Quantifying the Long-term Benefits of Interruptible Load Scheme for Distribution Network Investment

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***Abstract*—This paper seeks to measure the long-term benefits brought by the interruptible load scheme (ILS) to network utilities and customers. Normally, the ILS is adopted as necessary to reduce system peak demand. By contrast, this paper states that if the scheme is adopted during network contingencies that drive future reinforcement, great benefits might be obtained. It assumes that the long-term benefits incurred from introducing the scheme needs to be investigated and long-term use-of-system pricing is qualified for this purpose. In order to encourage customers to participate in the scheme, the derived charges can work as economic incentives. Hence, the long-run increment cost (LRIC) pricing for interruptible loads is reported, which is able to truly recognize the impact of ILS on network investment in long-term. The benefits from introducing the scheme are evaluated in terms of deferral in present value of future reinforcement of network investment and the reduction in nodal use-of-system charges. The concept is demonstrated in a practical Extra-high voltage (EHV) distribution network, indicating its effectiveness.**

***Index Terms*—Network pricing, Long-run incremental cost, Interruptible load scheme, Investment**

I. Introduction

IN order to operate their networks more flexibly and efficiently, network utilities have introduced interruptible load scheme (ILS) to control loads to regulate customers' reliability and reduce demand during system peak period. By signing contracts with customers who are willing to allow their load fully or partially to be curtailed in contingencies or during system peak time, DNOs can plan and operate their networks in such a way that future investment in generation and networks might be deferred or scraped.

The roles that the voluntary ILS can play in electricity industry have been recognized and investigated in numerous references from different aspects[1]. One major focus is to design ILS contracts so as to devise appropriate incentive rate structures for interruptible loads based on spot prices [2, 3]. The target is to provide sufficient incentives to network customers so that they are more willing to sign up ILS contracts. The other hot research area is to determine and assess the impact and benefits that the ILS can bring on network operation, reductions in generation costs, the improvement in system reliability [4, 5], and the adequacy of generation [6], etc. An dynamic ILS is proposed in [7] so that utilities can resort to interruptible loads in both network normal and contingency situations. A Gaussian approximation whose parameters can be specified with data from samples is utilized to the probability of their interruptible loads.

Despite the previous intensive research on ILS, quite little has ever investigated the influence of ILS on network investment and the benefits to the scheme participants. Paper [8] proposes a new optimal power flow (OPF) based scheme to manage ILS, in which several factors associated with ILS, such as notification of load curtailment, short-term discounts, long-term discounts are incorporated. The paper stresses the importance of evaluation long-term benefits of ILS, but it only assigns a prefixed rate to represent the benefits in $/kW. The shortcoming is that the rate is not practically calculated and consequently is not cost-reflective. In order to encourage more customers to participate in the scheme, the benefits on network investment needs to be quantified and the economic signals need to be sent so as to influence their behaviors. Long-run network pricing, as a measure to recover the investment costs in systems from users [9], can be utilized to examine the impact of the ILS on network investment and calculate network charges.

The LRIC model assumes that network security requirement [10, 11] needs to be respected in pricing and it works on the basis that network customers of or over certain sizes need to be secured against N-1, N-2 or even higher level contingencies, whatever their occurrence probability and outcome [11]. Such a planning philosophy might lead to overinvestment in networks, especially if the future network reinforcement is driven by a demand spike. Take the demand of GB in 2004 demonstrated in Fig.1 as an example. The peak demand is around 44GW, and if future investment is conducted based this value during network contingencies, it would be rather costly as most of the demand in the year is below 41GW. Hence, if part of the demand can be curtailed in the network contingences that drive future reinforcement, the investment might be deferred. Thus, the implementation of the ILS under such circumstances is fairly promising.

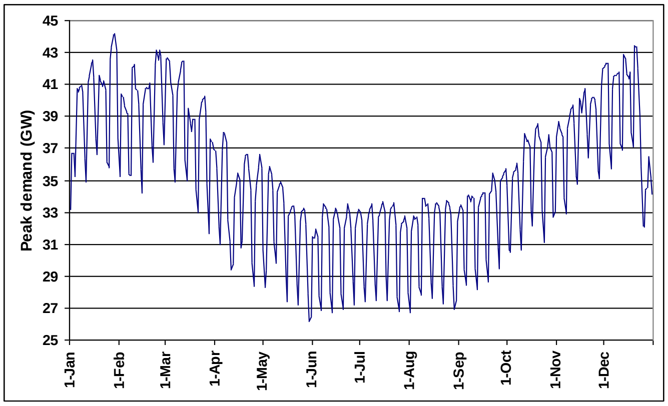

Fig.1. The GB peak demand in 2004 [12].

