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Long-run Network Pricing to Facilitate Users' Different Security Preference

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***Abstract*— This paper proposes a new long-run network pricing model that can account for network users' preference for security of supply when assessing their impact on network development costs. The new model firstly classifies load at each node into interruptible and uninterruptible parts according to their different security preference. It then seeks to examine the impact on the network development costs from a marginal increment of the two types of loads at each node. It assumes that interruptible loads can be interrupted under contingencies, whereas both loads should be satisfied under normal conditions. Use-of-system (UoS) charges are then calculated by translating the impact on network development costs into locational long-run network charges. Compared with the existing approach which assumes that consumers at the same locations are subject to the same security levels, the proposed approach acknowledges users' different security preference, respects the reduced requirement on the network development costs from interruptible loads, and prices users' UoS charges accordingly.**

The paper demonstrates that network charges for interruptible loads are cheaper than those for the uninterruptible loads at the same node. The degree of the difference depends on the percentage of interruptible loads in the system and at the node. The pricing signals could incentivize prospective users to switch their behaviors in favor of lowering the overall network security requirements, and thus lowering network reinforcement costs. This will ultimately bring down users' UoS charges. The effectiveness of the proposed approach over the basic security-based long-run pricing model is illustrated on two networks in terms of charges for the two s load and the impact of load composition on the charges.

***Index Terms*-- Network charging, security preference, contingency, interruptible load, uninterruptible load.**

I. Introduction

Since privatization was introduced into the UK's electricity power industry in early 1990s, market forces have been playing a vital role in promoting competition and enhancing network operation and planning efficiency. In this new competitive environment, most networks are operated close to their limits, yet, network operators are required to ensure the same level of security at the same busbars as mandated by network security and quality standards [1, 2].

Security of supply is crucial to both network users and operators [3]. Higher level of security means that users' supply is less likely to be interrupted under both normal and abnormal conditions and hence the cost due to loss of supply is lower. For network operators, if they opt to provide high security levels, they need to ensure enough investment in their networks to maintain sufficient available network capacity. This would come at high costs to them and consequently high electricity price to customers [4]. If, on the other hand, network operators choose to operate systems with lower security levels, thus reducing the required investment costs, consumers would pay for lower electricity prices but could suffer more frequent supply interruptions [5]. The cost of the supply interruptions differs from sector to sector and depends on the seriousness of the network contingencies and the nature, size and location of the interrupted loads [6]. To minimize the overall system costs, network operators have to strike a right balance between network security and network investment [7, 8]. In arriving at the right balance, the majority of network operators assume that customers at the same busbars require the same security levels and they thus do not offer customers price differentiations for different security levels. This philosophy is thus unable to reflect the potential impact on networks if customers are willing to lower their security level of supply, partially or fully.

Most of approaches reported in literature for charging based on differing security levels are for transmission systems, and by large they only reflect the impact on network operation rather than network investment [9-15]. For the first time, paper [9] incorporates network security into pricing for transmission systems from the operational aspect, in which each participant makes a socially optimal contingency usage assessment based on a forecast for potential contingent usage for its own benefits. The approach in [11] prices network users for their use of a system by simulating the change in the system's reliability margin with and without the users and then allocating the costs relating to the decrease in reliability or the increase in investment cost. It brings all network users to a similar reliability level, thus ignoring users' security preference. Papers [12-15] consider that each circuit has two functions: i) to allow power to flow between two nodes and, ii) to provide reliability benefit for maintaining system reliability. In paper [12], the cost of capacity use is in proportion to the sum of the absolute power flows caused by transactions in normal states. Components' reliability margins are calculated by introducing a probabilistic contingency index. The disadvantage is that the approach is highly dependent on the number of transactions, which in reality is very hard to predict. Paper [13] splits

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circuit's capacity-use and reliability benefit into a 80%-20% ratio, but no rigorous technical justifications are given. Papers [14-15] assign the ratio based on power flows, where capacity use is based on the absolute power flow under normal condition and the remaining capacity is for maintaining reliability. The calculated charges are based on the ratio between the two functions of each component. For a system with very low utilization, the method would generate very low UoS charges and thus over evaluate the reliability cost. These papers although link network costs to system security and reliability but not to users' security preference.

