On-line Control of DERs to Enhance the Dynamic Thermal Rating of Transmission Lines

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Abstract— **The increasing penetration of variable distributed generation causes the transmission lines to operate closer to their design thermal limits. In this context, Dynamic Thermal Rating is a very promising technique, since it permits a better exploitation of the real capability margins of the infrastructures and eliminate network congestions. In this vein, the paper proposes a novel control strategy that allows maintaining the conductor temperature of a given line within its thermal limit through the real-time curtailment of distributed energy resources in the network. The impact of weather volatility and measurement uncertainty on the dynamic response of the controller is evaluated. A comprehensive case study, based on a real-world Italian sub-transmission system and measurement data serve to illustrate the dynamic behavior of the proposed controller. The effect of measurement noise and delays is also discussed. Finally, the performance of the proposed control strategy is compared with a conventional robust optimal power flow approach.**

Index Terms— **Dynamic thermal rating, distributed energy resources (DERs), optimal power flow, wind curtailment.**

NOMENCLATURE

$B_{i,j}$	Imaginary part of auto/mutual admittance between the i^{th} and the j^{th} bus
$\mathbb{B}_{\mathrm{gen}}$	Set of generator buses
f_{obj}	Objective function of the W-OPF problem.
$G_{i,j}$	Real part of auto/mutual admittance between the i^{th} and the j^{th} bus
I	Line Current
mC_p	Heat capacity of the conductor
$P^{\mathrm{fix}}_{\mathrm{inj},i}$	Active Power injected in the i^{th} bus
$P_{\mathrm{gen},i}$	Active Power generated in the i^{th} bus
$Q^{\mathrm{fix}}_{\mathrm{inj},i}$	Reactive Power injected in the i^{th} bus
$Q_{\mathrm{gen},i}$	Reactive Power generated in the i^{th} bus
q_s	Heat exchange rate due to solar irradiation
q_c	Heat exchange rate due to convective cooling
q_r	Heat exchange rate due to radiative cooling
R	AC resistance of the conductor
T_c	Conductor Temperature
V_i	Voltage Magnitude at the i^{th} bus
$\boldsymbol{x}$	Vector of decision variables
$\boldsymbol{y}$	Vector of measurements
α	mean reversion speed of the stochastic processes
β	diffusion term of the Ornstein-Uhlenbeck process
δ	scaling parameter of the Student-t process
θ_{ij}	Angle difference of i^{th} and j^{th}voltage phasors
μ	location parameter of the Student-t process
ν	number of degree of freedom of the Student-t process
ξ	normally distributed white noise

I. INTRODUCTION

A. Motivations

The precise on-line measurement of a power system components' temperature enables the safe exploitation of electrical equipment without increasing the risk of failure or reducing the overall reliability of the system. This is the rationale behind the concept of Dynamic Thermal Rating (DTR) policies utilized in power system operation [1], [2]. Despite its name, DTR is rarely considered in the design of the controllers of power system devices. It is, rather, a constraint included in optimal power flow and unit-commitment problems. This paper considers the actual thermodynamic behavior of transmission lines and proposes a control scheme of DERs that aims at improving the DTR of transmission lines.

B. Literature Review

Overhead transmission lines (OHLs) have proved to limit the transmission capacity among areas characterized by extreme different generation/load ratios [3]. A large specialized literature exists on DTR of OHLs. These address various aspects, such as technologies for conductor temperature estimation and measurement [4]–[6]; techniques for robust management of uncertainties affecting parameters and weather variables [7], [8]; and location of the spatio-temporal profile of the hot-spot section of the line [9]–[11]. The current limit of an overhead line conductor (thermal current limit or TCL, also known as *ampacity*) is determined by the maximum temperature that the conductor can reach without suffering from deterioration [3]. Such a limit can be determined through the equation of the thermal balance of the conductor. This is the basis of the IEEE 738 [12] and the CIGRE TB601 [13] Standards for determining the TCL of a conductor. The two models are very similar and are strongly sensitive to the weather parameters surrounding the line.

The TCL, can be either a fixed or a dynamic thermal rate. Static thermal rating is obtained using highly unfavorable

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weather parameters so the conductor is protected under all circumstances. This means that the conductor is utilized below its real capacity for long periods. In order to improve this situation, reference [14] proposes different static rates depending on seasons, months, and day/night. On the other hand, the DTR allows increasing the TCL of the conductor without damaging it by means of real-time ampacity estimation [15]. This approach has the advantage of maximizing the ampacity but it also confronts risks in case of weather data losses or delays. In particular, data loss may force the operator to make a high drop of the current which may have consequences for the grid, but that is not as bad as receiving misleading information that can potentially damage the conductor. Examples of misleading information are considered in Section V.

