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Optimal energy management of a distribution network during the course of a heat wave

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ABSTRACT

Heat waves are prolonged periods of excessive ambient temperature that may last up to several weeks. In addition to posing health threats to the society, these events may easily push the power grid towards its operational limits. The maximum capacity of many energy resources gets negatively affected by excess temperatures. This can be in addition to the expected loss of life due to operation under harsh conditions. Overhead lines, on the other hand, experience excessive conductor surface temperatures that can drastically reduce their power transmission capacity. To make matters worse, the reduction in generation and/or transmission capacity will coincide with a rise in electric demand, often attributed to the overutilization of air-conditioning systems. This can jeopardize the ability of the power grid to maintain system stability. A key to ensuring that the grid continues operating safely and securely is to incorporate the effect of temperature into its operation schedule. In this paper, we propose an optimal generation dispatch strategy for a distribution grid exposed to a heat wave event, while taking into account the dependence of operational constraints of various components on ambient temperature. We study a power grid equipped with renewable and non-renewable distributed generation, battery energy storage, and demand responsive loads. We evaluate the effectiveness of our proposed approach on a test system with data acquired from the heat wave event of July 2006 in Sacramento, CA.

1. Introduction

The last decades have witnessed severe changes in weather patterns. Among extreme weather events, past instances of heat waves in the United States especially in 2006 and 2012 [1,2], as well as the 2003 heat wave in Europe and some parts of Asia [3,4] and the 2009 heat wave in Australia [5] have gained widespread attention. Heat waves are meteorological events that are generally considered as a “prolonged period of excessive heat” [5]. Some researchers have defined heat waves as temperatures ranging above a certain threshold for two or more consecutive days, typically with heat threshold between 95 and 99 percentiles [6]. However, in general there is no common definition for a heat wave, and its interpretation may vary with location, since people living in different regions usually have a different perception of heat [5].

Several recent studies indicate considerable adverse effects that can be caused in the aftermath of a heat wave. In general, these can be attributed to any extended extreme temperature scenario:

- The health issues and consequent increase in heat-induced illnesses and mortality [1,4–6],
- Significant growth of power consumption especially for cooling purposes and possible failure to meet the energy needs due to fuel shortage [5,7],
- Increased greenhouse gas emissions per unit of energy consumed [5],
- Failure in operation and availability of critical infrastructures such as water sanitation systems [5] and transportation systems [8],
- Dependency of steam power plants on cooling water which becomes physically scarce during hot periods [9],
- Increased possibility of wildfire occurrence and consequent damages to the electrical and energy infrastructure [10].

Growth in electric demand, the need to meet the demand of critical infrastructure, and the affected capacity or availability of generation units are issues that are closely tied in with energy dispatch of the grid. Hence, adequate provisions should be planned ahead in order to manage the energy resources in the most effective fashion during the course of a heat wave. Extreme temperatures have significant impacts on different power system components.

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Nomenclature

A. Indices

b index used for branches (lines)
i index used for distributed generation (DG) units; may be used for a solar panel, a wind turbine, or a traditional dispatchable DG unit
j index used for demand responsive (DR) loads
k index used for battery energy storage systems
m index used for the buses (nodes) in the network. Node m may indicate node i with DG, node k with battery, node j with DR load, or node q with non-DR load. Hence, indices i, j, k and q may all be viewed as sub-indices for this index
q index used for non-controllable loads (i.e. non-demand responsive)
t index used for time

