Electric Power Systems Research 145 (2017) 175–184

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

An investigation on the impacts of distributed generation curtailment regulations on distribution network investment

Yalin Huang*, Lennart Söder

Osquldas vägen 6, KTH Royal Institute of Technology, Stockholm, Sweden

ARTICLE INFO

Article history:
Received 30 May 2016
Received in revised form
21 November 2016
Accepted 17 December 2016

Keywords:
Network investment
Curtailment
Distributed generation
Curtailment compensation
Curtailment regulation

ABSTRACT

This paper explores the impacts that different energy curtailment regulations have on distribution network investment. Energy curtailment regulation is increasingly applied in distribution networks. An important aspect of curtailment regulation is its impact on the network expansion investment and the distribution generation (DG) penetration level. The main interest of this paper is in curtailments due to the distribution network constraints. Energy curtailment regulation in Germany and Sweden are used and modified in this paper as case studies. All the costs are obtained by a network investment model, which considers network constraints, fluctuations of generation and load, and regulatory settings. The main contribution of this paper is in the application of optimal power flow to regulation modelling, in the quantification of the impacts of curtailment regulations on network investment and in the conclusions drawn on the implications of different curtailment levels for different networks. The quantified results obtained by the developed model are presented in the case studies. In one case, when the curtailment level is higher than 8%, curtailing more DG does not decrease the investment in the network. In the other case, when the compensation price is one fifth of the electricity price, the network is reinforced so that no curtailment would occur.

1. Introduction

The growth of distributed generation (DG) is adding complexity to the distribution network investment and network regulation. This is especially challenging for renewable energy with high fluctuations. The network investment can be based on accommodating the energy produced from DG without curtailment; however, a part of these investments is only relevant for a few hours annually when the generation is higher than the network capacity. Therefore, energy curtailment is an option to decrease the investment [1]. However, curtailed energy producers suffer economic losses. Furthermore, curtailing renewable energy is intuitively viewed as noneconomical given its low marginal cost. Therefore, curtailed producers may receive compensation according to energy curtailment regulation, which defines the compensation rules in terms of the price, the quantity and the payer. Energy curtailment can be due to network constraints, security constraints in the grid, low electricity price and strategic bidding [2]. The curtailment of DG due to network constraints is the focus of this paper.

This paper addresses the implications of curtailment regulations for DG by modelling two regulation arrangements and comparing them through simulations and analysis. Generation curtailment, including conventional generation and renewable generation, is a common practice in transmission levels [3]. Curtailment can also occur in the distribution network due to the increasing DG penetration level [4]. If curtailment is allowed by regulation in distribution networks, it would affect the investment decision of distribution system operators (DSOs) and DG owners. On the one hand, if the network was dimensioned according to the extreme scenario, the investment cost could be high without curtailment and the network would be redundant most of the time. On the other hand, high permissible curtailment would lead to under-investment in the network, less integrated renewable energy and possibly higher thermal losses.

The advantages of accepting curtailment have been studied by many researchers. Energy curtailment regulation combined with active network management is proposed in [5]. By accepting curtailment in combination with active control systems, more renewable generation can be accommodated in a distribution grid. It is also shown that by changing the DG connection point to the grid and curtailment regulations the capacity factors of wind farms can be greatly increased [6]. Voluntary curtailment has been shown as a good approach to integrating large-scale renewables efficiently

* Corresponding author.
E-mail address: yalin.huang@ee.kth.se (Y. Huang).

http://dx.doi.org/10.1016/j.epsr.2016.12.020

Nomenclature

Sets

L All fixed and possible lines, e.g. L1, L2, L3,...;
N All nodes in the network, e.g. N1, N2, N3,...;
N_S The substation node, subset of N;
R Set of reinforcement lines, subset of L;
K Set of all connection lines for all DG units, subset of L;
AL Set of alternatives;
N_{LD} Set of load nodes, subset of N;
N_{DG} Set of DG nodes, subset of N;
N_{sc} Set of scenarios;
K^{dg} Set of connection lines for connection of one dg in N_{DG}, subset of K
T Set of time periods in the planning horizon;