Applications of the DTR concept use a first order thermal model – as those described in IEEE [12] and CIGRE [13] Standards – to compute the line capability curve based on actual or predicted weather variables or on the estimated value of the conductor temperature. This curve is the basis of DTR policies, since it provides, for given weather conditions, the relation between how much power a line can transmit and for how long.

The line capability curve allows formulating optimization problems able to take into account thermal constraints on transmission lines instead of conventional DTR rating. The literature refers to this category of problems as Electro-Thermal Optimal Power Flow (OPF) or Weather-based OPF (W-OPF) [16]–[21]. In [22], the authors propose a robust formulation of the W-OPF problem based on a specific self-validated computing paradigm, namely Affine Arithmetic, which allows taking into account the effect of uncertainty on both thermal and electrical variables as well as their mutual correlations. The objective function to be minimized is the renewable power curtailed by the system operator, which is made possible through the exploitation of the real capability margins of the lines.

C. Contributions

The paper presents an innovative control strategy that allows exploiting the full capacity of transmission lines based on a re-dispatching strategy while keeping the temperature of the conductors under their design limits.

The specific contributions of the paper are as follows.

- Design a novel control strategy to enhance the DTR of lines that connect DERs to the grid.
- Study the effect of weather volatility on the thermal behavior of the lines.
- Model and evaluate the impact of measurement errors and communication delays on the proposed control strategy.

D. Organization

The remainder of the paper is organized as follows. Section II introduces the concepts of DTR and W-OPF with their respective mathematical formulations. Section III presents the proposed control scheme and Section IV and V present the case study and the results of the application of such a controller based on a real-world network characterized by a high penetration of wind generation, respectively. Finally, Section VI draws conclusions and outlines future work.

II. BACKGROUND

A. OHL Thermal Model

The model regulating the transmission line's critical span thermal behavior is based in the following first order ordinary differential equation:

$$mC_p\dot{T}_c = q_s + I^2R(T_c) - q_c - q_r, \tag{1}$$

where T_c and I are the conductor temperature and current, respectively; R if the AC resistance of the conductor at T_c; mC_p is the total heat capacity of the conductor; and the remaining terms are defined by a set of non-linear algebraic equations that rule the main heat exchange phenomena affecting the conductor thermal state, i.e. convection (q_c), radiation (q_r) and solar heating (q_s). The set of parameters included in these equations depend on both external weather variables, such us wind speed and direction, environmental temperature, and several physical factors, including conductor material, line geometry, critical span location. A detailed description of this model can be found in [12].

B. Weather-based Optimal Power Flow

A variety of approaches have been proposed in the literature to deal with the DTR assessment of OHLs. These include, for example, taking into account (1) and integrating distributed sensors for the direct measurement of the conductor temperature. The integration of such techniques in advanced optimization frameworks, called Electro-Thermal or Weather-based Optimal Power Flow (W-OPF), have proved to reliably improve the components loadability, enhancing the congestion management flexibility and maximizing DERs' exploitation [17], [19], [22], [23].

The basic idea of W-OPF analysis is to integrate a DTR technique into the formulation of a conventional OPF. This is achieved by replacing the conventional static rating limits with dynamic component limits based on the maximum allowable hot-spot conductor temperature. The overall optimization problem can be formalized as follows [22]:

$$\min_{\boldsymbol{x}} \quad f_{\text{obj}}(\boldsymbol{x}) \tag{2}$$

$$\text{s.t.} \quad V_i^{\min} \le V_{i\in[1,\ldots,N]} \le V_i^{\max} \tag{3}$$

$$P_{\text{gen},i}^{\min} \le P_{\text{gen},i\in\mathbb{B}_{\text{gen}}} \le P_{\text{gen},i}^{\max} \tag{4}$$

$$Q_{\text{gen},i}^{\min} \le Q_{\text{gen},i\in\mathbb{B}_{\text{gen}}} \le Q_{\text{gen},i}^{\max} \tag{5}$$

$$T_{c,k\in[1,\ldots,N_l]} < T_{c,k}^{\max} \tag{6}$$

$$P_{\text{inj},i}^{\text{fix}} = \sum_{j=1}^{N} V_iV_j(G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij}) \tag{7}$$

$$Q_{\text{inj},i}^{\text{fix}} = \sum_{j=1}^{N} V_iV_j(G_{ij}\sin\theta_{ij} - B_{ij}\cos\theta_{ij}) \tag{8}$$

$$T_{c,k} = T_{c,k}(t_0) + \frac{1}{m_kC_{p,k}}\int_{t_0}^{t_f} \dot{T}_{c,k}(\tau)d\tau \tag{9}$$

