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A novel hierarchical contribution factor based model for distribution use-of-system charges

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HIGHLIGHTS

- Customer classes' contribution factor to reflect burden imposed on network peaks.
- Usage based pricing signal to reduce contribution to peak network loadings.
- Investment deferral assessed as annuitized present value of future investment.
- Hierarchical Contribution Factor based model to enhance network utilization.

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ABSTRACT

Due to the limited visibility at low voltage (LV) networks, existing Distribution Use-of-System (DUoS) charging methodologies assume that all the network users use the network in proportion to their peak flows. This naive supposition fails to reflect the contribution of network users to network peak flows, which actually is the driver for network reinforcement. This can send an inadvertent signal to customers, leading to aggravated network pressure. This paper for the first time, brings the new dimension into the design of DUoS charging methodology by considering the true contribution of customer class's load on network peak flows. It proposes a novel Hierarchical Contribution Factor based Model (HCM), recognizing the contributions of differing customer classes to the network reinforcement of upstream asset. Such contribution will be further propagated to network assets at higher voltage level, forming a Hierarchical CF model and reflecting the true individual class contribution to the whole-system reinforcement. Benefit of the proposed model on investment deferral is assessed by determining annuitized present value (PV) of future investments, and consequences are assessed on a 22-bus practical Indian reference network. The approach helps customers as a class to reduce their network usage charges by minimizing their energy usage contribution during distribution network peaks, eventually reducing distribution network investment and energy transfer costs.

1. Introduction

The UK government has set an ambitious target to transit towards a low carbon energy future by reducing carbon emission and increasing renewable energy [1–3]. Year 2015 has witnessed £3.5bn annual subsidies in the UK just for photovoltaic (PV) installations. With the increasing number of low carbon energy technologies (such as PV, electric vehicles, battery storage and heat pumps) being connected to the edge of the grid, power distribution networks will have unprecedented complexity and uncertainty [4–9]. Load estimation at various network nodes is becoming a challenging task for the utilities in such a situation [10]. Currently, the default solution to this issue is passive network reinforcement, which will finally be paid from customers' rising energy bills. In order to accommodate the large influx of low carbon energy technologies without passing extra economic burden to customers, it is critical to design innovative technical and commercial solutions to guide the planning and operation of end-customers [11–16].

Network planning methodologies aim to model the actual network, while considering some assumptions to make for data deficit and unknown future variations. For this methodology, considered modeling may not be a true reflection of network and the overall formulation of network cost. Further, optimisation algorithms may not guarantee global optima, as it would depend on the accuracy of assumed parameters. Such methodologies may lead to erroneous solutions, despite

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adopting the best of optimisation algorithms and well thought out assumptions. In contrast to the use of optimisation algorithms, use of network pricing involves consideration of few basic assumptions. A robust and thoughtful pricing model would offer an appropriate signal to the user, who would respond to the economic signal by way of optimal location and utilisation, such that its network utilisation is minimized. This would eventually lead to low requirement of network reinforcement, thus minimizing network investment required to meet the specified load.

Distribution Use-of-System (DUoS) charges is an effective commercial tool for distribution network operators (DNOs) to guide new network users in a deregulated power market. The aims of DUoS charges are twofold: (i) to recover reinforcement cost for the distribution network operators (DNOs) based on an economic pricing model; (ii) to reflect industry regulation as a whole and to offer an efficient economic signal to the users. According to the energy market regulator in the UK, an ideal DUoS charging model should accurately reflect forward-looking costs, incentivise efficient usage and development of the system, and incorporate the generation use of system charges (GDUoS) [17].

A significant amount of research on DUoS model has been reported from industry and academia. The Distribution Reinforcement Model (DRM), a Postage Stamp method, was traditionally used by the UK industry, which allocates all the network cost to customers only according to the voltage level connected. DRM provides no locational signals or ex-ante cost information to customers [18]. It offers no guidance for the planning of distributed generators (DG's) [19]. DRM's weakness was rectified in many new models proposed by academia. Location is considered as the key factor in most of these models by charging against the critical power flow scenarios, network congestion and power losses [20]. Investment Cost Related pricing (ICRP) was proposed to not only recover the historical investment, but more importantly to evaluate the impact of future incremental cost placed on the system, as a result of new load or generation being added at any point on the distribution network [21,22]. Long Run Incremental Cost Pricing (LRIC) model considers utilisation rate of an asset in addition to distance [23,24]. This approach is recognized as an economically efficient approach for allocating distribution network cost, as it determines network charges as the difference in the present value of future investment, consequent upon nodal power perturbation for generation or demand. Further the impacts of network security, contingencies, and reliability have been integrated into the LRIC pricing approach [25–28]. The integration of DG is considered using DUoS price as a signal to encourage DG connection at the appropriate location [29]. The interaction of generation and demand in the distribution network is investigated by nodal pricing, contract pricing and value-based pricing [30–32]. The uncertainty introduced by DG is also considered in the network reinforcement and charging methodology [33,34]. Demand response plays a major role in demand reduction and demand shifting, and dynamic pricing models can effectively consider the same [35–38].

