The Impact of Dynamic Electricity Tariff on Long-run Incremental Cost

Yi Ding, Yang Li, Salvador Pineda, Jacob Østergaard and Tongdan Jin

Abstract— **Electricity plays an important role in the future energy framework around the world. The foreseen high penetration of renewable energy resources and electric vehicles (EV) will change the way of understanding and operating power systems. Consequently, significant investment in network infrastructure needs to be made in order to cope with this tremendous change in an efficient and effective manner. Long-run incremental cost (LRIC) pricing method is recognized as an economically efficient approach for pricing network charges, which provides forward-looking information for future investment cost. LRIC evaluation is usually conducted on the basis that demand is passive and uncontrollable. The impact of demand flexibility on LRIC has not been comprehensively studied. In this paper, the effect of dynamic electricity tariff and flexible demand on LRIC and network investment decisions is deeply analyzed and discussed. A modified test system (RBTS) illustrates the proposed method.**

***Index Terms*— LRIC, demand response, electricity tariff, pricing**

NOMENCLATURE

i,k	bus index
g	generating unit index
N_g	number of generating buses
N_L	number of load buses

For bus i

NG_i	number of generating units
C_{ig}	cost function of generating unit
P_{ig}	real power generation of unit
Q_{ig}	reactive power generation of unit
ΔB_i	change of customer's benefit due to demand response
ΔL_{pi}^f	deviation from the flexible demand reference (real power)
ΔL_{qi}^f	deviation from the flexible demand reference (reactive power)
L_{pi}^c	firm demand (real power)
L_{qi}^c	firm demand (reactive power)
L_{pi}^f	flexible demand reference (real power)
L_{qi}^f	flexible demand reference (reactive power)
$\Delta L_{pi}^{\min}$, $\Delta L_{pi}^{\max}$	Lower and upper limits of flexible demand response (real power)
$\Delta L_{qi}^{\min}$, $\Delta L_{qi}^{\max}$	Lower and upper limits of flexible demand response (reactive power)
$V_i = \lvert V_i \rvert \angle \theta_i$	bus voltage
$\lvert V_i \rvert^{\min}, \lvert V_i \rvert^{\max}$	Lower and upper limits of bus voltage
$Y_{ik} = \lvert Y_{ik} \rvert \angle \delta_{ik}$	element of admittance matrix
$P_{ig}^{\min}, P_{ig}^{\max}$	minimum and maximum real power generation of unit
$Q_{ig}^{\min}, Q_{ig}^{\max}$	minimum and maximum reactive power generation of unit
S_l	apparent power on the net component l (absolute value)
$S_l^{\max}$	limit of apparent power transfer on the net component l
ρ_{pi}	electricity tariff
annuity	annualized cost factor

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I. INTRODUCTION

Security of energy supply is a major challenge faced by the world. Future energy supply is relying on the efficient and effective use of renewable energy resources. The European Union (EU) will reach a 20% share of renewable energy in total energy consumption and increase energy efficiency by 20% in 2020 [1]. Denmark is leading the way in energy efficient and energy friendly economy in EU: the Danish energy consumption will be entirely independent of fossil fuels in the long-term plan. In Denmark the wind power penetration will increase from approximately 20% of the electricity consumption in 2008 to 50% by 2025 [2].

The existing network infrastructure cannot cope with the integration of high penetration of renewable energy resources and EV. The network has to be reinforced for handling the fluctuation of renewable energy generation and demand. Without serious upgrading of existing electricity network, the renewable energy generation cannot be efficiently utilized and system security may be jeopardized. However, network reinforcement and expansion will induce significant investment of electricity network, especially for the distribution network. Efficient and effective network charge policy is very important for securing a reasonable investment return. Network charges should not only reflect the extent of network use by customers but also release efficient economic signals for encouraging network expansion and reinforcement [3]. LRIC pricing method developed in [4] is recognized as an economically efficient approach for pricing network charges, which provides forward-looking information for future investment cost. The LRIC approach evaluates the cost of advancing or deferring future network investment consequent upon the increment of generation or load at a specific location [4].