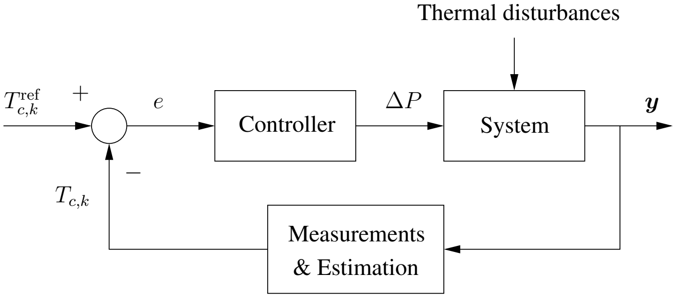

Fig. 1: Structure of the wind generator control scheme based on the thermal limits of transmission lines.

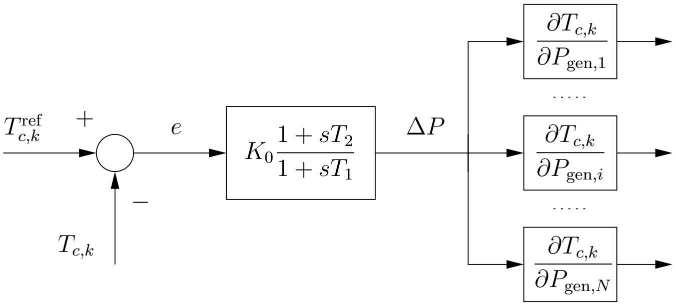

Fig. 2: Detailed control scheme for the wind curtailment.

where the decision variables $\boldsymbol{x}$ are:

$$\boldsymbol{x} = [\boldsymbol{P}_{\mathrm{gen}}, \boldsymbol{Q}_{\mathrm{gen}}, \boldsymbol{V}, \boldsymbol{\theta}, \boldsymbol{T}_c] \ .$$

The set of equations (2)-(9) defines an OPF problem, whose terms are described in the Nomenclature, and that includes thermal constraints of the critical lines. In particular, (6) represents the limit on the maximum allowable conductor temperature of the critical lines and (9) is the integral version of (1), which is evaluated using finite differences in the time interval $(t_f - t_0)$. Finally, the objective function $f_{\mathrm{obj}}(\boldsymbol{x})$ represents the amount of wind power curtailment.

The main issue in solving the optimization problem (2)-(9) lies in the large uncertainty affecting its parameters, namely, power injection fluctuations, conductor parameter drifting, and weather volatility. In [22], the OPF problem has been solved through the MATLAB `fmincon` function, that utilizes the Active-Set algorithm. The latter was shown to be reliable and effective to solve such an OPF problem. A comprehensive uncertainty analysis and the deployment of effective methodology for reliable computing are thus required in order to solve the problem. The interested reader can find an in-depth discussion of such a problem in [22].

III. ON-LINE CONTROL STRATEGY

Starting from the concept of electro-thermal coupling introduced by the W-OPF presented in [22], a technique based on a feedback control strategy is proposed in this paper. The idea is to regulate the maximum power injected by wind-farms distributed in the network, based on the temperature measurements of the conductors of relevant lines.

Fig. 1 shows the structure of such a control scheme where ΔP is the required power curtailment and $\boldsymbol{y}$ are the thermal states of the lines. This control scheme is independent from the DTR technology installed on the lines. In fact, $\boldsymbol{y}$ can be a measurement of the line conductor current or the result of a more complex estimation procedure which allows taking into account the spatio-temporal profile of the conductor hot-spot temperature [24].

We have tested a variety of the transfer functions of the controller of Fig. 1 and we have concluded the lead-lag controller is the best trade off between simplicity and performance. Once the re-dispatching power ΔP is determined, it has to be properly allocated among the selected generators. This can be done as in a conventional automatic generation control, as shown in Fig. 2.

To achieve an effective control, it is key to properly define an appropriate criterion to allocate the ΔP among the generators. A simple criteria is to weight the participation of each wind power plant based on its capacity. This approach works well in small networks with simple topology but, in general, can be ineffective if a generator has a little impact on the power flow of the considered line. This issue can be solved considering the sensitivity factors $\partial T_c / \partial P_{\mathrm{gen},i}$ in the control scheme in Fig. 2. These sensitivities can be computed as:

$$\frac{\partial T_{c,k}}{\partial P_{\mathrm{gen},i}} = \frac{\partial T_{c,k}}{\partial I_k} \frac{\partial I_k}{\partial P_{\mathrm{gen},i}} \tag{10}$$

where I_k is the magnitude of the current flowing in the line where the temperature is being monitored and the term $\dfrac{\partial I}{\partial P_{\mathrm{gen},i}}$, can be evaluated analytically, as discussed in [25], or approximated with numerical differentiation.

