Weather-Adaptive Carbon-Aware Optimal Power Flow: Synergizing Dynamic Line Ratings and Meteorological Dispersion via ML-Assisted Optimization

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The Weather-Aware Carbon Optimal Power Flow (WA-C-OPF) problem is formulated as a nonlinear optimization problem.

Nomenclature & Parameters

Sets and Indices

- $t \in T, g \in G, i \in N$: Time intervals, generators, buses
- $j \in N_i$: Set of buses connected to bus i
- G_i: Set of generators located at bus i

Decision Variables $x = \{P_{g,t}, Q_{g,t}, V_{i,t}, \theta_{i,t}\}$

- $P_{g,t}, Q_{g,t}$: Active/Reactive power of gen g at t
- $V_{i,t}, \theta_{i,t}$: Voltage mag/angle at bus i at t

System & Network Parameters

- $P_{D_{i,t}}, Q_{D_{i,t}}$: Active/Reactive power demand
- G_{ij}, B_{ij}: Conductance, Susceptance of line (i, j)
- R_{ij}, X_{ij}: Resistance, Reactance of line (i, j)
- I_{ij}, I_{ij}^{max}: Current and max limit for line (i, j)
- Pop_g: Population density factor near gen g

Weather-Adaptive Modifiers

- $D_g(t) = 1 + \eta_g \max(0, T_{g,t} - T_{ref})$: Thermal degradation multiplier (efficiency lost per °C) where η_g is efficiency of generator

Revised Objective Function

Minimizes degradation-aware generation cost and weather/population-weighted carbon emission cost:

$$\min \sum_{t \in T} \sum_{g \in G} \left[D_g(t) \cdot C_g(P_{g,t}) + \lambda \left(\frac{Pop_g}{MDI_{i,t}} \right) \cdot \alpha_g \cdot P_{g,t} \right] \tag{2}$$

- $D_g(t) \cdot C_g(P_{g,t})$: Active power generation cost, adjusted for thermal degradation efficiency losses.
- $\lambda(Pop_g/MDI_{i,t})$: Composite penalty combining population density and Meteorological Dispersion Index. Lower MDI (poor dispersion) and higher populations heavily penalize emissions.
- $\alpha_g \cdot P_{g,t}$: Weather-aware carbon emissions, where α_g is the carbon emission factor.

Equality Constraints

Active & Reactive Power Balance (Let $P_{i,t}^G, Q_{i,t}^G$ be total generation at bus i):

$$P_{i,t}^G - P_{i,t}^D = \sum_{j \in N_i} V_{i,t} V_{j,t} [G_{ij} \cos(\theta_{i,t} - \theta_{j,t}) + B_{ij} \sin(\theta_{i,t} - \theta_{j,t})] \tag{4}$$

$$Q_{i,t}^G - Q_{i,t}^D = \sum_{j \in N_i} V_{i,t} V_{j,t} [G_{ij} \sin(\theta_{i,t} - \theta_{j,t}) - B_{ij} \cos(\theta_{i,t} - \theta_{j,t})] \tag{5}$$

Slack Bus Angle: $\theta_{s,t} = 0 \quad \forall t \in T$ (6)

Temperature Dependent Resistance & Weather-Based Heat Balance:

$$R_{ij}(T_{ij,t}) = R_{ref}[1 + \alpha(T_{ij,t} - T_{ref})] \tag{7}$$

$$I_{i,j}^2 R_{ij} + \alpha_s G_t D = h(v_t) \pi D (T_{ij,t} - T_{a,t}) + \epsilon \sigma \pi D (T_{ij,t}^4 - T_{a,t}^4) \mathbf{[1]} \tag{8}$$

Where: $T_{a,t}$ = ambient temp, T_{ref} = ref temp, α = temp coefficient, v_t = wind speed, $h(v_t)$ = convective heat transfer, G_t = solar radiation, D = conductor diameter, α_s = solar absorptivity, ϵ = emissivity, σ = Stefan-Boltzmann constant.

Inequality Constraints

Generator Limits:

$$P_g^{min} \le P_{g,t} \le P_g^{max} \tag{9}$$

$$Q_g^{min} \le Q_{g,t} \le Q_g^{max} \tag{10}$$

Voltage Limits:

$$V_i^{min} \le V_{i,t} \le V_i^{max} \tag{11}$$

Current Limit:

$$\frac{V_{i,t}^2 + V_{j,t}^2 - 2V_{i,t}V_{j,t}\cos(\theta_{i,t} - \theta_{j,t})}{R_{ij}^2 + X_{ij}^2} \le (I_{ij}^{max})^2 \tag{12}$$

References: [1] IEEE Standard for Calculating the Current-Temperature Relationship of Bare Overhead Conductors, IEEE Std 738-2012.