Existing DUoS methodologies have covered many attributes of an ideal model, considering factors like forward-looking cost, distance, location, utilisation rate, reliability, and generation technology. Traditional methods assume that all customers consume energy in a similar way within a distribution network and follow the aggregated load profile. However, end-users actually consume energy in diverse manners and thus have different contribution to the networks' reinforcement. Likewise, the downstream assets contribute differently to the upstream assets, based on the coincidence level of the load profiles. The industry has attempted to address the issue by introducing a diversity factor, which is defined as the ratio of maximum demand at the substation to the sum of the maximum demand at all points of the immediate lower distribution network served by that substation. However, this factor aims to calculate the after-diversity peak load to evaluate the reinforcement cost, instead of accurately allocating such cost to individual customers [39]. In order to send customer-tailored signals to effectively guide individual's energy behavior, it is critical to develop a new DUoS model considering the additional dimension of energy consumption pattern variations among customers.

This work develops a novel customer-specific DUoS charging model based on a hierarchical contribution model (HCM), which distinguishes between different customer class contributions to the distribution network and all the way to the upstream assets. As a first, this considers customer class's contribution to network peak flow, instead of considering customer class's peak flow, which may occur at a different time. A novel concept of CF is proposed to evaluate contributions at two levels: (i) contribution of total load connected at any node to each upstream shared asset, and (ii) contribution of customer class to total load connected at any node. Based on this HCM model, the customer-specific DUoS charging model is implemented using basic LRIC approach. The proposed approach encourages various customer classes to modify their distribution network usage pattern to minimize network peaks, thus delaying network investment. The ultimate goal of proposed pricing scheme is to offer a customer class specific pricing signal to distribution network users, which incorporates CF to highlight users' contribution to network peak conditions, in addition to location based signal. Main contributions of this paper are summarized as follows:

(i) A novel hierarchical contribution model based on CF in order to reflect actual propagation of the key reinforcement driver within a distribution network.
(ii) It considers the contribution of customer class load to network peak, rather than merely considering peak flow of a customer class, thus reflecting the true impact of customer class load on network reinforcement requirement.
(iii) For the first time proposes a usage-based pricing signal to customer classes in addition to locational signal, directly encouraging them to modify their usage pattern in response to changed distribution network prices.

The research could make significant impact to the efficient planning and operation of DNOs in a low carbon environment, offering individual charges to customer class, considering their specific class characteristics. Lower distribution network charges can be offered for customer classes not expected to contribute to system peak, with their peak demand differing significantly from system peak demand characteristics. These charges attract customers with characteristics favorable for distribution network development at specific locations. Such charges would make the system efficient; utilities may delay network reinforcements, investments in new generation units, and network infrastructure [40,41]. LRIC pricing is a well-established approach to evaluate long term distribution network charges for UK distribution networks, assuming that network reinforcement would be required when the loading level of circuit reaches its capacity. Hence proposed HCM based approach to offer customer class specific signal is implemented using LRIC as the base approach. However, the HCM approach is equally applicable to other DUoS charging methodologies.

The rest of the paper is organized as follows: Section 2 gives a description of HCM based DUoS charging methodology. Section 3 discusses the test case system and analyses the results from proposed and traditional models. Finally, Section 4 concludes the work contribution.

2. Hierarchical contribution model based DUoS charging methodology

The proposed HCM based charging mechanism illustrated in Fig. 1 shows the algorithm for calculating customer class specific DUoS charges. This integrates the reflection of different customer class contributions to distribution network peak demand for network charging. The contributions are determined using CF, based on which coincident demand is calculated. CF is incorporated at two levels to reflect user's actual network usage. First, the contribution of total load connected at