This paper seeks to investigate the impact of interruptible load scheme on distribution network investment. It stresses that in order to fully appreciate the benefits from the ILS, its impact on network investment should be quantified and the use-of-system pricing is qualified for this purpose. The original LRIC charging model [9] is revised to accommodate the purpose of pricing interruptible load. The calculated reduced charges are good incentives to encourage customer's participation in the scheme. The benefits of introduction the scheme for utilities are quantified in terms of savings from network investment costs and reduction in nodal charges. The demonstration of the concept is carried out on a practical EHV distribution system taken from the UK networks.

The rest of the paper is organized as follows: Section II gives a brief introduction to the LRIC charging approach. In Section III, the pricing model for interruptible load is presented. Section IV introduces the approach to quantify the deferral in network investment. Section V provides a test system to demonstrate the introduced concept. Finally, some conclusions are drawn in section VI.

II. Long-run incremental cost pricing model

The LRIC model originally proposed by UoB in conjunction with the Office of Gas and Electricity Market (Ofgem) and Western Power Distribution (WPD) [9, 13] assumes that for network components affected by a nodal injection, either demand or generation, there will be a cost associated for the injection if their reinforcement horizons are accelerated or a credit if they are deferred. Fig.2 demonstrates the basic concept behind the model.

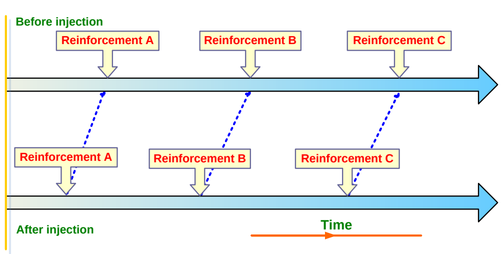

Fig.2. Principle of long-run incremental cost pricing.

In order to assess the impact due to nodal injections, the model needs to capture it by examining the changes in components' future reinforcement horizons affected and translating the changes into the variation of components' present value of future reinforcement. Generally, the LRIC model has the following three implementation steps [9].

1) to work out components' original reinforcement horizons without any injections. In this step, components' original loading levels are assessed with power flow analysis and the obtained results are then submitted into the formulas for demining their reinforcement horizons.

2) to determine components' new reinforcement horizons with injections. They are determined by examining how nodal injections would affect their loading levels with incremental flow analysis and submitting into the formulas assessing horizons.

3) to assess nodal unit price. The charge for a nodal is all the incremental costs incurred from its supporting components, which are then discounted back into as present value of future reinforcement.

Contingency factors of components are introduced to reshape components' maximum available capacity [10] in order to reflect network security. A contingency factor of a component is defined as the maximum contingency flow along the component under all contingency events over its base case flow. Thereafter, the maximum available capacity of a component becomes

$$MAC = \frac{RC}{CF} \tag{10}$$

where, MAC is maximum available capacity, RC stands for rated capacity and CF represents contingency factor.

This LRIC model is quite advanced for pricing customers' use-of-system to recover the investment costs and has been chosen as one of the two common methodologies utilized in EHV distribution networks in the UK by Ofgem.

III. Pricing with Interruptible Loads

If part of load can be interrupted during network contingencies which drive future network reinforcement, the needed investment can be delayed to some extent, the degree of which depends on the amount of the interrupted load. Therefore, it is essential to work out pricing scheme for interruptible loads.

In [14, 15] a novel charging strategy is proposed to price different load compositions according to their security preference. It is derived on the basis of the original LRIC mode, but examines the impact of interruptible and uninterruptible loads on network components in both normal and contingency situations. The model assumes that interruptible loads can be curtailed during network contingencies that derive network reinforcement, but the uninterruptible parts need to be secured. Its basic concept is expalined as follows.

For the radial system given in Fig.3, the two circuits are assumed to be identical, each carrying a normal case flow of D, classified into two parts: interruptible part, D_{inter}, and uninterruptible part, D_{unint}.

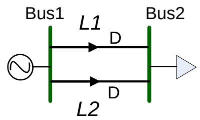

Fig.3. Layout of a two two-busbar test system.

A. Original Investment Horizon without Injections

In normal conditions, the investment horizons of the two circuit under a given load growth rate can be indentified with

$$RC = D \cdot (1+r)^{n_{norm}} = (D_{unint} + D_{inter}) \cdot (1+r)^{n_{norm}} \quad (1)$$

where, RC is their rating and r is the chosen load growth rate.