In distribution networks, limited effort has been put on examining users' respective impact on long-term network development and pricing them based on their security preference ~~and~~ . In the U.K., distribution reinforcement model (DRM) [16] is widely used by the majority of the distribution network operators (DNOs) for their high voltage (HV) and low voltage (LV) networks at present. The model lumps all costs into one, including investment and operational costs, and allocates the total costs according to the postage stamp approach for each voltage level. The model does not separately consider the security issue. The long-run incremental cost pricing (LRIC) reported in [17] uses a rudimentary approach to evaluate the impact of network security on network development costs. It assumes that all parallel circuits are of equal size and capacity and thus can only be loaded up to 50% to ensure the integrity of systems under N-1 contingencies. An improved security-based LRIC is reported in [18], which investigates the impact of security on network charges by conducting a full N-1 contingencies to determine the maximum power flow for each component, based on network configuration, the connection patterns of distributed generators (DGs) and demand. The key disadvantage with this approach is that it gives all users at the same busbars a uniform security level. It does not respect individual customer choice in supply reliability, nor does it recognize the impact to network investment costs if customers choose different security levels.

In the deregulated environment, network customers may prefer a higher or lower security level rather than an uniform level provided by network utilities [19]. In order to make electricity service reliability more of a private good, it is also necessary to provide correct signals that reflect locational and temporal costs and enable customers to respond to these prices through direct load response or through the choice of service levels [20]. Therefore, security-oriented charging models should be cost-effective not only in terms of reflecting the extent of the use of the network by a customer but also its security preference. They should be able to recognize customer choice for different security levels and price them accordingly.

This paper proposes a new long-run network pricing model that respects users' security preference when assessing their impact on network development costs. The loads at all busbar are firstly divided into interruptible and uninterruptible compositions according to their choices for security. The interruptible part should be secured under normal conditions, but can be curtailed under contingencies; on the other hand, the uninterruptible part should be secured at all times. By examining the impact from the two types of loads on the future network investment costs over time, the long-run incremental cost for each node can be calculated according to the extent to which they defer or bring forward the investment horizons of network components. Compared with the previous work, the proposed approach can respect users' preference for differing security levels. The locational charges can thus serve as economic messages to influence users' behaviors in terms of: 1) the choices for different levels of security of supply, 2) the connection sizes, and 3) connection sites. The approach is demonstrated and compared with the original security-based charging model in [18] on two systems in terms of charges.

The rest of this paper is organized as follows: Section II introduces the classification of load compositions from the security perspective. In Section III, the proposed model is presented. Sections IV and V demonstrate the proposed approach on two test systems and compare the results with those from the original security-based charging model. Section VI provides a short discussion concerning the proposed approach. Finally, Section VII concludes this paper.

II. Load Composition Classification

In line with planning standards, all networks are designed to withstand credible contingencies that might affect the security of supply [21]. In charging models, the costs for maintaining network security needs to be recognized. High security level, however, comes at a significantly high cost to network development due to greater requirement for component redundancy.

With regard to security level, some users might prefer securer supply as the consequential cost of load loss is very high, such as hospitals and airports; some, on the contrary, can tolerate lower security level if there are financial gains, e.g. passive appliances at home, commerce or factory, such as cooling, heating, washing could be interrupted for limited time. In line with users' preference, demand at each busbar can be categorized into uninterruptible part and interruptible part, which have the following features:

1) The uninterruptible load composition is the part of demand that should be secured during normal states and contingencies, regardless of whether the contingencies are unanticipated component failure or anticipated planned maintenance. This definition is also applicable to the prospective growth of this type of load.
2) The interruptible load composition is the part of demand that should be secured under normal conditions, but can be interrupted under contingencies. It is also applicable to the future growth of this part of demand.

The role and importance of interruptible loads has already been recognized in reliability analysis [22, 23] in order to promote network security. Most of the papers, however, focus on how interruptible loads could increase system reliability levels and reduce the level of system reserve; very few investigated their impact on network investment and how to price them UoS charges.

This paper proposes a new LRIC pricing model that charges users according to their security preference and their consequential impacts on network development. By adopting this scheme, DNOs can incentivise more flexible demand that can be interrupted during contingencies, thus reducing the need for costly network upgrading.

III. Charging for Different Load Compositions

In order to more accurately recognize users' preference for different security levels, both normal and contingent conditions should be taken into network costing and pricing assessment. The role of the spare capacity in a circuit to the two types of loads under normal and contingent conditions is first elaborated. The novel charging model is then presented by examining the impact of interruptible and uninterruptible loads on network components under both conditions.

A. Original Investment Horizon without Injections

For a simple two-busbar system given in Fig. 1, it is assumed that the two circuits are identical. Each of them carries a normal flow of D, which is classified into two parts: interruptible part, D_{inter}, and uninterruptible part, D_{unint}.

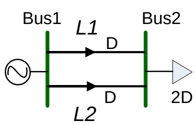

Fig. 1. Layout of a two two-busbar test system.

