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Experimental deployment of a self-organizing sensors network for dynamic thermal rating assessment of overhead lines

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ABSTRACT

Dynamic thermal rating (DTR) assessment of overhead lines is recognized as an enabling technology for reliably improving the exploitation of existing power transmission assets. In this context, the conceptualization of decentralized sensors networks aimed at performing all the DTR functions in an easy-to-use and well-defined way, represents one of the most promising research direction. To address this issue, this paper proposes a self-organizing computing framework based on a network of cooperative smart sensors, which solves the synchronization, identification and prediction problems required for DTR assessment, without the need for centralized data acquisition and processing. Experimental results obtained on a real test-bed are presented and discussed in order to demonstrate the effectiveness of the proposed framework.

1. Introduction

Modern power transmission systems are currently facing several challenging issues, which include the large increase of the electricity demand, which is expected to growth to 35% by 2030, the widespread deployment of the liberalized electricity markets, which resulted in a sensible increase of the power transactions, and the difficulties in upgrading the transmission assets, which are pushing power system components to operate closely to the their nominal ratings [1–6]. Consequently, the research for effective tools aimed at reliably increasing the components exploitation, by assessing their real load capability, represents a timely and relevant issue to address [7]. In the light of this need, overhead lines are one of the most promising application domain since they are frequently operated with reduced loading levels, representing the bottlenecks of transmission networks loading capability in many operating conditions. Consequently, a more effective exploitation of these components would have noticeable effects on power transmission system operation, increasing the loading flexibility, especially during emergency conditions [8,9].

Traditionally, Transmission system operators (TSOs) adopted static and precautionary thermal ratings in overhead lines loading, which are obtained by assuming conservative weather profiles (i.e. zero wind speed, and maximum solar radiation). This worst-case approach reduces the risk of potential line malfunctioning, but at the cost of a reduced power transfer capability, and a severe underutilization of the transmission asset [10,11]. In particular, when the line is operating at its nominal rating, and the actual weather conditions are more favorable than those assumed in the static thermal rating calculation, the conductor temperature lies well below its allowable limit. During these operating conditions, which are not infrequent in real application scenario, there is an extra power transfer capability that can be reliably exploited in addressing complex power system operation problems, including contingency management and security-constrained optimal power flow [12,13]. To this aim, the traditional thermal rating assessment procedures should be enhanced by adaptive models aimed at predicting, on short and medium terms, the real *load capability curves*, reporting the magnitude and the time duration of the electrical loads that the overhead line can reliably support. To address this issue, the adoption of analytical modeling techniques, based on simplified or detailed heat transfer Eqs. [14,15], is not a viable solution due to the difficulties in dealing with the strong uncertainties affecting the model parameters, and the complex spatial profiles of the meteorological variables ruling the heat-exchange along the line route [16].

Recently, thanks to the enhancement of modern distributed temperature sensing units based on fiber optical technologies, more advanced thermal rating prediction methodologies have been proposed in the literature [17]. The adoption of these advanced

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tools allows to accurately measure the conductor temperature profile, and to reliably predict the corresponding load capability margins on short and medium time horizons. Anyway, the large-scale deployment of these methods on existing overhead lines is still an open problem, and several critical issues should be addresses, such as the effective bounding of the optical fiber to the line conductors [18].

A promising research direction aimed at overcoming these limitations is based on the employment of cooperative sensors, which measure the conductor temperature along the line route, and send the acquired data to a central server by a wide-area communication network [19]. This sensors network, if properly designed and integrated with adaptive modeling tools, allows to reliably estimate the thermal state of the monitored asset, and its actual load capability. Despite these benefits, DTR assessment based on cooperative sensor networks is still embryonic and requires further investigations. In this context, the most promising research directions include [20,21]:

1. Enhance the sensor network with distributed estimation/detection features, in order to allow the sensors to reliably assess the spatial profiles of both the conductor temperature and the environmental variables, avoiding the need for deploying a central fusion center acquiring and processing all the raw measurements.
2. Deploy self-organizing paradigms aimed at allowing the sensors to detect and react to faults and measurement errors, which could compromise the thermal estimation accuracy.
3. Evolve from centralized to holistic computing architectures, in order to reduce the computational burden, and increase the computing reliability by deploying the DTR functions on distributed and cooperative sensors.
4. Implement a reliable time synchronization source, in order to allow the distributed sensors to measure the conductor temperature and the environmental variables with a unique and common time base.
5. Improve the sensor network scalability, in order to obtain flexible and cost-effective hardware deployments for different overhead line configurations.

