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Optimal power flow considering line-conductor temperature limits under high penetration of intermittent renewable energy sources

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ABSTRACT

Forecasts of the power generated by intermittent renewable energy (IRE) sources are typically characterized by high uncertainty levels. Hence, recent formulations of the optimal power flow (OPF) problem incorporate the costs associated with the increased risk of generation shortage due to IRE uncertainty. Additionally, IRE generation increases the power flow uncertainty, thereby increasing the possibility of violating the thermal limits of overhead conductors. Real-time monitoring of the thermal statuses of overhead lines has been considered effective in increasing the transmission-system usage; in addition, it can influence IRE scheduling and the associated uncertainty costs. This paper proposes the formulation of an OPF problem incorporating the thermal characteristics of the conductor, calculated from the monitored weather parameters, for a system with significant IRE-source generation. The resulting convex nonlinear optimization problem is solved using a primal-dual interior point solver. A simplified form of the overhead-conductor heat balance equation that expresses the conductor temperature as an explicit function of the current is proposed, simplifying the incorporation of the conductor thermal characteristics in the problem formulation. The application of the proposed formulation is demonstrated using a modified version of the IEEE 30-bus test system with IRE generation.

1. Introduction

Environmental concerns, government support, and advances in technology render intermittent renewable energy (IRE) sources economically viable, resulting in steady increases in their proportions in electric power networks [1]. While the advantages of these green energy sources are numerous, one of the main operational challenges is the high uncertainty in their output. Forecasts of the power available from the IRE sources used for establishing the system-generation schedules are generally characterized by uncertainty levels that are higher than typical in traditional load and generation forecasts [2]. This increased uncertainty in the available generation necessitates the operation of relatively more expensive, fast-acting spinning reserves to substitute for the generation shortages in real time, which result from the overestimation of the available IRE power in the system [3,4].

Energy management, i.e., economic dispatch (ED), unit commitment (UC), and optimal power flow (OPF) in networks with significant proportions of generation from IRE sources require mechanisms for handling the increased uncertainty owing to the intermittency of these sources. Practically, this can be realized in two ways: The first approach involves the application of stricter reserve requirements to ensure generation adequacy, even with large overestimations of the IRE output [5,6]. The reserve requirements can be set deterministically for worst-case forecasting conditions or stochastically, considering the statistical distribution of the IRE forecasts [7]. Alternatively, a risk-based approach, which adds an IRE-output uncertainty-related cost in the problem objective function, can be adopted. Several risk-based energy management approaches have been proposed in literature, utilizing stochastic programing techniques [8,9], chance-constrained approaches [10–12], and robust optimization [13,14]. While the underlying formulations and solution approaches may differ, the IRE uncertainty (risk) cost increases with the increase in the scheduled IRE output; the cost curve being dependent on the IRE source statistical characteristics (expected value and variance of the IRE output; and the statistical distribution of the forecasting error).

In addition to affecting the operational costs, increased IRE generation alters the line flows in a power system, which in turn increase the probability of violating the thermal limits of the transmission lines [15]; this mostly occurs in networks where the IRE sources are concentrated at particular locations in the system. Traditionally, highly conservative approaches are used in setting the line-flow limits; the maximum conductor current (or power) is calculated assuming poor cooling conditions (low wind speeds and high ambient temperature) [16,17]. The resultant rating, referred to as the static line rating (SLR),

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can be expensive because it may restrict the use of certain transmission paths carrying power from cheaper generation sources. Additionally, this may impact the scheduled IRE generation, which is characterized by near-zero fuel costs.

Ambient weather conditions around overhead transmission lines have a significant impact on conductor cooling and consequently, on their thermal limits [18–20]. Therefore, the conservativeness enforced by the SLR approach can be relaxed by monitoring the ambient weather conditions around the conductor and by utilizing this data to estimate the conductor temperature and loadability. An approach in which line rating (in terms of power or current carrying capacity) is continuously varied based on monitoring of prevailing weather conditions is referred to as dynamic line rating (DLR) [16,21].

It has been variously demonstrated that the less conservative approach of setting transmission line loadability based on conductor monitoring can results in benefits for both system operators and electricity consumers. Uski [22] shows that DLR could increase area-to-area transmission capacity thereby impacting electricity prices and benefiting electricity consumers. Nick et al. [23] demonstrate reductions in the optimal system operating costs based on a solution of the conventional UC problem with DLR. Simms and Meegahapola [21] illustrate an increase in the utilization of wind power owing to increased loadability of a transmission line connected to a wind farm. Similar results are reported by Xu et al. [24] who demonstrate that more wind power can be integrated into the grid with reduced load and IRE generation curtailments. The explicit incorporation of the overhead-conductor thermal characteristics in power system energy management software is illustrated in Banakar et al. [25], under the concept of electro-thermal coupling (ETC). The authors extend their work by illustrating possible practical applications of ETC in Alguacil et al. [26].