IV. CASE STUDY

In this case study, the dynamic behavior and performance of the proposed control strategy are evaluated and compared with the application of the robust W-OPF procedure described in [22]. The grid considered in this case study is a real-world section of a 150 kV sub-transmission system characterized by high penetration of wind generators, as shown in Fig. 3.

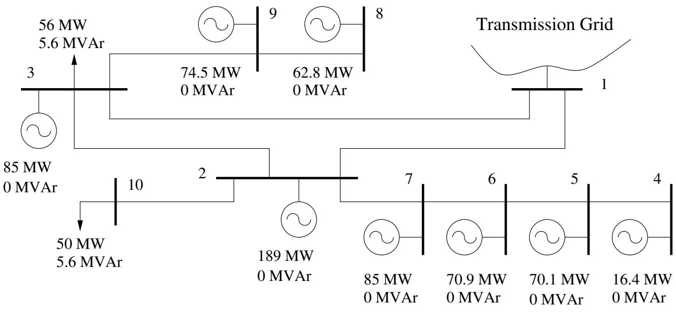

Fig. 3: 10-bus 150 kV test network.

Lines connecting buses 1-2 and 1-3 are equipped with DTR enabling technologies consisting in conductor temperature and/or weather variables sensors. These sensors continuously provide information to the operator control center about the thermal state of the lines and weather conditions in their surrounding. In the simulations, the temperatures of the aforementioned lines conductors are controlled as discussed in Section III.

V. Discussion of Simulation Results

Based on the case study described in the previous section, the following scenarios are considered. Section V-A shows the transient behavior of the proposed control scheme in ideal conditions, i.e., without considering noise. Section V-B discusses the impact of stochastic fluctuations of wind speed, direction and environmental temperature. Section V-C takes into account measurement errors and delays. Finally, Section V-D compares the dynamic response of the conductor temperatures obtained with the proposed control and with the W-OPF problem (2)-(9).

A. *Performance of the Control with Ideal Measurements*

The performance of the control scheme described in Section III is discussed by investigating its dynamic response following a wind speed ramp. A set-point of 333 K is assumed for the conductor temperature of the two lines under study, namely, lines 1-2 and 1-3. In this scenario, we consider ideal (deterministic) measurements and the 15-minute-rate wind forecast shown in Fig. 4 (black trajectory). Such a wind profile is based on actual measurement data.

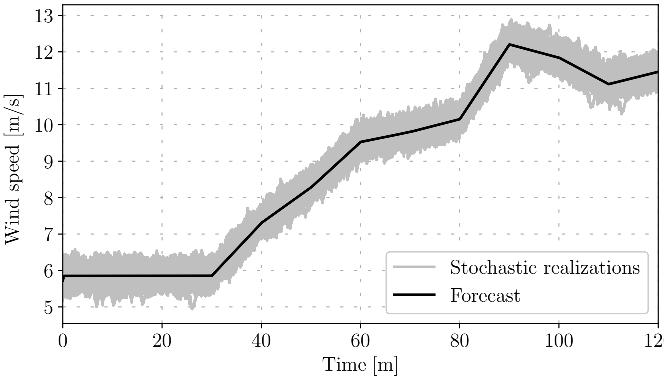

Fig. 4: Wind speed profile.

Figs. 5 and 6 show the effect of the controller on the wind power curtailment and conductor temperature, respectively. The lead-lag controller shows a relatively small steady-state error. However, the curtailment power signal has a smooth transient behavior, which makes this controller adequate for practical implementations. The latter is a very important feature, since the data acquisition rate characteristics of the measurement chain can sensibly affect the economic feasibility of the proposed architecture.

B. *Effect of Wind and Temperature Fluctuations*

This section discusses the impact on the proposed control scheme of weather uncertainty and volatility. With this aim, stochastic fluctuations are modeled as additive noise using the Ornstein-Uhlenbeck process, as follows [26]:

$$\dot{x} = -\alpha\, x + \beta\, \xi \,, \tag{11}$$

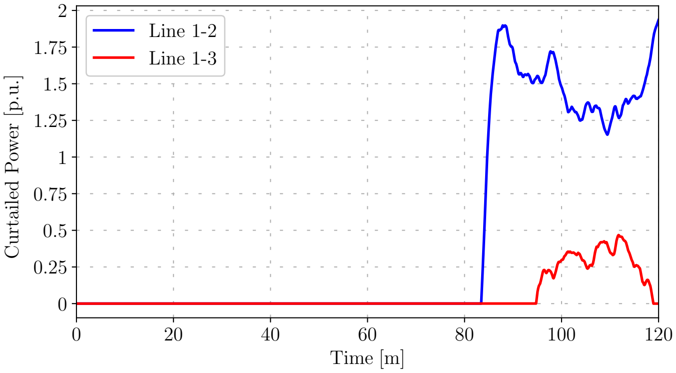

Fig. 5: Impact of lead-lag controller: curtailed wind power.

