final output the loadability curve of the line. This paper presents the first experimental results obtained by deploying this new DTR method on a real operation scenario, demonstrating the improved performance and effectiveness of the proposed method.**

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

I. Introduction

The growing presence of renewable energy sources (RES) in modern power systems and the increasing electrical load are producing several critical issues in power assets management. These issues are leading the power to flow through the existing overhead transmission lines (OHL) closer to the maximum transmission capacity.

A possible solution would be their reinforcement or the construction of new ones. However, due to their visual and environmental impact, this solution is contrasted by the public opinion. For these reasons, improving the exploitation of existing transmission lines' capacity represents a valid solution to avoid the construction of new assets.

Transmission capacity, which in terms of the maximum allowable current is called ampacity, is strictly related to the conductor's temperature and limited by the physical characteristics of the line itself, especially to the available phase-to-ground clearance. In other words, the ampacity depends on the current and on the local weather conditions, which largely affect conductor temperature [1].

The most common, but less accurate method to estimate the ampacity of an OHL is to consider the worst weather conditions for the heat exchange, (e.g. 0.63 m/s wind speed, 40°C environmental temperature, 1000 W/m2 solar irradiance, etc.). This method is called Static Thermal Rating (STR), and since it is very conservative and does not consider the conductor thermal inertia, it limits the full exploitation of transmission lines.

An alternative to this conservative method is represented by the Dynamic Thermal Rating (DTR), which allows to increase the considered available transmission capacity through real time measurements of conductor's temperature and ambient conditions [2-6]. Hence, DTR represents an additional flexibility source for the Transmission System Operators (TSOs) in case of grid congestions [7] and a useful tool for security assessment and contingency management [8].

The accuracy of DTR depends on the considered model. A simple approach can be to assume the same heat transfer conditions for all the conductor's span [9][10].

Other more precise approaches employ temperature measurements of conductors along the line at each time step (e.g. 1 minute) to solve the algebraic "mechanical problem", i.e. to calculate tensions, sags and clearances at each span of the line. Thus, advanced mechanical models of overhead line are able to provide a description of both the mechanical interactions between adjacent spans due to the insulator strings rotation and the variation of the conductor's temperature for each span due to different weather variables [11]. By means of these features, the mentioned methods can estimate the vertical and horizontal components of the conductors' mechanical tension. This consists of a sensible improvement of multi-span lines analyses, compared to the traditional simplified "ruling-span" technique [12] [13] [14].

Predicting ampacity of transmission lines require an accurate knowledge of local weather forecasts, whose accuracy strongly affects the DTR technique [4]. Since weather variables are better described by random variables, characterized by a time-dependent probability distribution function, probabilistic DTR was proposed as an improvement of deterministic DTR [3].

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On the other hand, weather forecasting accuracy can be improved through more advanced thermal rating prediction techniques, proposed in the literature [15].

Although the techniques presented in these papers have a great potential accuracy, they may introduce economic and technical challenges in terms of scalability [16].

A possible solution is based on employing cooperative sensor networks, which can improve accuracy by combining measurements of sensors distributed over all the line route [17]. These distributed sensors acquire temperature measurements directly and send the data to a central server for post-processing activities by a short-range communication system (e.g. via radio). This way the TSO obtains a trustable estimation of the actual thermal state of the line, and it is also able to know the location of the critical hot-spot along the route. Despite these benefits, the large-scale deployment of these technologies in modern transmission systems is still embryonic and several open problems need to be addressed. In particular, deploying reliable solutions involve the following technical requirements [18] [19]:

1. Detailed heat transfer modelling of conductors;
2. Distributed measurements, in order to assess the spatial profile of the temperature;
3. Self awareness of faults, data outliers or problems to the estimation process;
4. Time stamping capabilities, required to synchronize measurements over a wide area;
5. Adaptive features, which allow accounting for time-varying conditions;
6. Scalability, required for large networks.

These features are included in a distributed computing framework for DTR, conceptualized within the H2020 Osmose project, by ENSIEL consortium. The framework integrates a self-organizing sensor network composed by cooperative sensor nodes deployed along the line route, which estimate the loadability curve of the transmission line for a given period of time. These sensors allow measuring local weather variables and computing the corresponding conductor temperature by solving a calibrated thermal model.

II. OSMOSE PROJECT OVERVIEW

Osmose H2020 project started in 2018 and will end in 2021, it foresees the cooperation of 33 European partners. The project is currently at the beginning of the testing phase.

Working Package 5 (WP5) is led by Terna, the Italian TSO, and it involves various research centers, aggregators, universities and industrial partners.

The WP5 is focused on assessing and improving the flexibility services, both from technical and economical points of view, through a zonal Energy Management System (Z-EMS), managing DTR solutions and a DSR resources, for the optimal management of RES Generation, often responsible for grid congestions. The demo area is located in a 150 kV grid in South Italy.