Parameters

δ The annual discount rate;
δ_t^{cap}, δ_t^{oper} Present value factors for the investment and operation costs in planning period t;
$V_{\min}^N$, $V_{\max}^N$ Vector of minimum and maximum node voltage limits;
$I_{\max}^{l,al}$ Maximum current limits on each line and each alternative;
$R^{l,al}$, $X^{l,al}$ Resistance and reactance of each alternative of each line;
A node-line incidence matrix;
$P_{t,sc}^n$, $Q_{t,sc}^n$ Active and reactive power of demand or supply on each node in planning period t scenario sc;
$C^{l,al}$ $C^{N_S,al}$ Investment cost of the alternative al of line l and substation N_s respectively;
λ_{loss} Price of power losses;
λ_{cur} Price of DG curtailment;
λ_{cm} Compensation price of DG curtailment;
λ_{el}, λ_{el}^{DG} Electricity price for non-renewable generation, electricity price for renewable generation;
$Pb_{t,sc}$ Probability of scenario sc in planning period t;
$V_{re,t,sc}^N$ Vector of real part and imaginary
$V_{im,t,sc}^N$ part of voltage in planning period t scenario sc;
γ Maximum annual curtailment percentage per unit;

Binary variables

$E_t^{l,al}$ Existence of alternatives of each line in planning period t;
$D_t^{l,al}$, $D_t^{N_s,AL}$ Binary decision on investment of alternative al of line l and substation N_s respectively;

Variables

$P_{t,sc}^{cur}$ Total curtailed power in planning period t scenario sc;
$P_{t,sc}^{loss}$ Loss in the system in planning period t scenario sc;
$g_t^{n,cm}$ Curtailed energy from node n that is compensated in planning period t;
τ_t Time duration in planning period t;
$I_{re,t,sc}^L$, $I_{im,t,sc}^L$ Vector of real part and imaginary part of current flows in each line in planning period t scenario sc;
$P_{t,sc}^{n,cur}$ Real curtailed power from node n in planning period t scenario sc;
$I_{re,t,sc}^N$, $I_{im,t,sc}^N$ Vector of real part and imaginary part of current injection from node N in planning period t scenario sc;
$I_{t,sc}^{N_S}$, $I_{t,sc}^l$ Current from substation S and current on line L in planning period t scenario sc;
$V_{re,t,sc}^N$, $V_{im,t,sc}^N$ Vector of real part and imaginary part of all nodal voltages in planning period t scenario sc;
C_t^{cap}, C_t^{oper} Capital expenditure (CAPEX) and operational expenditure (OPEX) in planning period t;
C_t^{loss}, C_t^{cur} Cost of losses and curtailment in planning period t;
C_{total} Net present value (NPV) of the total cost.

in Germany [7]. Furthermore, voluntary curtailment designed as modified bilateral contracts in the context of the electricity market has been shown to increase flexibility in system operation [8]. Some impacts of curtailment regulation have also been studied. For example the impact of curtailment regulation on generation cost [9] and the impact of curtailment regulation on network investment [4]. It is shown that by allowing DG curtailment the network investment decreases; however, only two levels of DG and load are considered. Analysis of impacts of different energy curtailment regulations on distribution network investment, considering the fluctuations from DG and load in the planning periods, has not been performed to the authors' knowledge.

Equilibrium between network investment and energy curtailment is reached when the marginal network investment cost due to DG is equal to the marginal expected compensation for the curtailment over the lifetime of the network investment [2]. The challenge to quantify the equilibrium lies in estimating the cost of reinforcing and expanding the grid to accommodate the energy and the value of the curtailed energy under different energy curtailment regulations.

This paper addresses this challenge from the engineering and economic points of view. The engineering perspective considers the network constraints, the optimal power flow (OPF) and the optimal energy curtailment in the grid. The economic perspective contains the regulation regarding DG connection charges and compensation for curtailed energy. The equilibrium is reached when the DSO cannot find lower investment solutions which fulfil all engineering constraints and regulatory constraints. Different regulatory arrangements for curtailment and DG connection schemes are modelled and compared through simulations and analysis.

2. Background

Curtailment in this paper is defined as the difference between the energy that is potentially available from the generation unit and the energy that is actually produced. The reasons for curtailment can be categorized into four kinds: network constraints, security constraints in the grid, excess generation relative to load and strategic bidding [2]. In the distribution level, the most relevant reason that causes curtailment is the network constraints. Curtailment due to network constraints can be interpreted as underinvestment in the network or excess generation. Achieving a balance between the network investment and DG integration is an important aspect for designing the curtailment regulation.

The amount of curtailment is also affected by the network hosting capacity. The network hosting capacity in this paper is defined as the capacity that can be integrated into the network without reinforcement. The available hosting capacity is different in different points of the grid. The DG owner can choose to a connection point which has higher hosting capacity or to a point which requires reinforcement. The decision is evaluated by the DG owner given the limitation from the generation itself, the cost