Armed with such a vision, in this paper we outline the potential role of self-organizing sensors network in DTR assessment of overhead lines. In particular, we explore the possibility of decentralizing the entire set of DTR processing and synchronization functions on a network of interactive smart sensors deployed along the line route, and equipped with distributed consensus protocols, according to the computing architecture presented by the authors in Ref. [22]. The main idea is to start from the theory of information spreading for coordinating a network of cooperative smart sensors, which (*i*) acquire the conductor temperature by querying a local temperature sensor according to a common virtual clock, (*ii*) check for the consistency of the measured conductor temperature, (*iii*) estimate the conductor thermal parameters and the weather conditions, and (*iv*) compute the real load capability curve by exchanging and processing only local information. Thanks to these features, the smart sensors can synchronize their measurements, check their consistencies, and reliably compute the dynamic thermal ratings, without the need for a central server acquiring and processing all the local measurements.

Moreover, each smart sensor can compare the measured conductor temperature with the corresponding maximum, minimum and average values sensed by the entire sensor network, thus a comparison between local and global variables can be made at any time, and subsequent reactive actions can be taken if the sensor measurements strongly deviate from proper confidence intervals. This feature is very important in detecting data anomalies and/or sensor faults, hence improving the reliability of DTR assessment.

Experimental results obtained on a prototype smart sensors network installed on a thermally constrained overhead line of the Italian power transmission system are presented and discussed in order to prove the effectiveness of the proposed framework.

2. Dynamic thermal rating assessment by self-organizing sensor networks

In this section a DTR framework based on a network of cooperative and self-organizing sensors is conceptualized. The main idea is to decentralize the sensing, synchronizing and processing functions required for DTR assessment, by equipping the sensor nodes with distributed consensus protocols. The adoption of these protocols allows the distributed sensors to spread information across the communication network by updating their state by a weighted average of the state of their neighbors. Thanks to this feature the smart sensors can synchronize their local acquisitions, and dynamically assess the line thermal ratings without the need for a central fusion center acquiring and processing all the sensor measurements. To implement these tasks, each smart sensor periodically invokes the following interactive services:

- *Synchronization*: it manages the smart sensors time-synchronization by adopting a decentralized scheme based on the mutual coupling of proper dynamic systems. Thanks to this feature, the local clocks are able to lock to a common phase, despite the differences in the frequencies of the local oscillators, without the need for any global or hierarchical synchronization infrastructure;
- *Acquisition*: it adjourn the set of local variables, which include the environmental temperature, the line current, and the conductor temperature, by querying the local sensors;
- *Bad Data Detection*: it detects sensor failures and/or data anomalies, estimating the confidence intervals of the measured variables, by employing a decentralized estimation protocol based on the distributed consensus theory. This process allows each smart sensor to check if it can be considered as a “reliable node”;
- *Parameters Calibration*: this process, which is activated only if the smart sensor is marked as “reliable node“, identifies the actual value of the main parameters ruling the heat-exchange between the conductor and the environment (e.g. wind speed), by solving a parameter identification problem on the basis of the measured variables;
- *Temperature Calculation*: it validates the accuracy of the latest parameters set computed by the *Parameters Calibration* service by solving an embedded thermal model. If the difference between the predicted and measured conductor temperature lies below a fixed maximum threshold, the actual parameter set is considered as “validated”, otherwise a notification is sent to *Parameters Calibration* service, requiring asking an adjournment of the calibrated parameters set;
- *Critical Span Location*: this process, which is activated only if the smart sensor is marked as “reliable node”, estimates the highest conductor temperature measured on the entire line route by deploying a decentralized protocol aimed at solving the max-consensus problem;
- *Loadability Prediction*: this process, which is activated only if the smart sensor is installed at the critical span, computes the load capability curve, by invoking the *Temperature Prediction* service with a set of hypothetical load levels, and spreads the corresponding results to all the smart sensors. Thanks to this feature the TSO can acquire the load capability by enquiring any smart sensor.