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Energy loss minimization through peak shaving using energy storage☆

Vaiju Kalkhambkar*, Rajesh Kumar, Rohit Bhakar

Centre for Energy and Environment, Malaviya National Institute of Technology Jaipur, 302017 Rajasthan, India

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Summary This paper presents an optimal placement methodology of energy storage to improve energy loss minimization through peak shaving in the presence of renewable distributed generation. Storage sizing is modelled by considering the load profile and desired peak shaving. This storage is suitably divided into multiple storage units and optimally allocated at multiple sites with suitable charge discharge strategy. Thus the peak shaving for maximum loss reduction is explored here. Renewable distributed generation (RDG) is modelled based on the seasonal variations of renewable resources *e.g.*, solar or wind and these RDGs are placed at suitable locations. A high-performance Grey Wolf Optimization (GWO) algorithm is applied to the proposed methodology. The results are compared with the well-known genetic algorithm. The proposed methodology is illustrated by various case studies on a 34-bus test system. Significant loss minimization is obtained by optimal location of multiple energy storage units through peak shaving.

Introduction

Energy storage (ES) is as an essential component in distribution system when large amount of renewable resources are involved with their inherent intermittency. ES can mitigate the intermittency associate with renewable sources (Yang and Nehorai, 2014). Also large integration of RDG may produce reverse power flow in the feeder (Alam et al., 2013). The optimal allocation of ES adjusts the power flow and reduces power losses in distribution system (Zheng et al., 2014). The placement of ES at non-optimal places increases system losses and may require large sized storage.

Planning the best allocation of ES can have a significant impact on the power system including minimizing power losses (Vaiju et al., 2014). One of the effective ways to reduce distribution losses is load levelling or peak shaving. Peak shaving is a process of shaving the peak load and filling the load valley. It shifts some of the current or load from the peak period to off-peak period and decreases the net ohmic losses (Saboori and Abdi, 2013; Shaw et al., 2009; Nourai

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* Corresponding author. Tel.: +91 9610408703.
E-mail address: kvaijnath@gmail.com (V. Kalkhambkar).

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et al., 2008). Loss minimization also depends on the operation schedule *i.e.*, charging discharging of the ES (Bozchalui and Sharma, 2014).

From the current literature on ES, it is found that a few have addressed the loss minimization through peak shaving using ES. The optimal location of suitably sized ES for peak shaving is hardly addressed. This paper presents the application of peak shaving for improved energy loss minimization by shifting the peak load at optimal locations on the feeder in presence of RDGs. The proposed methodology is applied to a 34 bus test system using a competitive optimization algorithm call Grey Wolf Optimizer (GWO) in MATLAB. The results are compared with genetic algorithm (GA).

Problem formulation

Wind power model

Wind power model gives the expected generation obtained from the historical data. Wind generation is modelled with Weibull pdf due to its simplicity and best fit to experimental data (Lun and Lam, 2000). The pdf indicates the probability or fraction of time. Weibull pdf $F_w(v)$ for wind turbine is as given below (Sathyajith, 2006).

$$Fw(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} \exp\left[-\left(\frac{v}{c}\right)^{k}\right] \tag{1}$$

Here, k, c and v are the shape index, scale index and wind speed respectively. Rayleigh distribution is a simplified case of the Weibull distribution where shape factor 'k' is assumed as 2. The cumulative distribution function *cdf* and probability of wind speed being between v_1 and v_2 can be obtained as given in Eqs. (2) and (3).

$$fw(v) = 1 - e{-}^{[\pi/4(v/v_m)]} \tag{2}$$

$$f_w(v)(v_1 < v_2 < v_3) = f_w(v_2) - f_w(v_1) \tag{3}$$

The power delivered by a wind turbine $Po(w)$ is usually represented through its power curve, where a relation between the wind speed and generated power is established.

$$PO(w) = \begin{cases} 0 & 0 \le v_{av} \le v_{ci} \\ P_r \times \left(\dfrac{v_{av} - v_{ci}}{v_r - v_{ci}}\right) & v_{ci} \le v_{av} \le v_r \\ P_r & v_r \le v_{av} \le v_{co} \\ 0 & v_{co} \le v_{av} \end{cases} \tag{4}$$

where, v_{ci}, v_{co}, v_r, v_{av} and P_r represent the cut-in speed, cut-off speed, rated speed, average speed and output power of wind turbine respectively. The total expected wind power P_W at any time interval can be obtained as,

$$P_W = \int_0^{\infty} Po\,(w)\, fw\,(v)\, dv \tag{5}$$

Battery storage model

The minimum battery size required for peak shaving can be calculated when the desired peak shaving power is decided. Power peaks on the load curves are the area above the reference value P_{ref}. If $P_{PS,t}$ is the required maximum power to shave and $T_{d,t}$ is the discharge time then the area above P_{ref} gives battery capacity (E_{BE}) as given below (Oudalov et al., 2007).

$$E_{BE} = \sum_{t=1}^{T} P_{PS,t} T_{d,t} \tag{6}$$

This battery size gets increased due to minimum state of charge (*i.e.*, *SOC*) and efficiency of the battery. Loss minimization gets improved if the large sized storage is splitted into multiple storage units (N_d) of same size and load shifting is obtained at multiple sites rather than at one site with a single storage (Nourai et al., 2008). These multiple storage units by optimal allocation provide further improvement in loss minimization. The energy rating of these ES units is given as,

$$E_{BES} = \frac{E_{BE}}{N_d} \tag{7}$$

Observing the total peak time period T_d and off-peak time period T_c from load pattern, maximum charge discharge power can be obtained as,

$$P_{B,dis}^{max} = \frac{E_{BES}}{T_d} \quad \text{or} \quad P_{B,ch}^{max} = \frac{E_{BES}}{T_c} \tag{8}$$

Load model

The load considered in this system is hourly peak load expressed as a percentage of daily peak load. The load profile follows IEEE-RTS system (Probability Methods Subcommittee, 1979). The hourly loads for three different seasons *i.e.*, summer, monsoon and winter are considered.

Power flow model

The power losses P_{Loss} at each hour is calculated with backward/forward sweep method (Hosseini et al., 2007). System is assumed to be balanced and is represented on per phase basis. The total power loss in the system is,

$$P_{Loss} = \sum_{i=0}^{n-1} I_i^2 r_i \tag{9}$$

where, I_i and r_i gives the gives the branch current and resistance respectively. Now considering RDG power and charging discharging power of battery at node i, the active power P_i during charging and discharging gets modified as shown below,

$$P_i = P_{Li} - P_{W,i} + P_{B,ch,i} \tag{10}$$

$$P_i = P_{Li} - P_{W,i} - P_{B,disch,i} \tag{11}$$

where P_W, P_{Li}, $P_{B,ch,i}$ and $P_{B,disch,i}$ represents expected RDG power, active load power at ith bus, charging power and discharging powers at ith bus respectively.

Objective function

The objective is to minimize annual energy losses by optimal allocation of energy storage. Considering each season of four