In current power systems, demand is considered to be totally inelastic and a fixed electricity tariff for all customers is used. The development of smart grid over the last years enables more active market participation of demand. The development of dynamic electricity tariff may induce the customers' flexible usage of electricity and increase the reliability of the system. References [5, 6] developed methods for evaluating electricity price risk, customers' reliabilities and their corresponding correlation. Based on [5, 6], a technique for evaluating the volatility reduction of locational marginal prices (nodal price) and the reliability enhancement considering demand–price elasticity was proposed in [7].

Previous research on LRIC evaluation is usually conducted on the basis that demand is passive and uncontrollable. However the customers' flexible usage induced by dynamic electricity tariff can affect LRIC and defer network investment, therefore relieving network burden. This paper proposes an approach to evaluate LRIC considering the flexibility of demand under the framework of dynamic electricity tariff. In section II, an optimal power flow model is developed to represent the demand response to dynamic electricity tariff. The LRIC pricing model considering the flexibility of demand is developed in section III. A modified test system (RBTS) is used to illustrate the proposed method in section IV. Finally, Section V concludes.

II. Demand Response to Dynamic Electricity Tariff

Electricity demand is generally classified into two categories: firm demand and flexible demand. Firm demand includes uncontrollable passive loads and inelastic loads, which are less affected by price changes such as hospitals, banks and military units. Flexible demand represents loads which can modify their electricity consumption profile responding to control signals. The development of information and communication technology (ICT) and smart metering has the potential of enabling flexible demand to respond to dynamic electricity tariff. Customers may reduce their flexible demands when the electricity price increases.

The objective of flexible demand response is to maximize its benefit:

$$Max\ \Phi = B(L_{pi}^f) + \Delta B_i(\Delta L_{pi}^f) - \rho \times (L_{pi}^f + \Delta L_{pi}^f) \tag{1}$$

where L_{pi}^f is the reference point of flexible demand at bus i (real power), which represents the equilibrium under the fixed electricity tariff; ΔL_{pi}^f represents the deviation to the reference point of flexible demand i under the dynamic electricity tariff; $B(L_{pi}^f)$ is the customer benefit for utilizing L_{pi}^f ; $\Delta B_i(\Delta L_{pi}^f)$ represents the change of customer's benefit due to demand response; ρ is the electricity tariff. The customer benefit function can be assumed as a quadratic function [9].

When $B(L_{pi}^f)$ is constant, the necessary condition to maximize Φ is:

$$\frac{\partial\left\{\Delta B_i(\Delta L_{pi}^f)\right\}}{\partial(L_{pi}^f + \Delta L_{pi}^f)} - \rho = 0 \tag{2}$$

$$\frac{\partial\left\{\Delta B_i(\Delta L_{pi}^f)\right\}}{\partial(\Delta L_{pi}^f)} \cdot \frac{\partial(\Delta L_{pi}^f)}{\partial(L_{pi}^f + \Delta L_{pi}^f)} - \rho = 0 \tag{3}$$

$$\frac{\partial\left\{\Delta B_i(\Delta L_{pi}^f)\right\}}{\partial(\Delta L_{pi}^f)} = \rho \tag{4}$$

Customer with flexible demands tends to increase their electricity consumption when its marginal benefit is higher than electricity tariff. At the equilibrium point, the marginal benefit of demand response equals to electricity tariff as shown in equation 4. It means that the customer response to the dynamic electricity tariff can be measured by using the change of the customer's benefit. The large customers' benefit functions can be deduced from their bids to the power pool [9]. For the small customers such as households, the development of smart grid and ICT enables them to receive and react on variable electricity tariff for scheduling their electricity consumption. The benefit function of the small customers' aggregation can be estimated by system operator. The concept of integrating smaller assets into electricity market through the reaction of variable electricity tariff is implemented in the European Union's smart grid project – Ecogrid EU.

The following optimal power flow (OPF) model is used to determine electricity tariff at each node, flexible demand response and generation dispatch. The objective function is to maximize the social welfare:

$$\max\left\{\sum_{i\in N_L}\left\{B(L_{pi}^f) + \Delta B_i(\Delta L_{pi}^f)\right\} - \sum_{i\in N_g}\sum_{g\in NG_i} C_{ig}(P_{ig}, Q_{ig})\right\} \tag{5}$$

$B(L_{pi}^f)$ is constant, the objective function is functionally equivalent to minimize the generation cost taking into account the flexible demand response to the dynamic electricity tariff.