To satisfy the supply requirement, both interruptible and uninterruptible loads have to be secured under normal conditions. The investment horizon of each circuit is influenced by the sum of interruptible and uninterruptible load supported by the circuit, which can be identified by

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

where, RC is the circuits' rated capacity and r is the underlying load growth rate.

Rearranging and taking logarithm of (1) gives

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

On the other hand, to satisfy the supply requirement that all uninterruptible loads have to be secured under N-1 contingencies, the circuits have to reserve sufficient capacity to accommodate potential uninterruptible loads under contingencies. For example, L1 needs to support its own uninterruptible load and the additional uninterruptible load normally supported by L2 in case L2 fails, while the interruptible loads supported by the two circuits can be curtailed. Hence, for the purpose of maintaining essential network security, the circuit's investment horizons is influenced by the sum of normal and contingent uninterruptible loads, calculated by

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

where, $D_{unint,cont}$ is the maximum uninterruptible flow along the circuit under contingency, which is twice of D_{unint} in this example.

To ensure the system to simultaneously satisfy the two supply requirements, the minimum of the two investment horizons defines their future reinforcement horizons.

B. New Investment Horizon due to Interruptible Injections

When an interruptible injection is applied to busbar 2, its impact on the circuits can be reflected by examining the changes in the investment horizons whilst satisfying the two supply requirements under both normal and contingent states.

If ΔP is the incremental flow along L1 due to the interruptible injection, and if the supply requirement under the normal condition defines the circuit's investment horizon, the circuit's new investment horizons can be determined by

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

Rearranging above formula and taking logarithm of it gives

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

As stated in part A, the supply requirement under contingencies could also define the circuit's investment horizon. In this case, the additional interruptible flow that a circuit can carry can only be increased on top of the maximum contingency flow - $D_{unint,cont}$. This leads to L1's investment horizon being defined by $D_{unint,cont}$, determined by

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

C. New Investment Horizon due to Uninterruptible Injections

When an uninterruptible injection is applied to busbar 2, it would impact the two circuits under both normal and contingency situations. To satisfy the supply requirement under the normal conditions, its influence is the same as that caused by an interruptible injection and thus the two circuits' new horizons can be evaluated with (5). To satisfy the supply requirement under potential contingencies, only uninterruptible loads need to be secured, leading to the new reinforcement horizon to be determined by

$$RC = (D_{unint,cont} + \Delta P_{cont}) \cdot (1+r)^{n_{cont,new}} \quad (7)$$

where, ΔP_{cont} is the incremental uninterruptible flow change along L1 due to the uninterruptible injection.

Similarly, (7) can be rewritten as

$$n_{cont,new} = \frac{\log RC - \log(D_{unint,cont} + \Delta P_{cont})}{\log(1+r)} \quad (8)$$

D. Annual Unit Price

Unit prices for the two load compositions are evaluated by assessing the changes in their supporting components' present values of future reinforcement caused by the injections.

The present value of future reinforcement of a component is calculated as

$$PV = \frac{Cost}{(1+d)^n} \tag{9}$$

where, d is the chosen discount rate, n is its original reinforcement horizon without any nodal injection.

By replacing n in (9) with its new investment horizon, n_{new}, calculated with a nodal injection, its new present value of future investment can be determined. Thus the difference between the two present values is

$$\Delta PV = Cost \cdot \left(\frac{1}{(1+d)^{n_{new}}} - \frac{1}{(1+d)^n} \right) \tag{10}$$

The incremental cost of a network component is the change in the present value of future investment as a result of the nodal injection and annuitised over its life time, given by

$$\Delta IC = \Delta PV \times AnnuityFactor \tag{11}$$

The LRIC charge for a studied node, i, is thereby evaluated by reviewing the change in the annuitized present value of future reinforcement cost over all its supporting components

$$LRIC_i = \frac{\sum IC}{\Delta PI_i} \tag{12}$$

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

E. Implementation Procedures

This new charging model seeks to differentiate customers' differing security preference and price them according to their impact in both normal and contingency situations. The overall implementation procedures are summarized as follows.