B. Parameters

A_i area swept by the rotor of wind turbine i (m^2)
B_m mth row of the network susceptance matrix
C^P Albert Betz constant
c_k^B price of using battery k over its lifetime; this value can be determined based on the total cost of purchasing and maintaining the battery and the maximum amount of ampere hours (A h) it can provide over its lifetime ($)
c_t^{sub} price of power purchased from the grid at time period t ($/kW)
c_i^{fuel} price of fuel for generation unit i ($/m^3, $/l, $/kg)
H_i^{fuel} net thermal value of the fuel (kW h/m^3, kW h/l, kW h/kg)
k^{PV} PV temperature coefficient of power ($^\circ$C^{-1})
K^T temperature correction factor for the lifetime of a battery at temperature T_t^a
LF_k nominal battery lifetime for battery k (months)
NB number of batteries
NDG number of DG units
NDR number of DR loads
NL number of loads
NT number of operation time steps
$P_k^{B,Total}$ total capacity that battery k can deliver over its lifetime (kW h)
$P_k^{B,\max}$ maximum allowable power level for battery k (kW)
$P_k^{B,\min}$ minimum allowable power level for battery k (kW)
$P_i^{DG,\max}$ maximum allowable power generation level for DG unit i (kW)
$P_i^{DG,\min}$ minimum allowable power generation level for DG unit i (kW); it is assumed not to be cost effective for the DG to generate power below this level
$P_j^{DR,\max}$ maximum allowable power reduction level for DR load j (kW)
$P_j^{DR,\min}$ minimum allowable power reduction level for DR load j (kW); it is assumed not to be cost effective for the DR load to provide demand reduction below this level
$P_{m,t}^L$ active demand for the load connected to bus m during time period t (kW)
$P_b^{Line,\max}$ maximum allowable power flow through line b (kW); also known as line rating or line ampacity
$P_{i,t}^{PV}$ power output of PV panel i during time period t (kW)
$P_i^{PV,STC}$ power provided by PV panel i under standard test condition (STC) (kW)
$P_t^{sub,\max}$ maximum allowable power passing through the transformer at the distribution substation at time period t (kW)
$P_{i,t}^W$ output power of wind turbine i during time period t (kW)
SHGC solar heat gain coefficient
$SOC_k^{B,\max}$ maximum limit of battery k state-of-charge (SOC); battery is not allowed to be charged to higher than this level
$SOC_k^{B,\min}$ minimum limit of battery k SOC; battery is not allowed to be discharged to lower than this level
T_t^a ambient temperature during time period t ($^\circ$C); assumed to be the same for all components in the power grid
T^R PV reference temperature ($^\circ$C)
t_T^D time period during which battery works at temperature T (months); assumed to be the same for all battery systems
$v_{i,t}$ wind speed at wind turbine i during time period t (m/s)
β_j^{DR}, γ_j^{DR} cost function coefficients for DR load j ($/kW and $/kW^2)
δ_k self-discharge rate for battery k
$\Delta P_{k,T}^{B,\max}$ maximum power correction factor for battery k due to ambient temperature T_t^a (%)
$\Delta P_{i,T}^{DG,\max}$ maximum power correction factor for DG i due to ambient temperature T_t^a (%)
$\Delta P_{b,T}^{Line,\max}$ maximum capacity correction factor for line b due to ambient temperature $T^a{}_t$ (%)
$\Phi_{i,t}$ incident solar irradiance at PV panel i during time period t (W/m^2)
Φ^{STC} solar irradiance at STC (W/m^2)
$\eta_k^{B,c}$ charging efficiency of battery k (%)
$\eta_k^{B,d}$ discharging efficiency of battery k (%)
η_i^{DG} generation efficiency for DG unit i (%)
η^W wind turbine efficiency (%)
ρ^a air density (kg/m^3)

C. Variables

$C_{k,t}^B$ operation cost of battery k during time period t ($)
$C_{i,,t}^{DG}$ operation cost of DG unit i during time period t ($)
$C_{j,t}^{DR}$ cost of DR load j at time t ($); DR is modeled as negative demand
$\mathrm{CLF}_{k,T}$ corrected lifetime for battery k due to ambient temperature T_t^a (months)
$P_{m,t}$ injected active power to the network at node m during time period t (kW)
$P_{k,t}^{B,c}$ amount of charging power provided to battery k during time period t (kW)
$P_{k,t}^{B,d}$ amount of power discharge provided by battery k during time period t (kW)
$P_{i,t}^{DG}$ active power provided by DG unit i during time period t (kW); DG may be a wind resource (denoted as W) or a solar resource (denoted as PV)
$P_{j,t}^{DR}$ active power of DR load j during time period t (kW)
$P_{b,t}^{Line}$ active power flowing thorough line b at time t (kW)
P_t^{sub} power injected to the grid from the distribution substation at time period t (kW)
$SOC_{k,t}^B$ state of charge of battery k during time period t (%)