Long-run Incremental Cost Pricing Considering Uncertain Future Load Growth

Chenghong Gu, and Furong Li, *Member IEEE*

Abstract-- **The importance of efficient and effective charging methodologies to regulatory authorities has resulted in a significant amount of research into methods for deriving economic charges. The majority of the previous work is however limited on the assumption that a given future scenario or a fixed load growth rate, and the fundamental problem of uncertain future load growth rates in charging methodologies imposes great difficulties on precise assessing of charges. In this paper, a novel methodology of evaluating long-run incremental charges with uncertain load growth rate is proposed to handle the uncertainty of load growth rate. Fuzzy logic concept is utilized here to model uncertain load growth rate, and then it is incorporated with long-run incremental cost (LRIC) methodology to calculate charges. The membership functions of years which take circuit to be fully loaded and LRIC charges are deduced by employing the theory of fuzzy extension method. A simple example is given to testify the proposed concept and some important conclusion are presented at last. It is found that compared with original LRIC method new method considering fuzzy load growth rate can effectively model uncertain instinct of load growth rate.**

Index Terms-- **Long-run incremental cost pricing, Network charges, Load growth rate, Fuzzy logic**

I. INRODUCTION

Network charges are charges against generators, large industrial consumers, and suppliers for their use of a network. Methodologies used for setting network charges needs to recover the costs of capital, operation, and maintenance of a network and provide forward-looking, economically efficient messages for both customers and power companies [1-2].

In providing forward-looking and efficient economic message, it is essential that network charges reflect the cost/benefits that new network users impose on the network, i.e. they should discriminate between network users who incur additional operating costs or network reinforcement and expansion, and those who reduce or delay otherwise needed network upgrades. It is for this reason that the concept of incremental charging methodologies was introduced to overcome the drawback. Short-run incremental cost (SRIC) or marginal cost (SRMC) pricing approaches are concerned with the additional operating cost typically resulting from congestions and constraints [3-4]. Long-run incremental cost (LRIC) pricing approaches are concerned with incremental network cost as well as incremental operational costs [5-12].

Developing a LRIC pricing model has been viewed as a formidable task [5-10]. Most existing approaches to long-run pricing require a least-cost future network planning to work out network increment cost with nodal demand/generation increment. It is impractical to evaluate the cost to network with injection at every single node of a network, therefore most long-run cost pricing methods evaluate the incremental network cost associated with projected demand/generation pattern and subsequently allocate the cost to new (and existing) customers. This approach has several drawbacks: 1) they are passive, reacting to a set of projected patterns of future generation and demand, rather than proactively influence the patterns of future generation/demand through economic incentives; 2) the approaches require the knowledge of future generation/demand, while this knowledge is far from certain in a competitive environment and any projected pattern of generation and demand could prove very different in the outturn.

In 2007, Dr Li and Mr. Tolley proposed a novel approach to calculate LRIC in network charges [2]. The methodology seeks to reflect the influence on the advancement or deferral of future investment in network components as a result of a 1MW injection or withdrawal of generation or load at each study node. Compared with existing long-run incremental charge pricing approaches, the proposed approach produces forward-looking charges that reflect both the extent of the network needed to service the generation or load, and the degree to which that network is utilized [13-14].

The basic LRIC charging model works on the assumption that the load growth rate is fixed into the future. Using an underlining load growth rate, the future reinforcement and its timing can be estimated and translated into present value of future reinforcement. In practice, it is however not easy to predict future load growth rates, because they can be affected by many uncertain factors such as economy, policies, regulations and markets. The impact to LRIC charges under different load growth rates can be significant, and such impact can affect the revenue recovery for utilities as well as customers' satisfaction [15-16]. Having said the above, for developed countries, the load growth has already saturated and becomes relatively steady, it is less likely for load growth rates to have huge variations over long term. But for medium developing countries, load growth rates can vary considerably with time, and this is the subject that the paper aims to address.

F. Li is with the Department of Electronic and Electrical Engineering, University of Bath, Bath BA2 7AY, U.K. (e-mail: f.li@bath.ac.uk).