In the following Section III, the new DTR Sensor Based method developed by Ensiel and selected for the project is described. In Section IV the first experimental results and issues are shown.

III. SENSOR BASED DTR METHOD

The role of Ensiel (University of Sannio) in the OSMOSE project has been the development of a DTR prediction technique, based on decentralized and self-organizing sensor networks, as shown in Fig.1.

The novelty of the proposed technique lies in the decentralization of all DTR functions through a cooperative sensor network, where each node is equipped with distributed consensus protocols. The information is spread through the network by updating sensors' states after calculating the weighted average of the neighbor states. This decentralized paradigm allows an accurate measurement of conductor's temperature and does not require a central server to process local measurements from different nodes. Among these "smart nodes", it is possible to distinguish Sensor nodes and Master nodes.

Sensor nodes periodically invoke the following interactive functions:

- Synchronization: adapts the local clocks through the theory of mutual coupling oscillators. In this way the clocks are locked to a common phase regardless of their frequency and without a centralized synchronization source.
- Acquisition: smart sensors acquire different sets of variables such as ambient temperature, wind speed and direction, solar irradiance, by querying a set of local sensors
- Conductor Temperature Calculation: starting from the set of measured weather variables and the set of conductor thermal parameters computed by the set of master nodes, the smart sensors estimate the corresponding conductor temperature by solving a built-in thermal model.
- Bad Data Detection: each node is equipped with estimation protocols which allow spotting failures and anomalies, through a protocol based on distributed consensus theory.
- Critical Span Location: the nodes cooperate by solving a max-consensus problem in order to estimate the hot-spot temperature along the line route.

Once the hot-spot temperature is estimated, it is sent from the front-end Sensor nodes to the Master node.

The role of the Master Node is to calibrate the parameters of the thermal model of the conductor, through the solution of an indirect parameter identification problem, which is continuously checked for consistency. The main input variables are conductor temperatures, weather variables and line current from the sensors on the network. These data are obtained through the communication between the Master Node, the cooperative sensor network, the central TSO server and the Meteorological Service Provider, feeding weather forecast profiles on a 3 to 6 hours ahead basis.

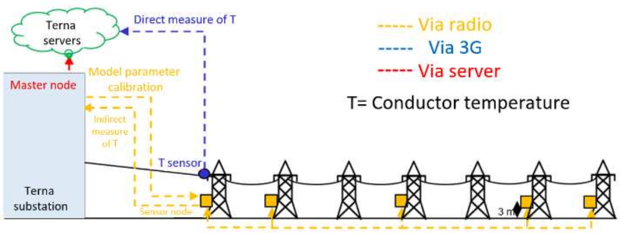

Fig. 1. Sensor-based DTR Architecture

IV. Experimental Setup

A. Installation on the lines

The DTR approach is already being used by Terna: more than one hundred sensors have been installed to measure the conductor's temperature. These sensors, which are hereinafter called "traditional sensors", are installed on conductors and communicate the measurements to Terna's servers via 3G.

OSMOSE project is testing the proposed DTR method on 7 lines of a 150 kV grid. On these lines, traditional sensors have been installed, together with weather-based solutions for two of them. For each of these two lines, Terna installed the aforementioned cooperative sensors system, mounting three sensors nodes on three different pylons.

The Master Node servers are installed in the closest substation and communicate via radio with the sensor nodes and other servers. In total, there are 6 Sensor Nodes and 2 Master nodes.

Fig.2 shows the distribution of the Sensor along the involved lines.

Line ID	Length [km]	# of Micca sensors	Type of Installation
701	14	2	Micca
702	8	1	Micca
729	16	2	Micca
705	11	2	Micca
938	15	2	Micca
934	10,8	2	Micca+Sensor Node
			Sensor Node
			Micca+Sensor Node
769	7,3	1	Micca+Sensor Node
			Sensor Node
			Sensor Node

Fig. 2 Comparison between STR (black line) and DTR (orange line).

B. ICT architecture

In order to allow the Master Nodes to interact with the power system operation tools, a distributed processing architecture has been designed and implemented under the OSMOSE Project. The proposed solution allows the sensors networks to communicate with:

1. SCADA system, in order to periodically acquire the line currents.
2. Conductor temperature sensors, in order to get measured data aimed at calibrating the built-in thermal model parameters.
3. Repository server, which is the common point of the ICT architecture that: *(i)* acquires the short term weather forecasts from RSE (Energy System Research), which are processed for predicting the line ampacity up to 3 hours ahead; and *(ii)* sends the computed ampacity curves to the zonal EMS, which integrates these data in solving optimal power flow studies.