$$Min\ f = \sum_{i\in N_g}\sum_{g\in NG_i} C_{ig}(P_{ig}, Q_{ig}) - \sum_{i\in N_L} \Delta B_i(\Delta L_{pi}^f) \tag{6}$$

The objective function (6) is subject to the following constraints:

Load flow equations:

$$\sum_{g\in NG_i} P_{ig} - L_{pi}^c - (L_{pi}^f + \Delta L_{pi}^f) = \sum_{i=1}^{N} V_i V_k \left|Y_{ik}\right| \cos(\theta_i - \theta_k - \delta_{ik}) \tag{7}$$

$$\sum_{g\in NG_i} Q_{ig} - L_{qi}^c - (L_{qi}^f + \Delta L_{qi}^f) = \sum_{i=1}^{N} V_i V_k \left|Y_{ik}\right| \sin(\theta_i - \theta_k - \delta_{ik}) \tag{8}$$

Limits of flexible demand response:

$$\Delta L_{pi}^{\min} \le \Delta L_{pi}^{f} \le \Delta L_{pi}^{\max} \quad (9)$$

$$\Delta L_{qi}^{\min} \le \Delta L_{qi}^{f} \le \Delta L_{qi}^{\max} \quad (10)$$

Generating unit limits:

$$P_{ig}^{\min} \le P_{ig} \le P_{ig}^{\max} \quad (11)$$

$$Q_{ig}^{\min} \le Q_{ig} \le Q_{ig}^{\max} \quad (12)$$

Line flow constraints:

$$S_l \le S_l^{\max} \quad (13)$$

Voltage limits:

$$\left|V_i\right|^{\min} \le \left|V_i\right| \le \left|V_i\right|^{\max} \quad (14)$$

The optimal generating unit outputs (P_{ig} , Q_{ig}), and the optimal flexible demand response (ΔL_{pi}^{f} , ΔL_{qi}^{f}) can be obtained by solving the OPF problem using Newton methods, the sequential quadratic programming (SQP) algorithm, etc.

We can also obtain the electricity tariff at bus i , which is the Lagrangian multipliers associated with the real power flow equation (7).

III. Pricing Modeling Considering Flexible Demand

The LRIC method proposed in [3, 4] is focused on studying the impact of future investment as the result of the additional injection or withdrawal of generation or demand at a specific node. For the additional injection, there will be a cost or benefit associated with accelerating or deferring the network investment [4]. The LRIC for firm demands and flexible demands will be evaluated, respectively, in the following paragraphs.

Suppose the network component *l,* such as a transmission line, has a capacity limit of $S_l^{\max}$. For given firm demand and flexible demand of real power and reactive power at node *i*, we can obtain the power flow $S_l(L_{pi}^c, L_{qi}^c, L_{pi}^f, L_{qi}^f)$ through the component *l* by solving the above OPF problem. For a load growth rate *r* of line *l,* the time horizon (number of years n_l) for the loading level from $S_l(L_{pi}^c, L_{qi}^c, L_{pi}^f, L_{qi}^f)$ to $S_l^{\max}$ can be evaluated by the following equation:

$$S_l^{\max} = S_l(L_{pi}^c, L_{qi}^c, L_{pi}^f, L_{qi}^f) \cdot (1+r)^{n_l} \quad (15)$$

Rearrange (15), we can obtain:

$$n_l = \frac{\log(S_l^{\max}) - \log\left\{S_l(L_{pi}^c, L_{qi}^c, L_{pi}^f, L_{qi}^f)\right\}}{\log(1+r)} \quad (16)$$

For a discount rate *d*, the present value of future investment cost ($Asset_l$) for a new network component after the net component *l* reaches its capacity can be calculated as [4]:

$$PV_l = \frac{Asset_l}{(1+d)^{n_l}} \quad (17)$$

An additional withdrawal of demand at node *i* will result in the power flow change of the net component *l*. Suppose the firm demand of real power has been changed from L_{pi}^c to $L_{pi}^c + \delta L_{pi}^c$ at node *i*, the power flow through the net component *l* becomes $S_l(L_{pi}^c + \delta L_{pi}^c, L_{qi}^c, L_{pi}^f, L_{qi}^f)$. , which can be obtained by solved the proposed OPF problem (6)-(14).