1) Determine the original flows under normal conditions and the maximum uninterruptible contingency flows under N-1 contingencies along all components. The original normal flows are obtained by running power flow analysis; the maximum uninterruptible contingency flows are evaluated by removing all interruptible loads and then running contingency analysis.
2) Determine incremental flows along all components due to interruptible and uninterruptible injections under both situations. Under normal conditions, the incremental flows due to interruptible and uninterruptible injections are obtained by running power flow with a tiny increment to each studied node. Uninterruptible increments' effect in contingencies is determined by: i) removing all interruptible loads; ii) running incremental contingency flow under all contingency events with a tiny uninterruptible injection to each studied node; iii) finding out the maximum contingency flow along each component.
3) Calculate all components' original reinforcement horizons. The smaller one between (2) and (3) defines them.
4) Calculate the new reinforcement horizons of all components in the cases with nodal injections with equations (5), (6), and (8). The ratings of components, the chosen load growth rate, the base case loading levels of all components under the two situations determined in step 1, and the incremental flows in both conditions derived in step 2 are fed into the three equations to determine them. With an interruptible increment connected, the new horizons are the smaller one between (5) and (6). For an uninterruptible connection, under normal cases, its impact on network investment is similar to the impact incurred by an interruptible injection, which is identified with (5). Under potential contingencies, its impact on network components is assessed with (8). Thus, the new horizons of its supporting components are the smaller horizon derived by (5) and (8).
5) Calculate unit prices for all studied nodes. Once the original and new reinforcement horizons are indentified for each component, the unit prices for both interruptible and uninterruptible loads can be assessed by submitting the horizons obtained in steps 3) and 4) into (9)-(12).

Unlike the original charging model which produces one charge at each busbar, this new method produces two nodal charges at each studied busbar: one is for interruptible loads and the other is for uninterruptible loads. The two types of charges are determined based on users' security preference so as to influence their prospective behaviors.

IV. DC Load Flow Demonstration on a Small System

In this section, the two-busbar system in Fig. 1 is utilized to demonstrate the proposed concept. It is assumed that the two circuits are identical, each with a rated capacity of 45MW and a cost of £1596700. The discount rate of 6.9% is taken in this study, which is the rate of return set by the industry regulator in the UK for the period up to 2010. Load growth is set as the project long-term rate in the U.K, 1%. The proportions of interruptible and uninterruptible loads at busbar 2 are assumed to be 20% and 80% respectively. Since the two circuits are identical, the same proportion retains for the two circuits under normal conditions.

A. Charge Evaluation with Different Load Compositions

Under normal conditions, each circuit can be maximally loaded up to its full capacity, 45MW and the system has 90MW capability. Under N-1 contingency, only one circuit is available, so the maximum uninterruptible loads can be accommodated is 45MW. By adopting the proposed model, the original reinforcement horizons of the two circuits without any injections at busbar 2 at four loading levels are examined, given in Table I.

TABLE I
ORIGINAL HORIZON WITHOUT ANY INJECTION

D (MW)	Horizon driven by normal situation (yr)	Horizon driven by contingency situation (yr)
5	220.82	173.58
10	151.16	103.92
15	110.41	63.17
20	81.50	34.26

Under both normal and contingency driven situations, the two circuits' reinforcement horizons become small with the increase in demand. At each loading level, network contingencies can greatly bring forward the horizons as each circuit needs to pick up extra contingency flows. For example, in 20MW loading case, the investment horizon is 81.50yrs under the normal case, which is dramatically brought down to merely 34.26yrs under contingencies. Hence, the circuits' actual reinforcement horizons are those obtained in contingency situations.

Table II provides the circuits' new investment horizons due to interruptible injections and the resultant charges for interruptible loads at busbar 2 under the two conditions. Compared with normal conditions, contingencies could greatly reduce their new horizons especially at higher loading levels. For example, at 20MW loading level with 4MW interruptible load, the normal case investment horizon is 79.02yrs, which decreases to 32.71yrs under contingencies. The charges outlined in the last column are rather low when loading conditions are light, merely 1.04 £/MW/yr when the interruptible load is 1MW. They increase exponentially with the rise in the loading level, soaring to 2454.14 £/MW/yr with 4MW interruptible load.

TABLE II
RESULTS FOR INTERRUPTIBLE LOAD COMPOSITION

D (MW)	Interruptible load (MW)	New horizon driven by normal situation (yr)	New horizon driven by contingency situation (yr)	Charge (£/MW/yr)
5	1	211.24	167.49	1.04
10	2	146.26	100.83	49.18
15	3	107.11	61.10	482.54
20	4	79.02	32.71	2454.14

The new investment horizons of the two circuits combined with the calculated charges with an uninterruptible injection applied to busbar 2 are outlined in Table III. Similarly to the previous cases, heavy loading cases lead to nearer horizons in the two conditions, with the contingency case horizons even smaller. The charge also increases dramatically with the rise in loading level, which is merely 2.48 £/MW/yr when the uninterruptible load is 4MW but jumps to 5133.48 £/MW/yr when the uninterruptible load grows to 16MW. By comparing with the charges in Table II, noticeably at each loading level (the proportions of interruptible and uninterruptible loads keep unchanged, 20% and 80% respectively), charges for interruptible loads are smaller than those for uninterruptible loads at the same bus and the difference grows with the rising loading conditions.