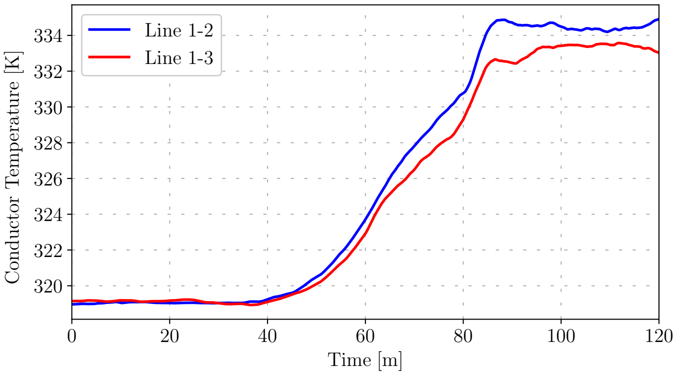

Fig. 6: Impact of lead-lag controller: conductor temperature.

where ξ is the normally distributed white noise and α and σ are the mean reversion speed and diffusion term, respectively, of the process whose variance is thus given by $\sigma^2 = \beta^2/(2\alpha)$.

Stochastic fluctuations are added to the following variables:

- Wind speed of wind power plants ($\alpha = 0.01$, $\beta = 0.2$) as shown in Fig. 4 (gray trajectories).
- Wind speed direction in the critical transmission lines ($\alpha = 0.017$, $\beta = 0.5$).
- Environmental temperature in the critical transmission lines ($\alpha = 0.01$, $\beta = 2$).

Figs. 7 and 8 show the curtailed power signal and the temperature, respectively, for 1,000 Monte Carlo simulations. Simulation results show that the proposed control scheme is robust with respect to the randomness introduced by weather volatility, keeping the conductor temperature under its limit value. Moreover, the static error of the lead-lag controller is at most 2°C (see Fig. 8).

C. *Practical Consideration on the Temperature Measurement*

The most important measurement of the proposed control scheme is the temperature of the conductors of the transmission lines. The quality of this measurement can be deteriorated by several practical issues. The data acquisition performed by weather stations may involve several potential problems that must be taken into account for the estimation of the dynamic rate of an overhead line. Reference [7] discusses the consequences of the variation of weather parameters.

In particular, the location of the weather stations has a significant impact on the estimation of conductor temperatures.

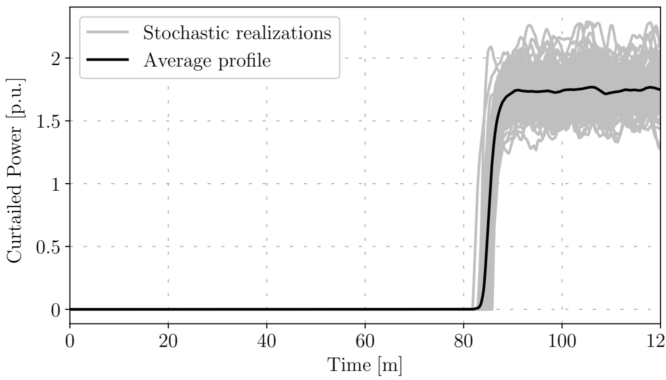

Fig. 7: Curtailed wind power – Monte Carlo simulation.

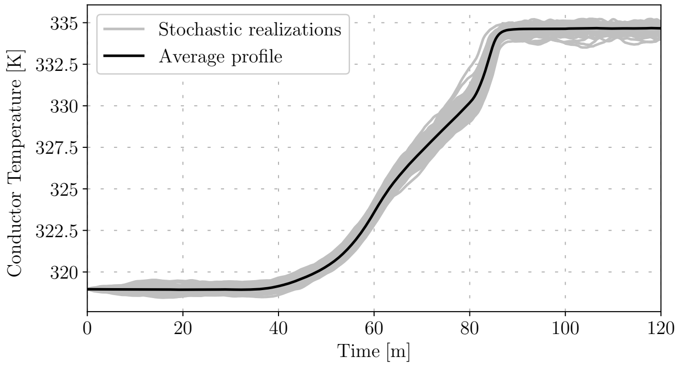

Fig. 8: Conductor temperature – Monte Carlo simulation.

The stations should be placed in the point of the line with most unfavorable weather conditions. However, such locations are often in places with no access to reliable power supply nor communications, such a mountain forest far away from a reliable power supply.