C. Sensors

The sensors installed on the lines, in order to estimate ambient conditions, are the following:

- Ultrasonic 3D anemometer: which can measure wind speed up to 45 m/s and wind direction with a maximum expected measurement error of 1%.
- Temperature sensor: its working range falls between -40°C and 60°C, with an accuracy of +/- 0.15°C and resolution of 0.1 °C. It can also estimate humidity with a maximum measurement error of 2%.
- Thermopile sensor: used for solar radiation.

D. Experimental results

The described technique has been experimented on real 150 kV power lines. The measurements from sensor nodes are sent to Master Nodes, where they are gathered, through a cooperative radio-based TCP/IP network.

These data allow assessing the Key Performance Indexes (KPIs) characterizing the effectiveness of the proposed method, which quantify the increased amount of power which can be transmitted through the proposed methodology, compared to STR.

Fig. 3 shows the difference between the maximum transmission capability for 15 minutes, in terms of active power, between STR and the proposed DTR technique. Measurements are taken over an observation period of about 12 days. The STR transmission capability corresponds to the conservative conditions assumed in STR, such as absence of wind, high ambient temperature and maximum irradiation, whereas the proposed DTR depends on the estimated weather conditions. Fig. 3 demonstrates that DTR can be employed to greatly increase the utilization of the transmission line over a 15 minutes period: STR allows 100 MW as the maximum transmittable power, whereas calculations from DTR return values from 150 to more than 400 MW. This extra flexibility could be beneficial especially in managing emergency conditions.

The improved performance of the proposed DTR, over STR, is even clearer by plotting the corresponding duration curve, as in Fig. 4. The curve shows that for the considered time window, DTR allows improved short-term transmission capabilities. Hence, DTR can provide improved capabilities, which can keep the robustness characterizing STR.

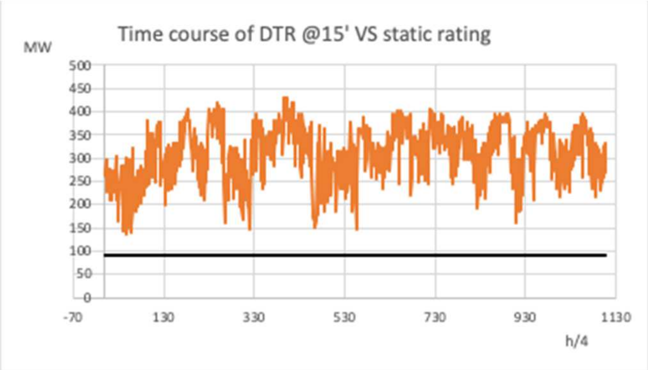

Fig. 3 Comparison between STR (black line) and DTR (orange line).

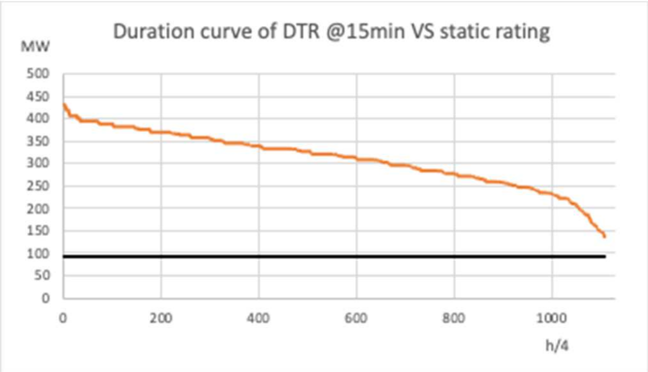

Fig. 4 Duration curve of DTR for both STR (black line) and DTR (orange line).

Furthermore, since the deployment of the proposed method allows the use of advanced short term forecasting and statistical models, the capability curve estimation can be considered robust against the intrinsic uncertainty characterizing weather variables.

Finally, the proposed DTR technique is being tested on additional sub-transmission lines, whose results will be presented in a future work.

V. Conclusions and Next Steps

This paper presented and discussed the first experimental results obtained by cooperative sensor networks-based DTR in real operation scenario. The overall sensor-based DTR framework has been developed by Terna and Ensiel, in the context of the European project OSMOSE.

The experimental results presented, showed how the proposed DTR technique can sensibly improve the line loading with respect to conventional STR-based approaches. Furthermore, the DTR estimation has been proven to be robust. Hence, it could be an important input for novel OPF formulations, constrained by dynamic load capability curves, instead of the traditional steady-state limits. This new formulation is expected to reduce the number of grid congestions, the power curtailments of RES, and the need for activating re-dispatching procedures.

Finally, WP5 of OSMOSE includes several flexibility resources, which require to test the whole ICT infrastructures for assessing the performances of the proposed EMS, which includes additional features than the proposed DTR method.

VI. Acknowledgment

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