C. Gu is with the Department of Electronic and Electrical Engineering, University of Bath, Bath BA2 7AY, U.K. (e-mail: c.gu@bath.ac.uk).

In 1965, Mr. Zadeh introduced the concept of fuzzy sets as a mathematical means of describing vagueness in linguistics to treat some uncertain conceptions in reality [17]. A fuzzy set is a generalization of an ordinary set in that it allows the degree of membership for each element to range between 0 and 1. The biggest difference between crisp and fuzzy sets is that crisp sets always have unique membership functions, whereas fuzzy set has an infinite number of membership functions [18]. To date, in power system area, some fuzzy methodologies have been developed to model the uncertainty of load and load growth with fuzzy theories to capture their inherent uncertainties into the future [19-21]. This model can i) effectively reflect the uncertain characteristics of load, ii) make it easier to account for future load and load growth in system planning.

In this paper, a novel fuzzy approach in calculating long-run incremental charges with uncertain load growth rates is proposed. Fuzzy load growth rate model is introduced and incorporated with original LRIC method based on the instinct of load and the characteristics of system. According to the theory of fuzzy extension method, namely vertex method, the fuzzy load growth is mapped into fuzzy LRIC charges through an intermediate variable – fuzzy time to reinforce. The concept of fuzzy LRIC pricing is demonstrated on a simple network, illustrating its effectiveness in dealing with uncertain load growth.

The rest of the paper is organized as follows: Section II introduces fuzzy load growth rate model. Section III gives a simple introduction to LRIC charging methodology. In section IV a LRIC methodology with fuzzy load growth rate is presented. Section V provides a small test system to demonstrate the fuzzy LRIC pricing concept. Finally, the conclusions are drawn in Section VI.

II. Fuzzy load growth rate model

Supposing initially load amount is L_0 with a load growth rate r, the load amount in year n can be calculated using

$$L_n = L_0 \cdot (1+r)^n \tag{1}$$

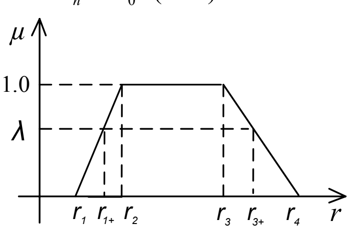


Fig. 1. Fuzzy load growth rate model

Load growth rates can be described using fuzzy set theory to translate propositions like "*load growth rate might be between r_1 and r_4, my confidence in different growth rates varies from 0 to 1 as shown in figure 1*". Unlike crisp load growth rate which represent load growth rate with a single constant value, the fuzzy modelling method can capture the confidence level associated with different load growth rates, thus providing better assessment in future reinforcement, leading to more acceptable network charges. As shown in figure 1, load growth rate may occur any where between r_1 and r_4, however, it is most likely to occur between r_2 and r_3, less likely to occur between r_1 and r_2, and r_3 and r_4. In the area out of r_1- r_4, load growth rate definitely not occurs.

III. Long-run incremental cost charging model

For network components that are affected by the injection there will be a cost associated with accelerating the investment, or a benefit associated with its deferral. Depending upon the magnitude of the reinforcement cost and the discount rate chosen, the present value of the cost for each affected component can be calculated. The long-run incremental cost is the accumulation of the present values of the cost of all affected network components in supporting a nodal injection or withdrawal. It has the following implementation steps [2].

A. Determine when investment will occur in the future

If a circuit l has a capacity of C_l, supporting a power flow of D_l, then n_l is the number of years it takes D_l to grow to C_l for a given load growth rate r

$$C_l = D_l \cdot (1+r)^{n_l} \tag{2}$$

Rearranging equation (2) and taking the logarithm of it gives the value of n_l

$$f(r) = n_l = \frac{\log C_l - \log D_l}{\log(1+r)} \tag{3}$$

Assume that investment will occur in n years when the circuit utilisation reaches C_l. If a discount rate of d is chosen, then the present value of future investment in n_l years will be

$$PV_l = \frac{Asset_l}{(1+d)^{n_l}} \tag{4}$$

Where, $Asset_l$ is the duplicated asset cost.