There are two solutions to this problem. Either install the weather station in a convenient location, which however is not the optimal one or, install the weather station in the optimal location and feed it through DERs. In the first scenario, i.e., using a station far away from the optimal locations, measurements can be affected by both by systematic and stochastic errors. In the second scenario, it is possible that the DERs do not provide, in certain periods, enough power to supply the weather stations. If the power supply has low reserve, sampled weather data are sent to the control center with low rate, e.g., every ten minutes or more. These two scenarios are considered in sections below.

1) Measurement Errors: As discussed in Section III, the conductor temperature measurement/estimation process represents the weak link of the proposed DTR-based on-line control. This section discusses the effect of measurement errors on the transient response of the proposed control strategy.

Based on measurement data taken at both the optimal and non-optimal locations of transmission line in Northern Spain, the temperature errors have been modeled through a Student Ornstein-Uhlenbeck-type t process, as follows [27]:

$$\dot{\Delta T} = \alpha(\mu - \Delta T) + \sqrt{\frac{2\alpha\delta^2}{\nu - 1}\left[1 + \left(\frac{\Delta T - \mu}{\delta}\right)^2\right]}\,\xi \ , \quad (12)$$

where ξ is the normally distributed white noise, α is the mean reversion speed, μ is the location parameter, δ is scaling parameter, ν is the number of degree of freedom. The Student t-process has probability distribution function:

$$\mathrm{PDF}_t(\Delta T) = c(\nu, \delta)\left[1 + ((\Delta T - \mu)/\delta)^2\right]^{-(\nu+1)/2} \ , \quad (13)$$

where:

$$c(\nu, \delta) = \frac{\Gamma(\frac{1}{2}(\nu + 1))}{\delta\sqrt{\pi}\Gamma(\frac{1}{2}\nu)} \ , \quad (14)$$

where Γ is the incomplete unnormalized Gamma function. The Student t-process has been chosen as its distribution fits better than the normal distribution a series of measurement data acquired by sensors installed around transmission line. The parameters used in the simulations are $\alpha = 0.00008$, $\mu = -0.25$, $\delta = 1$ and $\nu = 3$. The stochastic fluctuations ΔT are finally included in the actual value of the temperature T_c utilized by the proposed control scheme (see Fig. 9.a).

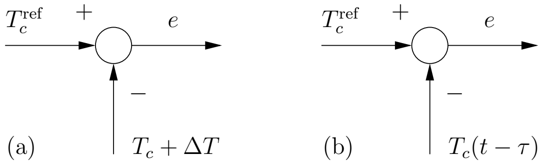

Fig. 9: Temperature measurement issues: (a) error ΔT; (b) delay τ.

Simulation results show that the proposed control scheme is robust against temperature measurement errors, since in the worst case condition such errors leads to an overestimation of the conductor temperature of almost 2°C (see Fig. 11). An in-depth comparison of Figs. 10 and 11 indicates that the main effect on the true conductor temperature profiles are due to systematic deviation of the estimated profile, while almost all the "noise" content is filtered by the thermal inertia of the conductor. Thus, once the effect of the uncertainty associated with the measurement errors is fully characterized, it is possible to compensate it by defining an acceptable risk of overloading and easily define a precautionary correction to the measured temperature which make the control action robust against the measurement/estimation errors.

Fig. 10 shows that the temperature of the conductors can be over-estimated. This leads to an unnecessary wind curtailment. While not compromising the safe operation of the system, such a conservative control may lead to increase the operational costs of the grid. The controller can be made more robust by implementing a consensus strategy that utilizes backup temperature estimation processes based on different physical phenomena, e.g. those based on PMU measurements at the ends of the line [23], [28].

2) Measurement Delays: As discussed above, the collection of conductor temperature measurements can be delayed due to the low transmission rate of remote weather stations. Another cause of delay is the case of the measurement of the conductor temperature by means of an optical fiber with Bragg grating inside the conductor [29]–[31]. The measurement of the temperature is progressive along the line and can take

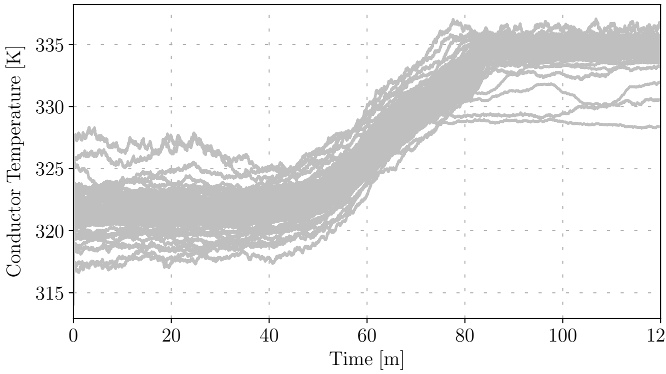

Fig. 10: Estimated conductor temperature of line 1-2. The temperature in line 1-3 shows similar trajectories.