TABLE III
RESULTS FOR UNINTERRUPTIBLE LOAD COMPOSITION

D (MW)	Uninterruptible load (MW)	New horizon driven by normal situation (yr)	New horizon driven by contingency situation (yr)	Charge (£/MW/yr)
5	4	211.24	161.75	2.48
10	8	146.26	97.83	107.64
15	12	107.11	59.07	1024.64
20	16	79.02	31.17	5133.48

In order to elaborate the charge difference of the newly proposed and original models, the results from the original security-orientated LRIC approach are outlined in Table IV.

TABLE IV
RESULTS FROM THE ORIGINAL CHARGING MODEL

D (MW)	New horizon driven by normal situation (yr)	New horizon driven by contingency situation (yr) (yr)	Annual charge (£/MW/yr)
5	151.16	141.58	8.22
10	81.50	76.59	370.88
15	40.75	37.45	3573.5
20	11.84	9.36	18011.54

In the original model, one circuit can only be maximally loaded to 22.5MW, as its capacity is halved with a contingency factor of 2 for catering for N-1 contingencies. In both normal and contingency conditions, the new horizons are smaller than those from the previous two cases, leading to higher charges. When each of them is loaded with 10MW (the total supported load by the two circuits is 20MW), the charge is 370.88 £/MW/yr, approximately 370 times of the charge for interruptible load (1.04 £/MW/yr) and 150 times of the charge for the uninterruptible load (2.48 £/MW/yr). If each circuit is loaded with 20MW (the total supported load is 40MW), the charge difference becomes extremely wide.

As seen from Tables II-IV, at the same loading levels and with the same ratio between interruptible and uninterruptible loads, charges for interruptible loads are always the smallest, followed by those for the uninterruptible loads, and the charges generated by the original approach are the highest. The different charges for interruptible and uninterruptible loads are able to reflect their differing security preference.

Additionally, it should be pointed out that the maximum amount of load supported by the original model is only 45MW, as the two circuits' rated capacity is halved by their contingency factors, leaving 50% capacity unused under the normal condition, which accounts for 99.99% of the time. The new model can maximally support 45MW uninterruptible load and a certain amount of interruptible, the size of which depends on the compositions of the two load types. In other words, the proposed model allows components to be loaded more heavily, thus deferring potential network reinforcement.

B. Charge Comparison under Different Load Compositions

This section compares the charges from the original and proposed approaches with various load compositions under different scenarios.

Fig. 2 compares charges for interruptible loads under four scenarios that have different interruptible load proportion: scenario 1: 50%, scenario 2: 30%, scenario 3: 10% and scenario 4: 0% (this is the case of the original model). As seen, charges increase exponentially with the rise in circuit loading levels in all four scenarios. In scenario 1, the charges are fairly low, when the interruptible load proportion is high. However, the decrease of its proportion tremendously propels the charges, as shown in scenario 3, which are greater than charges in both scenarios 1 and 2 at the same loading level. Scenario 4, in which the proportion of the interruptible load is zero, generates the highest charges.

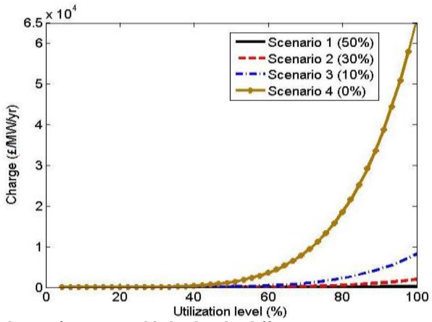

Fig. 2. Charges for interruptible load under different scenarios.

The actual maximum load at busbar 2 that the two circuits can support is quite different in the four scenarios. The maximum uninterruptible load which can be supported is 45MW in all four cases. But the maximum supported interruptible load diversifies: scenario 1: 45MW, scenario 2: 19.3MW, scenario 3: 6MW, and scenario 4: 0MW. It is because less spare capacity is available to interruptible loads with the rising proportion of uninterruptible loads.

Charge comparison for uninterruptible load in the foregoing four scenarios is presented in Fig. 3. The lines show quit similar patterns to those in Fig. 2: charges increase exponentially with the increase in loading levels and the increasing proportion of uninterruptible load. Compared with the results from the original model in scenario 4, charges from the other three scenarios are fairly small.