B. Cost associated with ΔP_l incremental addition

If the power flow change along line l is ΔP_l as a result of 1MW injection, which in turn brings forward future investment from year n_l to year n_{lne}

$$C_l = (D_l + \Delta P_l) \cdot (1+r)^{n_{lnew}} \tag{5}$$

Equation (5) will lead to the new investment horizon $n_{l\,new}$

$$h(r) = n_{lnew} = \frac{\log C_l - \log(D_l + \Delta P_l)}{\log(1+r)} \tag{6}$$

This in turn affects the present value of the investment

$$PV_l = \frac{Asset_l}{(1+d)^{n_{lnew}}} \tag{7}$$

The change in present value as a result of investment brought forward by 1MW injection will be

$$g(r) = \Delta PV_l = PV_{lnew} - PV_l \tag{8}$$

Cost for circuit l will be annuitized change in present value of future investment horizon as a result of 1MW injection

$$IC_l = \Delta PV_l \cdot annuityfactor \tag{9}$$

C. Long-run incremental cost

Long-run incremental cost to support node N will be the summation of charges over all circuits, given by:

$$LRIC_N = \frac{\sum_l \Delta IC_l}{\Delta P_{In}} \tag{10}$$

Where, ΔIC_l is the change in unit cost as a result of 1MW injection given by equation (9). ΔP_{In} is the power injection at node N, and assume it is 1MW.

IV. LRIC INCORPORATING FUZZY LOAD GROWTH RATE

This section presents mathematical formulations for LRIC methodology incorporating fuzzy load grow rate.

A. Fuzzy extension method

Vertex method, which is developed by Dong and Shah [22], is utilized to extend principle for continuous-valued fuzzy variables. This method is based on a combination of the λ–cut concept and standard interval analysis. The Vertex method consists of the following steps.

a) Any continuous membership function is represented by a continuous sweep of λ–cut intervals from $\lambda=0^+$ to $\lambda=1$;

b) For fuzzy sets $\underline{A}$ and $\underline{B}$, suppose that a single-input mapping is given by $y=f(x)$, which is extended for fuzzy sets, or $\underline{B} = f(\underline{A})$ and the decomposition of $\underline{A}$ into a series of λ–cut intervals is desired, say I_λ.

When the function $f(x)$ is continuous and monotonic with $I_\lambda=[b, d]$, the interval representing $\underline{B}$ at a certain value of λ, says B_λ, can be obtained by

$$B_\lambda = f(I_\lambda) = [\min(f(a), f(b)), \max(f(a), f(b))] \tag{11}$$

B. Membership functions of n_l and n_{lnew}

From equation (3), taking derivative of n_l with respect to load growth rate, r, gives the following equation

$$\frac{dn_l}{dr} = (\log C_l - \log D_l)\cdot\frac{1}{1+r}\cdot\left(-\frac{1}{(\log(1+r))^2}\right) \tag{12}$$

Similarly, taking derivative of n_{lnew} with respect to r, following equation can be obtained

$$\frac{dn_{lnew}}{dr} = (\log C_l - \log(D_l + \Delta P_l))\cdot\frac{1}{1+r}\cdot\left(-\frac{1}{(\log(1+r))^2}\right) \tag{13}$$

From equation (8), it can be found that ΔPV is a function of n_l and n_{lnew}. Obviously, it can be seen from (12) and (13) that both n_l and n_{lnew} new are monotonic and decreasing functions with regarding to r. The membership functions of n_l and n_{lnew} with respect to fuzzy load growth model sketched in figure 1, are calculated with vertex method as following.

a) In case of $\lambda=0^+$, $I_{0+}=[r_1, r_4]$

$$B_{0+} = [\min(f(r_1), f(r_4)), \max(f(r_1), f(r_4))] \tag{14}$$

b) In case of $\lambda=\lambda_m$, $I_{\lambda m}=[r_{1+}, r_{3+}]$

$$B_{\lambda_m} = [\min(f(r_{1+}), f(r_{3+})), \max(f(r_{1+}), f(r_{3+}))] \tag{15}$$

c) In case of $\lambda=1$, $I_1=[r_2, r_3]$

$$B_1 = [\min(f(r_2), f(r_3)), \max(f(r_2), f(r_3))] \tag{16}$$

A complete λ-cut representation can be obtained by repeating step (b) for different values of λ. The same method can be utilized to get membership function of n_{lnew}.