While the potential benefits are clearly apparent, a challenge exists in the direct use of the conductor temperature limits in the solution of the OPF and UC problems because of the complex, nonlinear nature of the equations that model the heat transfer processes acting on the conductor. In Wang and Han [27] the problem complexity is reduced by ignoring the variations of conductor heating and cooling rates with temperature. Similarly, in Banakar et al. [25] and Alguacil et al. [26] constant conductor heating and cooling rates are assumed resulting in an over-simplified formulation though the simulations illustrate the benefits of DLR. Additionally, formulations that study the link between IRE integration and relaxed transmission line ratings such as Xu et al. [24] assume perfect IRE forecasts thereby neglecting costs due to the uncertainty of the IRE sources.

This paper deals with the formulation and solution of the OPF problem considering uncertainty costs due to the IRE sources and explicit conductor temperature limits calculated from monitored ambient weather conditions. In summary, the main contributions of the proposed formulation can be summarized as follows:

(i) The thermal characteristics of monitored overhead conductors are incorporated using a simplified version of the heat balance equation (HBE) that retains the dependence of conductor temperature on ambient weather conditions.
(ii) The proposed formulation considers not only the cost of conventional generation but also the costs due to uncertainty of IRE sources in the power system.
(iii) A detailed analysis and discussion of the effects of monitored weather conditions on generation scheduling and related costs is also presented.

The proposed conductor temperature model simplifies the integration process with the existing OPF-problem solution software. Numerical simulations conducted on a typical test system demonstrate the effects of the IRE uncertainty costs and the economic benefits of conductor-temperature monitoring, based on the OPF solutions. In addition, sensitivity analyses illustrate the dependence of the obtained generation schedules on the IRE uncertainty costs and the monitored conductor temperature.

The remainder of the paper is organized as follows. Section 2 introduces the CIGRE model for the calculation of the overhead-conductor temperature and the proposed simplified version applied in this paper. The formulation and solution methodology for the OPF problem, with the IRE uncertainty costs and explicit conductor-temperature limits, are presented in Section 3. The numerical simulations are described in section 4 and research conclusions are drawn in Section 5.

2. Conductor-temperature calculation

The thermal characteristics of an overhead conductor are governed by the heating and cooling processes acting on it. The two main mathematical models used in industry for estimating conductor heating and cooling, and by extension, the conductor temperature and rating, are those proposed by the CIGRE [28] and IEEE [29].

Both the models describe two main heating and cooling processes. Conductor heating is a result of (1) *Joule heating*, which is the effect of electric-power-loss conversion to heat, as current flows through the conductor and (2) *solar heating* due to the absorption of solar radiation energy by the conductor, when exposed to the sun. On the other hand, conductor cooling is due to (1) *radiative cooling*, when the heat energy is radiated away from the conductor surface owing to the temperature difference between the conductor surface and ambient air, and (2) *convective cooling*, which occurs mainly when heat energy is carried away from the surface of the conductor by wind blowing across it. At low wind speeds, convection occurs as a natural process, as cold air slowly replaces the hot air on the surface of the conductor. Other thermal processes that may act on the conductor but whose effects are relatively small and can be neglected in the calculation of the conductor temperature include magnetic heating, heating due to corona effects, and evaporative cooling [28]. The mathematical models for the four thermal processes are outlined in the following subsection.

2.1. Original CIGRE model

2.1.1. Solar heating

The solar heat gain, P_S, is given by

$$P_S = \alpha_s DS, \tag{1}$$

where S is the global solar radiation, D is the overall conductor diameter, and α_s is the conductor solar absorptivity factor. α_s varies from 0.23 for bright, stranded aluminum conductors to 0.95 for weathered conductors in industrial environments. Generally, a factor of 0.5 is adopted for convenience [28].

2.1.2. Joule Heating

The Joule heat gain, P_J, is given by the electric power loss equation:

$$P_J = R_{ac}^{T_c} I_c^2, \tag{2}$$

where I_c is the conductor current and $R_{ac}^{T_c}$ is the AC resistance. $R_{ac}^{T_c}$ is dependent on the conductor temperature, T_c:

$$R_{ac}^{T_c} = R_{ac}^{T_{ref}} [1 + \alpha (T_c - T_{ref})], \tag{3}$$

where α is the temperature coefficient of the resistance and $R_{ac}^{T_{ref}}$ is the AC resistance at a reference temperature, T_{ref}. Eq. (3) can be re-written as

$$\begin{aligned} R_{ac}^{T_c} &= R_{ac}^{T_{ref}} \cdot [1 + \alpha (T_a - T_{ref}) + \alpha (T_c - T_a)] \\ &= R_{ac}^{T_a} + \alpha R_{ac}^{T_{ref}} T_x, \end{aligned} \tag{4}$$

where $T_x = T_c - T_a$.

The first term of (4) represents the AC resistance at ambient temperature, whereas the second term represents the increase in conductor resistance when its temperature increases above T_a.

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