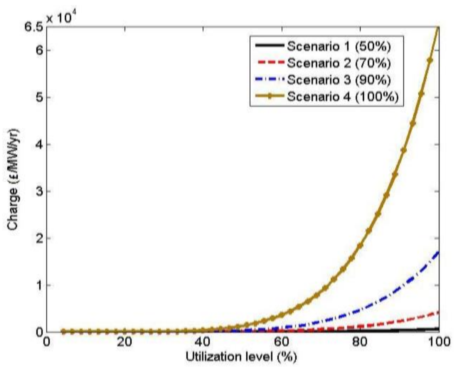

Fig. 3. Charges for uninterruptible load under different scenarios.

Fig. 4 carries out the charge comparison for interruptible and uninterruptible loads in two scenarios: scenario 1: 40% interruptible load and 60% uninterruptible load, and scenario 2: 20% interruptible load and 80% uninterruptible load. In both scenarios, the charges for the uninterruptible loads are higher than those for the interruptible load at the same loading levels. One noticeable point is that charges for the interruptible load in scenario 2 are even higher than both the two types of charges in scenario 1 at the same loading conditions. It is because that less circuit capacity is available due to much of it reserved for uninterruptible loads.

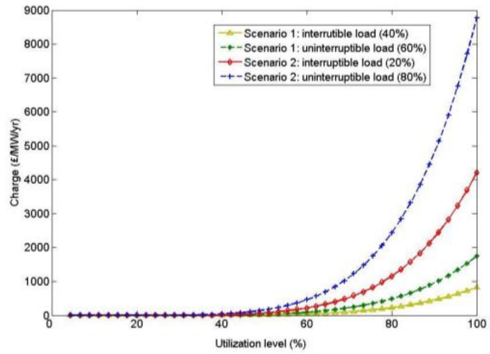

Fig. 4. Charges comparison under two different scenarios.

How customers make their security preference depends on the magnitude of the difference between the financial gain from lower security levels and the consequential financial and social costs from potential interruptions. For risk adverse customers, they would look for cost-saving opportunities with their passive loads, for example heating, cooling, white goods, electric vehicles, etc.

Based on this simple example, it can be said that the proposed charging concept based on the division of loads can effectively differentiate the differing security levels required by network customers. Moreover, it can bring down charges dramatically in all loading conditions for both interruptible and uninterruptible loads, especially at higher loading levels. Furthermore, the proposed model allows more interruptible loads to be accommodated when the same size of uninterruptible loads are met, the amount of which depends on the proportion of the two types of loads.

V. A Practical Network Demonstration

In this section, the proposed pricing model is demonstrated and compared with the original model on a practical grid supply point (GSP) area taken from the UK distribution networks, given in Fig. 5. The GSP network has three voltage levels, 66kV, 22kV, and 11kV, consisting of 11 circuits, 9 transformers, 6 loads and 1 generator.

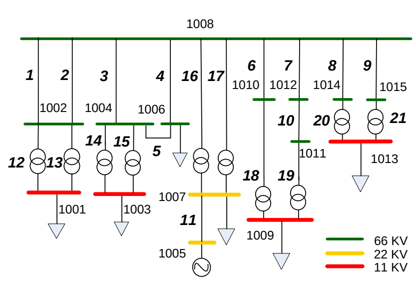

Fig. 5. A grid supply point area test system.

In this example, the proportions of interruptible and uninterruptible loads are also assumed to be 20% and 80%. The discount rate and load growth rates are the same as those used in section IV, 6.9% and 1% respectively.

All branches' rated capacity is provided in Table V. Here, the circuit No.11 is not taken into consideration as it is owned by the generator connected to busbar 1005.

TABLE V
CAPACITY OF ALL BRANCHES

Branch No.	Capacity (MVA)	Branch No.	Capacity (MVA)
L1	49.73	L12	28.75
L2	49.70	L13	28.75
L3	54.87	L14	40.00
L4	54.87	L15	40.00
L5	61.16	L16	31.25
L6	36.58	L17	31.25
L7	23.78	L18	40.00
L8	19.09	L19	40.00
L9	19.09	L20	28.75
L10	36.20	L21	28.75

A. Charge Evaluation

To assist analysis, Fig. 6 depicts all branches' utilization levels. As seen, the most heavily loaded circuit is line L4 linking busses 1008 and 1006. Line 3 and transformers 12-17 also have relatively high loading levels.

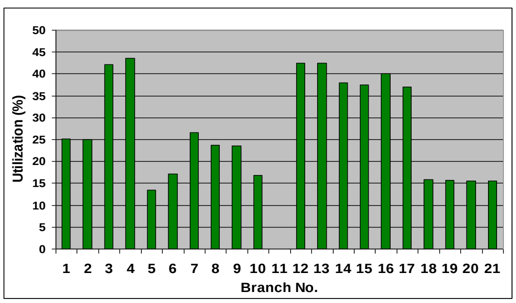

Fig. 6. Branch utilization levels.