C. Membership functions of LRIC charge

Similarly, membership function of LRIC charges can also be obtained using vertex method. The derivatives of ΔPV_l with respect to load growth rate r is

$$\frac{d(\Delta PV_l)}{dr} = Asset_l \times \ln\left(\frac{1}{(1+d)}\right)\times\left(\frac{1}{(1+d)^{n_{lnew}}} - \frac{1}{(1+d)^{n_l}}\right) \tag{17}$$

In this case, extreme points might exit within the region of the membership function. Fortunately, this can be determined using a derivative of the function with respect to load growth rate r. if the relating load growth rate is r^*, that is

$$\frac{d(\Delta PV_l)}{dr} = g'(r^*) = 0 \tag{18}$$

a) In case of $\lambda=0^+$, $I_{0+}=[r_1, r_4]$

$$B_{0+} = [\min(g(r_1), g(r_4), g(r^*)), \max(g(r_1), g(r_4), g(r^*))] \tag{19}$$

b) In case of $\lambda=\lambda_m$, $I_{\lambda m}=[r_{1+}, r_{3+}]$

$$B_{\lambda_m} = [\min(g(r_{1+}), g(r_{3+}), g(r^*)), \max(g(r_{1+}), g(r_{3+}), g(r^*))] \tag{20}$$

c) In case of $\lambda=1$, $I_1=[r_2, r_3]$

$$B_1 = [\min(g(r_2), g(r_3), g(r^*)), \max(g(r_2), g(r_3), g(r^*))] \tag{21}$$

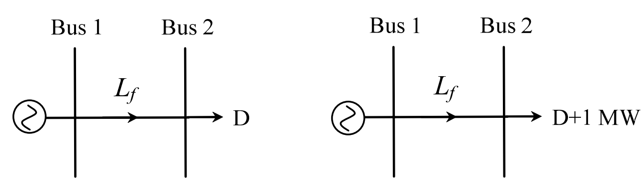
A complete λ-cut representation of the solution can be computed by repeating step (b) for different values of λ.

V. A CASE STUDY AND DISCUSSION

Our concept is testified using a two-busbar simple network given in figure 2[2].

A. Test System Data

The circuit rating of L_f is 45MW after security redundancy and its cost is £236,760/yr. The annuity cost is based on 6.9% discount rate over 40 years life span, and this leads to the circuit total cost as £3,193,400. In this example, five λ-cut situations are considered, showed in figure 3, and the corresponding load growth rates are also provided in table 1.



(a) (b)

Fig. 2. (a) Origianl network (b) Network with1 MW increment

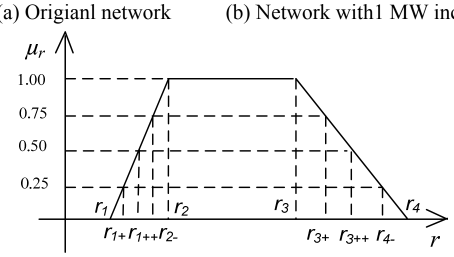


Fig.3. Fuzzy load growth rate of the test system

TABLE.1 FIVE CUTS AND CORRESPONDING LOAD GROWTH RATES

λ =0	λ =0.25	λ =0.50	λ =0.75	λ =1
r_1=0.013	r_{1+}=0.01325	r_{1++}=0.0135	r_{2-}=0.01375	r_2=0.014
r_4=0.018	r_{3+}=0.016	r_{3++}=0.017	r_{4-}=0.0175	r_3=0.016

B. Results and Discussions

Three indices are calculated: time horizon to reinforcement (HtR), time horizon after 1 MW addition (HaA), and annual charge (AC), and results are given in figure 5 and table 2.

