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Assessing the impact of incentive regulation on distribution network investment considering distributed generation integration

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ABSTRACT

In a deregulated power system, incentive regulations for network owners are designed to direct the network investment. An innovative method that assesses the incentive regulation in distribution networks is proposed in this paper. The method quantifies the interplay between incentive regulation, network investment, and network performances. It allows regulators and the distribution system operators (DSOs) evaluating the economic effects of investments within the incentive regulation framework. Considered network investments include the investment in network infrastructure and performance improving. The assessment is based on a network investment optimization model considering multi-period optimal power flow and regulatory constraints. The main contributions of this paper include the modeling of the incentive regulations and the quantification of the impacts of incentive regulation on network infrastructure investment and performance improving investment.

1. Introduction

1.1. Motivation

In a deregulated power system, power system operators transit from cost-based regulation to incentive regulation. This transition can impact on distribution system operators' (DSOs') investment decisions [1]. Incentive regulation has shown an impact on short-term innovation and cost reduction, but the impact on long-term infrastructure investment has proven to be limited [2]. However, incentive regulation should be designed to encourage efficient long-term infrastructure investment to achieve a sustainable energy sector [1]. At the same time, more and more distributed generation (DG) is connecting to the distribution systems, and DG should be considered by DSOs as an alternative to network expansion, according to the EU Electricity Directive Article 14/7 [3]. Therefore, regulations of DSOs should recognize the impact of DG on DSO performance since the DG penetration affects the economic benefit and costs for the DSO [4]. Moreover, investigating metrics for the quantification of the most important performances is recommended by the Council of European Energy Regulators (CEER) [5]. Therefore, it is important to analyze and quantify the interplay between the incentive regulation, network investment and network performance. Moreover, the quantification has been studied by individual DSOs or by a case-to-case approach, but not much academic research has been found to the authors' best knowledge.

1.2. Literature

This paper presents the results of interdisciplinary research. It combines regulatory economics and power system engineering. The literature focusing on both research areas regarding incentive regulations is reviewed below.

Papers [6,7] discuss the design of incentive regulation from the point of view of economic theory. The advantages and disadvantages of different regulatory schemes are analyzed theoretically. Regulatory impact on infrastructure investment is analyzed in [8]. Review studies on how investment decision in an energy utility changes with the change of regulatory schemes in European countries can be found in [1,9]. The studies show that the investment is sensitive to regulatory settings in the incentive regulation.

Moreover, many empirical studies are found regarding incentive regulation in distribution networks. An empirical model, using input distance functions, is developed in [10] to estimate the relationship between efficiency gain and investment under the incentive scheme. A statistical model, Bayesian Model Averaging, is used in [11] to consider the uncertainty around the response of the regulated firms to different incentive instruments. Data Envelopment Analysis technique is used in [12] to study the impact of incentive

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Nomenclature

ω	adjusted incentive for network utilization improvement during the regulatory period
ω_1	incentive from loss reduction during the regulatory period
ω_2	incentive from network load factor increase during the regulatory period
ω'_2	limited incentive from network load factor increase during the regulatory period
λ_{loss}	energy price for losses
α	DSO's share of benefit from loss reduction
β^E	network fee for the consumed energy to the upper stream grid (€/kW h)
β^P	network fee for the subscribed peak power to the upper stream grid (€/kW,yr)
γ	limit on the total incentive in percentage of the allowed return on costs
B_0	reference value of fee paid to the upper stream grid
B_t	fee paid to the upper stream grid during year t
C_t^{cap}	annual network investment
C_t^{oper}	annual operational cost which includes the cost for losses and curtailment
D	number of days considered
E_0^{loss}	reference value of the energy loss
E_0^Q	reference value of the energy flow through the feeding point Q
E^Q	energy flow through the feeding point Q during the regulatory period
m_{fp}	load factor at the feeding point
m	load factor at the load point
P_d^{avg}	average power at the feeding point in a day during the regulatory period
$\widehat{P}_0$	reference value of the peak power at the feeding point
$\widehat{P}$	peak power at the feeding point during the regulatory period
$\widehat{P}_d$	peak power at the feeding point in a day during the regulatory period
R_t	annual revenue in during year t
$\widehat{R}$	allowed return on costs during the regulatory period
$\widehat{R}^{EG}$	revenue cap for a more efficient grid during the regulatory period

regulation of quality of service in the UK distribution networks. Benchmarking analysis is used in [13] to study the impact of incentive regulation on network security.