Rearranging and taking logarithm of it gives

$$n_{norm} = \frac{\log RC - \log(D_{unint} + D_{inter})}{\log(1+r)} \quad (2)$$

Under an contingency event, such as L2 fails, L1 only needs to accommodate the uninterruptible load along the two circuits as the interruptible load of the two circuits can be curtailed. Hence, L1's investment horizon is calculated with

$$n_{cont} = \frac{\log RC - \log(D_{unint,cont})}{\log(1+r)} \quad (3)$$

where, $D_{unint,cont}$ is the maximum uninterruptible flow along L1 in the contingency, which should be 2 times of D_{unint} here.

B. New Investment Horizon due to Interruptible Injections

When an interruptible injection connects to busbar 2, in normal conditions, if ΔP is the incremental flow along L1 due to the new interruptible connectee, the two circuits' new horizons are determined with

$$RC = (D + \Delta p) \cdot (1+r)^{n_{norm,new}} \quad (4)$$

Rearranging above formula and taking logarithm of it gives

$$n_{norm,new} = \frac{\log RC - \log(D + \Delta P)}{\log(1+r)} \quad (5)$$

L1 also needs to take up the uninterruptible flow part along L2 when L2 fails in contingencies Thereby, the new interruptible flow along L1 can only increase on top of the potential maximum contingency flow, leading to L1's new horizon, determined by replacing D in (5) with $D_{unint,cont}$

$$n_{cont,new} = \frac{\log RC - \log(D_{unint,cont} + \Delta P)}{\log(1+r)} \quad (6)$$

For the two circuits, their new reinforcement horizons with the incorporation of the interruptible injection should be the smaller one between (5) and (6).

When a new uninterruptible connectee comes to busbar 2, it also impacts the two circuits in both normal and contingency situations. It can influence network in both normal and contingency situations, the impact of which can be determined in the same way. The new horizons of the components by the interruptible injection are also the smaller one between the two situations.

C. Evaluation of Unit Charge

Once the two time horizons of each circuit are indentified, their unit prices for both the interruptible and uninterruptible loads can be assessed by submitting their supporting components' horizons into the following step.

The present value of future reinforcement is

$$PV = \frac{Asset_l}{(1+d)^n} \quad (7)$$

The change in the present value due to the injection is

$$g(r) = \Delta PV_l = Asset_l \cdot \left(\frac{1}{(1+d)^{n_{l\,new}}} - \frac{1}{(1+d)^{n_l}} \right) \quad (8)$$

The incremental cost for circuit l is the annuitized change in present value of future investment over its life span,

$$\Delta IC_l = \Delta PV_l \cdot AnnuityFactor \quad (9)$$

The nodal LRIC charge at busbar i is the summation of the incremental cost over all circuits supporting it, given by

$$LRIC_i = \frac{\sum_l \Delta IC_l}{\Delta PI_i} \quad (10)$$

where, ΔPI_i is the size of power injection at node i.

D. Implementation Steps

The major steps of the approach are to determine how interruptible and uninterruptible connectees would affect network components' reinforcement horizons in both normal and contingency situations and finally to derive nodal charges. The detailed flowchart of the model is given in Fig.4.

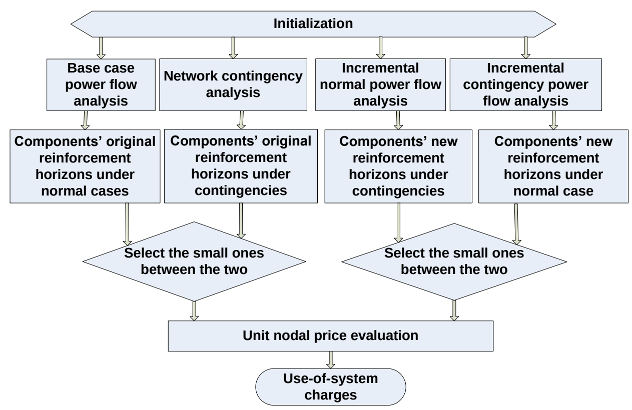

Fig.4 The implementation of the LRIC model [14].

Finally, two charges at each busbar will be produced: one is for interruptible loads at the busbar and the other is for uninterruptible loads at the same busbar.