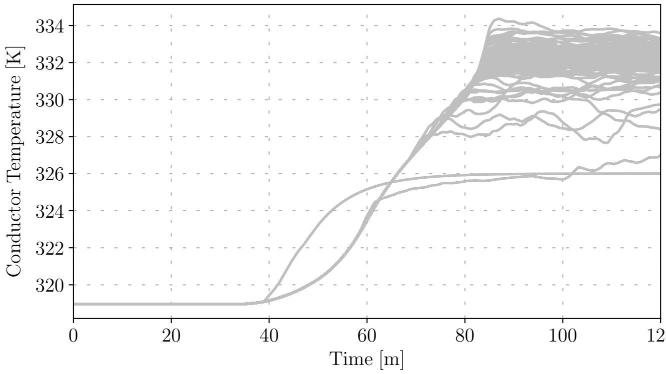

Fig. 11: Conductor temperature in line 1-2.

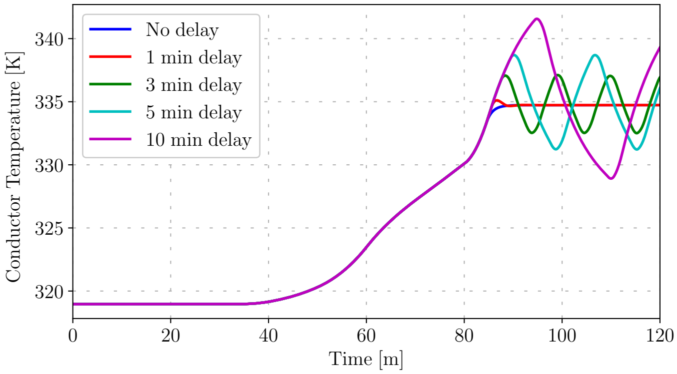

Fig. 12: Effect of delay – Line 1-2

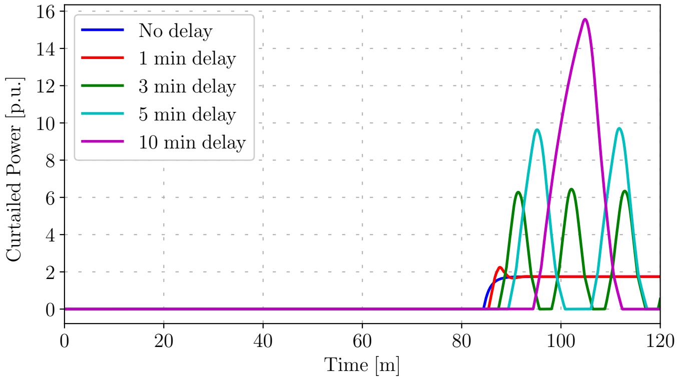

Fig. 13: Effect of delay – Curtailed Power

several minutes depending on the resolution. The result is a temperature vector where the values do not belong to the same instant but to the same several minutes interval so the provided data is an average of the all period between samples.

This section studies the impact of delay on the proposed control scheme (see Fig. 9.b). Results of these analyses show that the delay has a negative effect on the proposed control strategy. In particular, Figs. 12 and 13 show that a 3 minute delay already causes an instability of the control action. Simulation results indicate that the maximum acceptable delay in the proposed control scheme is about 1 minute. This implies that it is preferable to install the weather station in a non-optimal locations and have a continuous communication of the temperature measurements, rather than having precise but delayed measurements. These results also indicate that one-minute delay is the "delay margin" of the proposed control scheme for the considered case study. This means that all possible sources of delays must sum up a delay lower than one minute for the controller to be stable.

D. *W-OPF vs On-Line Controller*

In this section, we compare the performance of the proposed approach with the regulation actions provided by a robust W-OPF methodology in order to demonstrate its better performance for on-line application. In particular, Fig. 14 shows the comparison of the potential power generation of the WT installed at bus 2 and the one due to the curtailment action; Fig. 15 shows the conductor temperature profile; and Fig. 16 shows the wind-curtailed power profiles obtained using the set-points computed through the solution of a W-OPF problem are depicted.

The results above show that the proposed real-time control strategy performs well and achieves energy curtailments always sensibly lower with respect to those produced by W-OPF. Indeed, a close observation of Figs. 7 and 16 shows that the average power curtailment, in both cases, is around 1.6 p.u. It is also important to highlight that the control action of the controller starts always around min 85, while the W-OPF one starts around min 50. This happens because the proposed architecture allows maximizing the exploitation of the conductor capability margins and exploit its thermal inertia.