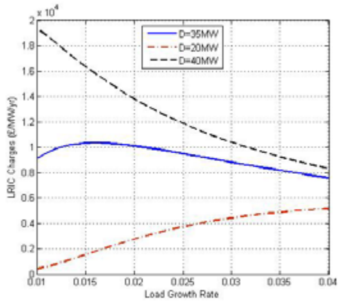


Fig. 4. Variations of LRIC charges with respect to D

In the process of deducing membership functions of LRIC charges, different load level would give birth to quite different shapes of membership functions. Figure 4 presents the changes of LRIC charges with respect to the increase of load growth rate in three scenarios. It is apparent that when D=20MW, charges increase steadily with the rise of load growth rate. While, in case of D=40MW, LRIC charges decrease steadily with respect to the increase of load growth rate. The case of D=35MW gives a quite different shape of characteristic line compared former ones. It is noted that charges increase steadily when load growth rate becomes big and after a peak point, charges drop gradually. Generally, it is found that charges of heavily loaded circuit are constantly higher than lightly loaded circuits.

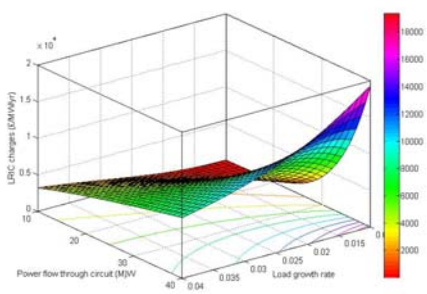
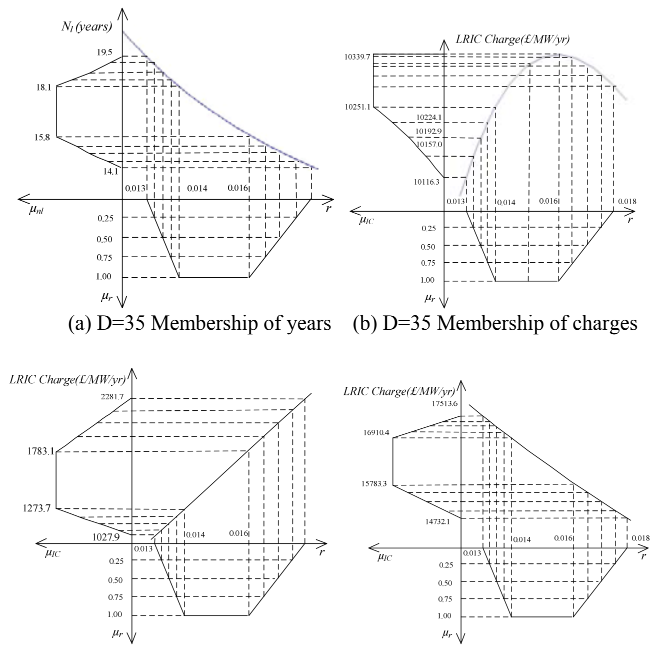


Fig.5. Changes of LRIC charges in different cases

A 3-D image in figure 5 generally indicates how LRIC charges change with respect to circuit loading level and load growth rates. This figure shows that functions of LRIC charges are non-monotonic. Both load growth rate and circuit carrying power influence LRIC charges to a great extent.

Four charts in figure 6 represent membership functions of years to reinforce and LRIC charges under different loading level with respect to fuzzy load model. (a) is the membership function profile of n_l in the case of D=35MW. It can be seen that, if load growth rates range between 0.013 and 0.018, n_l changes from minimal value 14.1 to maximum value 19.5. The degree of membership of n_l grows gradually between 14.1and 15.8, and the values of n_l between 15.8 and 18.1 have the biggest degree of membership 1.0. This figure gives us a clear map of how load growth rates influence n_l.



(a) D=35 Membership of years (b) D=35 Membership of charges

(c) D=20 Membership of charges(d) D=40 Membership of charges

Fig.6 Membership functions under different situations.