IV. Evaluation of Deferral in Present Value of Future Reinforcement

The benefit brought by interruptible loads for network investment is assessed in terms of the deferral in present value of future reinforcement of components. It is quantified by comparing the annuitized present value of future reinforcement in networks, given in (11), with and without the interruptible loads participating in the ILS. The final benefit is the summation of the change in present value of all network components. The mathematical formulation of the evaluation is described as

$$\Delta PV = \sum_{i=1}^{N}\left(PV_i - PV_{new,i}\right)\cdot AnnuityFactor$$
$$= \sum_{i=1}^{N}\left(\frac{Asset_i}{(1+d)^{n,i}} - \frac{Asset_i}{(1+d)^{n_{new,i}}}\right)\cdot AnnuityFactor \quad (11)$$

where, PV_i and $n_{,i}$ are the present value of future investment and reinforcement horizon of component i without interruptible loads curtailed and $PV_{new,i}$ and $n_{new,i}$ are its new present value of future investment with the interruptible loads curtailed.

Future investment in network can be caused by both network thermal limitation violations and aging of components and other factors and in this paper, only the first one is considered.

V. Example Demonstration

This section quantifies the benefits of adopting the ILS in terms of investment deferral and reduced network charges on a practical UK EHV distribution network, given in Fig.5. Load growth rate and discount rate are chosen as 1.6% and 6.9% respectively [9]. The proportion of loads participating in the ILS is supposed to be 20% at all busbars.

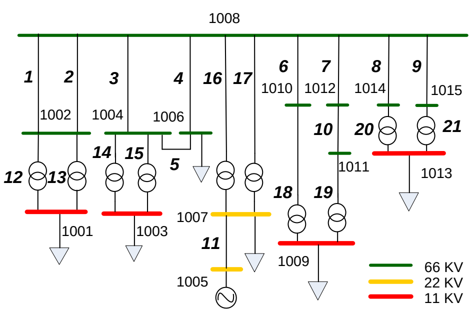

Fig.5. A grid supply point area test system.

A. Network Charges Evaluation

Table I provides the nodal charges from the original model and the model reported in the previous section.

TABLE I
Comparison of the Nodal Charges (£/kW/yr)

Busbar No.	1001	1003	1006	1007	1009	1013
Original model	4.88	18.29	15.38	1.95	5.69	3.45
Interruptible load	1.31	4.97	3.88	0.57	1.58	1.19
Uninterruptible load	3.62	10.00	9.21	1.19	3.43	2.65

The diversified charges imply the different levels of use of system by demand. Among them, charges from the original model at all the busbars are the highest, as the model assumes no interruptible loads can be curtailed during contingency events that drive network investment. The highest charge from the model is 18.29 £/kW/yr at busbar 1003, which is nearly 10 times of the lowest charge of 1.95 £/kW/yr at busbar 1007. The charges from the reported model, on the other hand, are relatively small for both interruptible and uninterruptible loads, between which the first ones are even lower. The highest charges for interruptible and uninterruptible loads are still at busbar 1003, which, by contrast, slide down to nearly 4.797 £/kW/yr and 10.00 £/kW/yr for interruptible and uninterruptible loads respectively.

Fig.6 demonstrates the percentage of all charges for interruptible and uninterruptible loads over the charges from the original model at the same busbar. As seen, charges for interruptible loads at all busbar are merely approximately 25% of the original charges. By contrast, charges for uninterruptible loads are higher, which range from about being 60%-70% of the original charges.

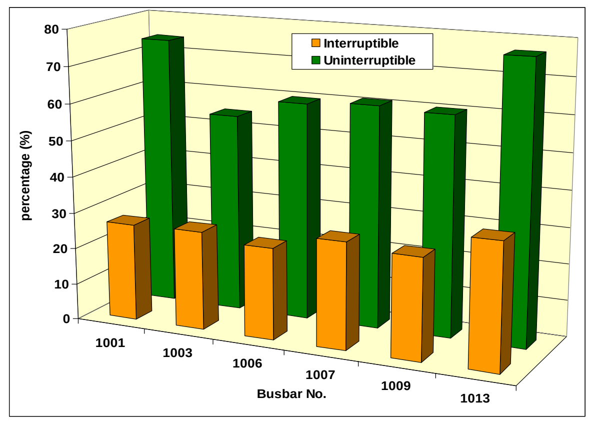

Fig.6. The percentage of the new nodal charges.

Despite the significant reductions in charges, the relativities between them at different locations are still maintained. Charges at busbar 1003 are the highest, followed those at busbars 1006 and 1001. The locational signals are able to influence prospective customers' behaviors to encourage efficient network utilization and delay the needed upgrades. In addition, the reduced charges can encourage more customers to participate in the ILS.