Another advantage introduced by this architecture lies in its immunity towards gross forecasting errors which may lead to severe under/over-estimations of the conductor temperature, hence to wrong decision, increasing the risk of line's overloading.

On the other hand, since the proposed approach is based on conductor temperature measurement/estimation, the robustness of such a measurement/estimation is crucial. Wrong values of the conductor temperature may lead to overload the transmission lines or to increase operational costs. Another relevant remark is the fact that, unlike the W-OPF, the proposed control strategy does not take into account all constraints included in the system but just the thermal limit of the transmission lines. Since such a limit is the one that is binding, the on-line control scheme is more effective than the off-line W-OPF. Table I summarizes the pro and cons of the proposed approach with

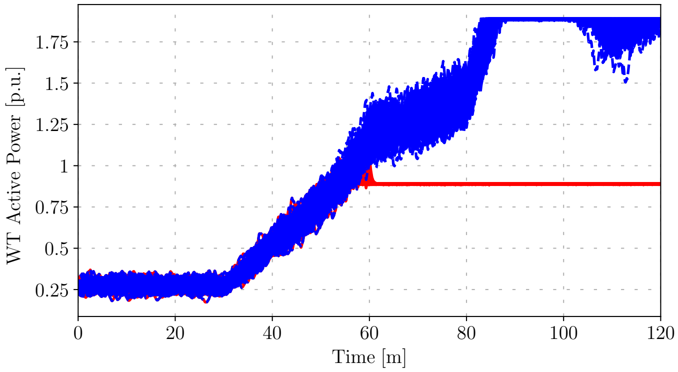

Fig. 14: W-OPF – full power (blue) vs curtailed power output (red).

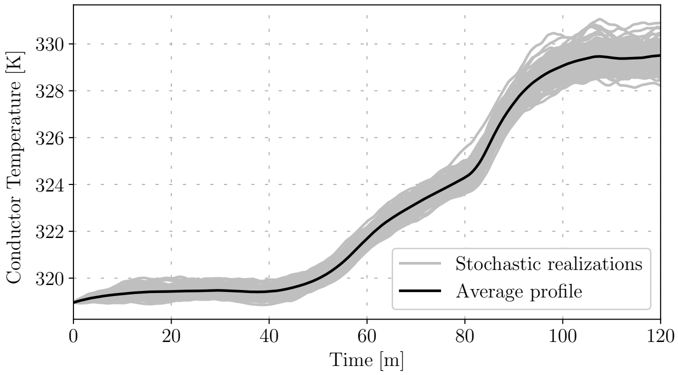

Fig. 15: W-OPF – Conductor temperature.

respect to W-OPF.

TABLE I: Control vs W-OPF

Pro	Cons
- robustness w.r.t. forecasting errors	- need for robust measurement systems
- robustness w.r.t. weather volatility	- not easy to guarantee well operating conditions among all the state variables of the system
- maximum line utilization rate	

VI. Conclusions

The paper discusses an on-line centralized control scheme to the reduce the curtailment of wind power plants and improve the utilization rate of critical transmission lines. A real-world Italian sub-system as well as series of measurement data are used in the case study. Simulation results lead to conclude that a simple lead-lag controller provides an adequate dynamic response and its performance considerably improves existing techniques based on the off-line solution of an optimization problem. The results of simulations with realistic temperature measurement errors and delays indicate that while measurement errors can be easily compensated, a delay above 1 minute is detrimental for the effectiveness of the proposed control. This requirements can be satisfied by installing the weather station in locations that ensure an uninterrupted supply of the weather station itself and thus uninterrupted transmission of the measurement data.

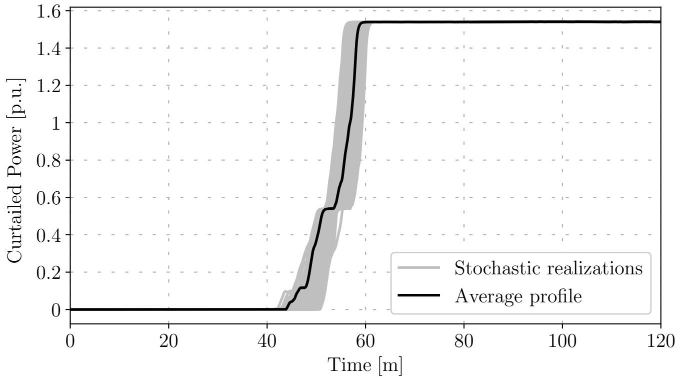

Fig. 16: W-OPF – Curtailed power.

Future work will focus on improving the proposed strategy, for example including weather forecasts and additional measurements from the system.

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