Besides these quantitative economic studies, some studies using an engineering modeling approach considering the incentive regulation in power systems are also found. Many researches have earlier studied DGs impact on distribution network investment [14–17], regulation impact on DG connection [18,19], and distribution network investment considering active demand management [20,21]. In addition, there are some studies that evaluate the impact of regulatory framework including incentives for network performances [2,22–25].

A network load flow model and a financial spreadsheet model are combined to study the incremental net impact of DG on DSOs in [22]. However, the physical planning model does not consider the economic regulation or the investment timing. Distribution network investment strategies for incentive regulation in a Finnish case are studied in [23]. The incentive regulation on network losses in distribution networks in Spain is analyzed in [24]. Both papers use a cost-benefit analysis in a case-to-case manner. A systematic method to evaluate the impact of the regulatory framework in the UK is presented in [2]. The DSO in the model has the possibility to select the type and number of wind turbines to be allocated. However, this possibility is not always allowed in an unbundled distribution network, even though the DG ownership for DNOs can be beneficial [19,26]. Moreover, the network upgrade is not considered in [2]. The analysis is only based on the current network without reinforcement. Network upgrade solutions are considered in [25] together with specific alternative solutions (non-traditional network investment solutions); however, the focus is on the network investment including the specific alternative network upgrade solutions rather than evaluating the impact of the regulatory framework. In this paper, we develop a model to study another regulatory framework, the Swedish one. The developed model optimizes the network upgrade and DG connection subject to the technical constraints and the incentive regulation. We use the developed model to evaluate the effectiveness of the regulation and the sensitivity of some parameters in the regulation.

1.3. Contribution

There is relatively little academic analysis of the effects of the incentive regulation mechanisms on the performance of DSOs ex-ante [6,25], especially considering DG integration, compared to empirical works that examines the effects of incentive regulation ex-post. All the ex-ante studies [2,22–25] do not establish a cost benchmark for investment in improving the performance based on the incentive regulation framework. The studies focus on some specific investment alternatives, for example demand response-based smart solutions. The here proposed method establishes a contribution to quantify the cost benchmark ex-ante in order to improve the performances based on the given incentive regulation framework.

In the assessment, we propose a modeling approach as shown in Fig. 1. One of the main contributions in this paper is that we model the incentive regulations and have effectively combined it into the network investment model. The model provides quantitative and systematic assessment. On the one hand, the model is able to consider the physical constraints, fluctuating load and DG, load shedding and DG curtailment (due to network limits); on the other hand, it considers the regulatory constraints due to incentive regulations. The modeled incentive regulations are revenue cap regulation, and performance incentive regulation for loss reduction and load factor increase. The other main contribution is the implication for the regulatory policy design. The implication is obtained from the quantifying costs as benchmarks for investing in performance improvement. The benchmarks can assist the DSOs in evaluating different investment options that relate to performance improvement. Furthermore, these benchmark can assist the regulators in determining the correct incentives for network performance considering DG integration.

The studied performance incentive regulation aims to reduce the losses in the system and to increase the load factor by engaging in demand side management (DSM) or other innovative solutions from DSOs. It induces DSOs to recognize the potential of the DG and consumers in order to invest and operate the network more efficiently. This is in line with the aim of EU smart grids regulation targets [27] and is currently applied in Sweden. We examine the impact of applying the Swedish incentive regulation in distribution networks with