B. Deferral in Long-run Investment Cost

The benefit of the ILS on deferral in network investment is demonstrated in Fig.7, which is in terms of the annuitized present value of future reinforcement over all branches.

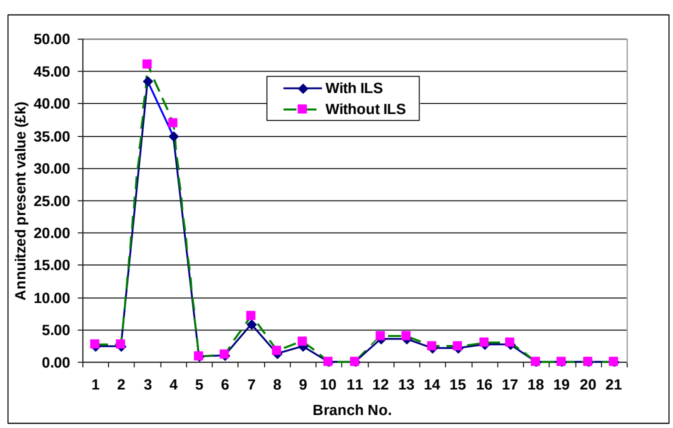

Fig.7. Comparison of annuitized present value.

As seen, the values all components become rather smaller in the case with the ILS. Particularly, the costs of branches 3 and 4 are around £2m, whose annuitized present value of future reinforcement are around £46k and £37k in the cases without ILS implemented. The two values are brought down to around £43k and £35k respectively when the ILS is adopted.

Fig.8 demonstrates the reductions in all components' present value. As seen, the values vary dramatically, with the highest for branches, 3, 4, 7 and 9. The amount of them depends not only on their loading levels, the amount of the interruptible loads they support, but also on their costs and the chosen load growth rate.

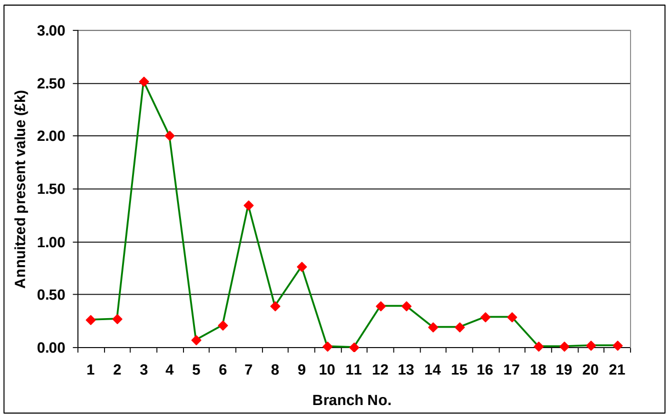

Fig.8. Reductions in annuitized present value.

TABLE II
COMPARISON OF ANNUITIZED PRESENT VALUE OF FUTURE REINFORCEMENT (£/YR)

Without ILS	With ILS	Deferral
121090	111467	9624

The summations of the present value of future reinforcement of all components in the system with and without the ILS implemented are given in Table II. Although only 20% of demand is interruptible, the total reductions in annuitized investment are rather generous. When no ILS is adopted, the total value is approximately £121k, which is reduced down to £111k, with a reduction by £9.6k.

VI. Conclusion

This paper examines the impact of the ILS on network investment and introduces the use-of-system pricing to measure the benefits obtained from implementing the scheme. They are quantified in terms of reduction in network charges and deferral of future reinforcement. As demonstrated on a practical system, the charges for interruptible loads are rather small compared to those generated from the original charging model. The reduction in charges can be an effective incentive for customers to participate in ILS. In addition, the deferral in present value of future reinforcement of components is significant even if only a small proportion load is curtailed during system peak contingency events.

It should be noted that the duration and the amount of loads could be curtailed vary greatly, depending on their types: residential, commercial or industrial and they should be considered to quantify the benefits. In this paper, the proportion of interruptible demand is hypothetical, but different proportions should be examined in order to work out the most beneficial one in the future research. In addition, this research focus only on benefits in terms of deferral in investment costs and reduction in charges, but the actual benefits are not limited to these, such as improvement in system long-term reliability, etc, which need further study.

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VIII. Biographies

Chenghong Gu (S'09) was born in Anhui province, China. He received his Master degree in electrical engineering from Shanghai Jiao Tong University, Shanghai, China, in 2007. In 2010, he received the Ph.D. in Electrical Engineering from University of Bath, U.K. His major research is in the area of power system economics and planning.

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