In order to elaborate the impact from interruptible and uninterruptible loads on network components, Fig. 7 depicts the changes in the reinforcement horizons of transforms and circuits supporting busbar 1003. For each branch, the first two bars represent their original reinforcement horizons without any injections (the reason for putting two identical bars here is to illustrate and compare the different impact on investment horizons from interruptible and uninterruptible injections). As seen, L5 has the largest original investment horizon, approximately 91yrs, and L3 and L4 have the smallest around 37yrs. The transposed "T" within each bar signifies how an injection at busbar 1003 brings forward or delays the reinforcement horizons from the original values. The transposed "T" in the first bar for each branch represents to what extent an interruptible injection brings down the reinforcement horizons, whilst the transposed "T" in the second bar for each branch represents how an uninterruptible injection would affect the horizons. Obviously, an uninterruptible injection brings forward branches' reinforcement horizons even closer compared with an interruptible injection of the same size.

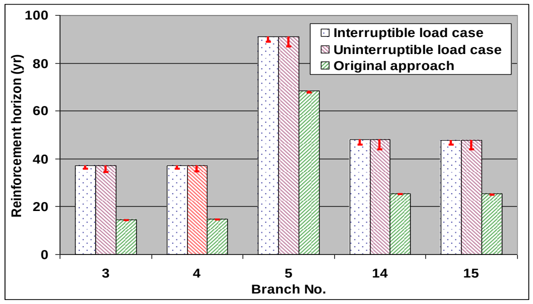

Fig.7. The comparison of components' investment horizons.

The computed charges for the two types of loads at all load busbars are provided in Table VI. Busbar 1003 has the biggest charges: 3.11 £/kW/yr for interruptible loads and 6.361 £/kW/yr for uninterruptible loads. It is because their supporting branches, No. 3-5 and 14-15, are all relatively heavily loaded. The smallest charges appear at busbar 1013, 0.19 £/kW/yr for interruptible loads and 0.47 £/kW/yr for uninterruptible loads, as their supporting branches are fairly lightly loaded.

TABLE VI
CHARGES FROM THE PROPOSED MODEL (£/KW/YR)

Charge type	1001	1003	1006	1007	1009	1013
For interruptible load	0.61	3.11	2.52	0.32	0.27	0.19
For uninterruptible load	1.98	6.36	5.96	0.69	0.62	0.47

B. Comparison with the Original Model

This part compares charges for interruptible and uninterruptible loads from the proposed approach with those generated by the original model. The original LRIC model generates one charge for each busbar and does not differentiate customers' security preference. In order to withstand network contingencies, it reshapes components' ratings with their contingency factors, producing the maximum available capacity (MAC), given in Table VII.

TABLE VII
CONTINGENCY FACTOR AND MAC OF ALL COMPONENTS

No.	Contingency factor	MAC (MVA)	No.	Contingency factor	MAC (MVA)
L1	1.99	24.95	L12	2.05	14.04
L2	2.01	24.71	L13	2.05	14.04
L3	2.05	26.77	L14	2.04	19.59
L4	1.98	27.66	L15	2.07	19.33
L5	3.77	16.21	L16	1.94	16.08
L6	2.04	17.95	L17	2.11	14.78
L7	1.93	12.32	L18	2.00	19.97
L8	2.05	9.31	L19	2.04	19.65
L9	2.05	9.30	L20	2.02	14.21
L10	2.07	17.49	L21	2.03	14.19

Bigger contingency factors indicate more of components' rated capacity reserved for catering for contingencies. As noticed, circuit No.5 has the maximum contingency factor, 3.77, which consequently reduces its rating from 61.16MVA down to merely 16.21MVA. The ratings of other branches are also brought down in proportion to their contingency factors.

The third bar for each branch in Fig. 7 depicts the investment horizons of the components supporting loads at busbar 1003 evaluated with the original model. Similarly, the transposed "T" in the bars represents to what extent a nodal injection at busbar 1003 would bring forward their horizons. Compared with the other two bars of each branch, the reinforcement horizons from the old model are all smaller. The biggest is 68yrs for L5, which is 91yrs in the new model; the horizons of L3 and L4 are merely 15yrs, which are 37yrs computed in the proposed model. The transposed "T" signifies that the horizons are slightly brought down by an injection at busbar 1003, which are smaller compared with the effects by the interruptible and uninterruptible injections at the same bus.