The new time horizon for the investment considering the change of the firm demand can be evaluated as:

$$n_{new}^c = \frac{\log(S_l^{\max}) - \log\left\{S_l(L_{pi}^c + \delta L_{pi}^c, L_{qi}^c, L_{pi}^f, L_{qi}^f)\right\}}{\log(1+r)} \quad (18)$$

The new present value of the future investment cost considering the firm demand change δL_{pi}^c can be evaluated as:

$$PV_{new}^{c,p} = \frac{Asset_l}{(1+d)^{n_{new}^c}} \quad (19)$$

The annualized incremental cost for the change of the firm demand of real power can be evaluated as:

$$IC_{new}^{c,p} = (PV_{new}^{c,p} - PV_l) \times annuity \quad (20)$$

The LRIC of the component *l* for the change of the firm demand (real power) can be calculated as:

$$LRIC_l^{c,p} = \frac{IC_{new}^{c,p}}{\delta L_{pi}^c} \quad (21)$$

Similar procedures can be used to evaluate the LRIC for the change of the flexible demand. Suppose the reference point of flexible demand (real power) has been changed from L_{pi}^f to $L_{pi}^f + \delta L_{pi}^f$, we solve the OPF problem for obtaining the power flow through the net component *l:* $S_l(L_{pi}^c, L_{qi}^c, L_{pi}^f + \delta L_{pi}^f, L_{qi}^f)$.

The new time horizon for the investment for the change of flexible demand reference can be evaluated as:

$$n_{new}^f = \frac{\log(S_l^{\max}) - \log\left\{S_l(L_{pi}^c, L_{qi}^c, L_{pi}^f + \delta L_{pi}^f, L_{qi}^f)\right\}}{\log(1+r)} \quad (22)$$

The new present value of the future investment cost considering the change of flexible demand reference δL_{pi}^f can be evaluated as:

$$PV_{new}^{f,p} = \frac{Asset_l}{(1+d)^{n_{new}^f}} \quad (23)$$

The corresponding annualized incremental cost for the change of flexible demand reference (real power) can then be evaluated as:

$$IC_{new}^{f,p} = (PV_{new}^{f,p} - PV_l) \times annuity \quad (24)$$

The LRIC of the component *l* for the change the flexible demand (real power) reference can be calculated as:

$$LRIC_l^{f,p} = \frac{IC_{new}^{f,p}}{\delta L_{pi}^f} \quad (25)$$

IV. System Studies

This section evaluates the impact of dynamic electricity tariff on LRIC and compares the proposed approach with the basic LRIC pricing method in a modified RBTS [8] system. As shown in Fig. 1, a transformer is used to connect the main transmission system with the distribution system at bus 6. It is assumed that the transformer is rated at 30 MW and costs €3.2×10^6 at its modern equivalent asset value. The distribution network connected to bus 6 has both firm and flexible demands. The load growth rate and discount rate are supposed to be 2% and 7% yearly, respectively. Two different cases are studied.

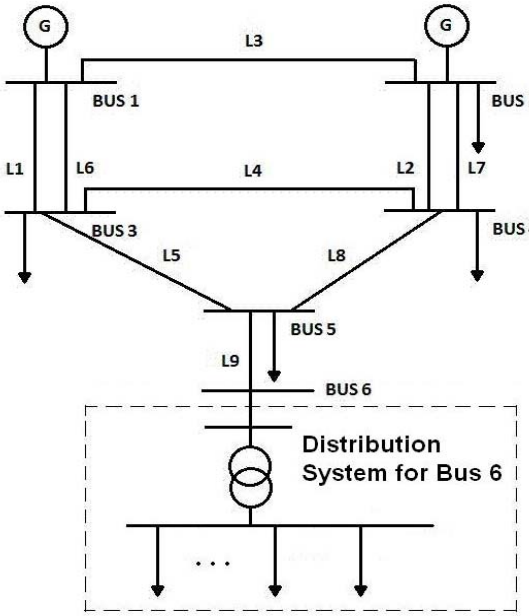

Fig. 1. The modified RBTS

Case A.

In this case, the flexible demand reference at bus 6 is constant with the value of 10MW, while the firm demand changes from 9 MW to 15 MW in 1-MW steps.

Table I presents the LRIC charges and the flexible demand ($L^f_{pi}+\Delta L^f_{pi}$) under the dynamic electricity tariff for case A. As shown in this table, varying the firm demand gives the respective LRIC charge, which increases dramatically when the transformer load is approaching to its capacity limit. It can also be observed that the flexible demand slowly decreases because of a higher electricity tariff with the increasing firm demand.