Figures (b), (c), and (d) depict the fuzzy membership functions of LRIC charges when D=35MW, D=20MW, and

TABLE.2 LRIC CHARGES IN DIFFERENT SITUATIONS

	D=20MW			D=35MW			D=40MW		
Load Growth Rate	HtR (years)	HaA (years)	AC (£/MW)	HtR (years)	HaA (years)	AC (£/MW)	HtR (years)	HaA (years)	AC (£/MW)
r_1	62.8	59.0	1027.9	19.5	17.3	10116.3	9.119	7.2	17513.6
r_{1+}	61.6	57.9	1088.3	19.1	16.9	10157.0	8.9	7.1	17361.3
r_{1++}	60.5	56.8	1149.5	18.7	16.6	10192.9	8.7	6.9	17209.8
r_{2-}	59.4	55.8	1211.3	18.4	16.3	10224.1	8.6	6.8	17059.5
r_2	58.3	54.8	1273.7	18.1	16.1	10251.1	8.5	6.7	16910.4
r_3	51.1	48.0	1783.1	15.8	14.1	10339.7	7.4	5.9	15783.3
r_{3+}	49.6	46.6	1908.2	15.4	13.6	10333.7	7.2	5.7	15499.9
r_{3++}	48.1	45.2	2034.7	14.9	13.2	10319.1	7.0	5.5	15237.3
r_{4-}	46.7	43.9	2158.4	14.5	12.9	10296.7	6.7	5.3	14981.3
r_4	45.5	42.7	2281.7	14.1	12.5	10267.7	6.6	5.2	14732.1

D=40MW respectively. As for (b), LRIC charges increase from 10,116.3(£/MW/yr) with degree of membership of 0 to 10,251.1(£/MW/yr) with degree of membership of 1. This section is followed by a straight line, which means charges increase synchronously with regarding to load growth rate to 10,339.7(£/MW/yr). The straight line indicates that during this sector, the degree of membership of is constant 1. The charges are dominated by degree of membership of 1.0 when the load growth rate reaches 0.014, because charges have a peak in this sector with regard to a load growth rate of 0.016. Figures (c) and (d) give quite similar membership functions of charges with respect to the given fuzzy load growth rates, but the biggest LRIC charges of (c) appear when load growth rates are quite large and the biggest LRIC charges for (d) happens when load growth rates are small. Figure 6 gives quite different shape of charge membership functions due to the fact that function characteristics of these three cases with respect to load growth rates are quite different.

VI. CONCLUSIONS

Uncertainty of load growth rate imposes great difficulties on LRIC charge calculation methodologies. In this paper, a novel methodology of evaluating long-run incremental charges with fuzzy load growth rate is proposed to handle the uncertain characteristics of load growth rate and fuzzy load growth rate model is introduced. Thereafter, the model is incorporated with LRIC methodology. A simple example is utilized here to demonstrate our concept. It is apparent that LRIC method with fuzzy load growth rate can effectively model uncertain nature of load growth rate. Unlike crisp model, this fuzzy model gives a range of LRIC charges with regard to the fuzzy model of load growth rate. Generally, fuzzy representations of years to reinforce and LRIC charges represent range values of years to reinforce and charges and their corresponding degree of membership, while deterministic model only provide a section of the whole load growth rate range. If load growth rate is difficult to determine and only some fuzzy characteristics can be captured, this fuzzy model is an effective tool for evaluation. While our concept is only tested with a simple example, in the future we are going to extend our concept to large-scale system.

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VIII. BIOGRAPHIES

Chenghong Gu was born in Anhui province, China. He received his Master degree in electrical engineering from Shanghai Jiao Tong University, Shanghai, China, in 2007. Now, he is a PhD student with University of Bath, UK. His major research is in the area of power system reliability pricing and long-run incremental cost charging

Furong Li (M'00) was born in Shannxi, China. She received the B.Eng. degree in electrical engineering from Hohai University, Nanjing, China, in 1990 and the Ph.D. degree from Liverpool John Moores University, Liverpool, U.K., in 1997. Her thesis was on Applications of Genetic Algorithms in Optimal Operation of Electrical Power Systems.

She is a senior lecturer in the Power and Energy Systems Group at the University of Bath, Bath, U.K. Her major research interest is in the area of power system planning, analysis, and power system economics.