The LRIC charges under the dynamic electricity tariff are also compared with those without considering the dynamic electricity tariff (fixed tariff). As shown in Fig. 2, the implementation of the dynamic electricity tariff can significantly decrease the LRIC charges of customers at bus 6.

Table I
LRIC charges and the flexible demand for case A

L^c_{pi} (MW)	$L^f_{pi}+\Delta L^f_{pi}$ (MW)	$LRIC^{c,p}_l$ (€/MW/yr)
9	10	1157.8
10	9.99	1295.9
11	9.91	1352.8
12	9.83	1468.4
13	9.80	1740.1
14	9.76	1876.1
15	9.71	2051.7

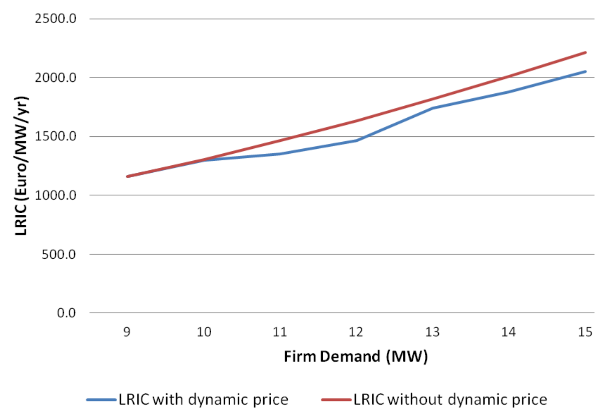

Fig. 2. LRIC charge comparisons for case A

Case B.

In this case, the flexible demand reference at bus 6 varies from 8 MW to 12 MW in 1-MW steps, while the firm demand is kept constant with the value of 15 MW.

Table II presents the LRIC charges and the flexible demand ($L^f_{pi}+\Delta L^f_{pi}$) under the dynamic electricity tariff for case B. As shown in Table II, the flexible demand ($L^f_{pi}+\Delta L^f_{pi}$) and the LRIC charges maintain relatively constant values because the flexible demand reduces its electricity consumption (ΔL^f_{pi}) under a higher electricity tariff.

Table II
LRIC charges and the flexible demand for case B

L^f_{pi} (MW)	$L^f_{pi}+\Delta L^f_{pi}$ (MW)	$LRIC^{f,p}_l$ (€/MW/yr)
8	8	1817.3
9	9	2009.8
10	9.71	2051.7
11	9.64	2039.2
12	9.64	2037.8

Fig. 3 compares the LRIC charges with and without considering the dynamic electricity tariff for this case. As shown in this figure, the demand response of flexible demand to dynamic electricity tariff has a serious impact on the LRIC charges: the LRIC charge is reduced about 23% when L^f_{pi} reaches 12 MW.

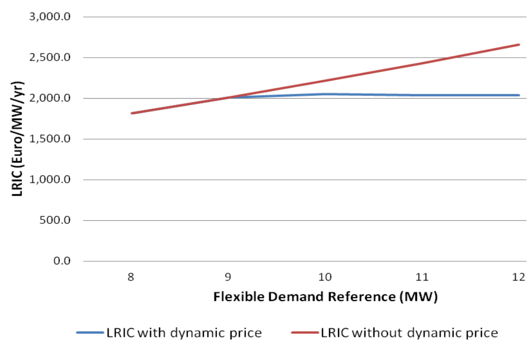

Fig. 3. LRIC charge comparisons for case B

V. Conclusion

With the integration of high penetration of renewable energy resources and EV, the existing electricity network infrastructure has to be upgraded, which may induce a significant growth of investment. LRIC method is an economically efficient approach for pricing future investment cost and encouraging network reinforcement and expansion. Previous studies on LRIC method are usually conducted on the basis that demand is passive and uncontrollable. The development of smart grid technology enables more active demand participation in responding to dynamic electricity tariff. Flexible demand response can affect LRIC and defer network investment. In this paper the impact of dynamic electricity tariff on LRIC is studied. It is illustrated in the examples that flexible demand response can significantly affect LRIC charges. In the future work, the impact of the dynamic of flexible demand with cross elasticity matrix can be considered.

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