The calculated charges from the original model and their times of the charges in Table VI are provided in Table VIII. As seen, the charges here at the same busbar are all greater. The highest is 19.44 £/kW/yr at busbar 1003, which is 3.06 times of the charge for the uninterruptible loads and 6.25 times of the charge for the interruptible loads at that busbar. The lowest charge is 0.89 £/kW/yr at busbar 1013, but it is still rather greater than the charges for interruptible and uninterruptible loads at the same busbar in Table VI.

TABLE VIII
CHARGES FROM THE ORIGINAL CHARGING MODEL AND COMPARIOSN WITH THE CHARGES FOR INTERRUTIBLE AND UNINTERRUPTIBLE LOADS (£/KW/YR)

Bus No.	1001	1003	1006	1007	1009	1013
Charge	3.87	19.44	17.43	1.68	1.53	0.89
Time of interruptible load charges	6.34	6.25	6.92	5.25	5.67	4.68
Time of uninterruptible load charges	1.95	3.06	2.92	2.43	2.47	1.89

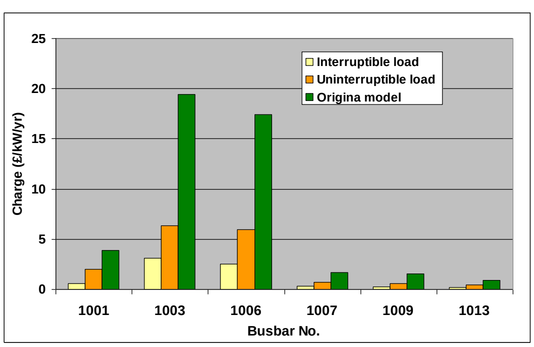

Fig. 8. The charge comparison between the two approaches.

Fig.8 graphically compares the nodal charges provided in Tables VI and VIII. The charges vary from one busbar to another, depending on their locations in the network. At the same busbars, charges for interruptible loads are lower than those for uninterruptible loads, indicating the charges can effectively differentiate and reflect their different security preference. Further, these charges are smaller than those from the original model at the same busbars, but they still maintain the original charge relativity. The locational security-oriented charges are able to reflect and influence prospective users' behaviors in favor of both network efficiency and security.

VI. Discussion

This new approach provides cost-reflective network charges that link network investment requirement with the extent of the use of the system by network users and their preference of security levels. The resultant charges encourage diversified security levels of supply, which benefit network operators from reduced investment requirement and network users from lower charges. It should be pointed out that the proportion between the interruptible and uninterruptible loads is crucial in this model for determining the two types of charges. Although users can reduce their UoS charges by increasing the proportion of their interruptible loads, they do need to understand the consequential costs due to supply interruptions.

How customers value the costs of energy loss due to an interruptible load scheme could vary dramatically, depending on many factors such as their types, i.e. residential, commercial, or industrial, types of commerce and industry, their locations, their interruption durations and consequential social and economic costs if the unlikely events do occur. It is thus essential for network customers to consider the potential costs before they determine their preference for different security levels.

At this stage, we expect most customers are risk aversive unless their UoS charges are increased by significant level with more cost-reflective charges. For majority of customers, we do expect them to be risk adverse and we expect them to find interruptible opportunities with their passive loads, such as heating, cooling and washing. By interrupting these loads, it neither degrades customers' quality of life nor adversely impact on the operation of business and commerce. In the future, we will envisage that customers can be more risk taking, especially for those who have to pay for high network charges. They may also consider shedding some of their active loads in addition to their passive loads in return for greater financial gains. Their security preference will have to be based on a proper risk assessment, evaluating the risks from network component failure, the likely social and financial costs that energy loss may bring, versus financial benefits they will earn from committing interruptible loads.

It should be pointed out that the proposed approach still follows the deterministic approach to reflect security standard, which might produce conservative results. Hence, it could be improved by including the failure probabilities of network contingencies while curtailing interruptible loads so as to reflect the stochastic nature of systems. Further, the scope of this research might also be expanded through using customers' utility functions to project the dynamic interactions between network charges and customers' responses over time.

VII. Conclusion

A novel charging methodology that can account for users' different security preference in distribution networks is proposed in this paper. It works by dividing the load at each busbar into interruptible and uninterruptible parts and pricing them accordingly. Based on the extensive analysis, the following observations can be reached:

1) The new approach addresses the network security issue in network pricing through close examination of different users' security preference on network components' long-term reinforcement requirement. It differentiates users' security preference by dividing them into interruptible and uninterruptible parts rather than delivering the same security levels for all. Charges are evaluated and levied on interruptible and uninterruptible loads based on their impact on network investment under both normal and contingency circumstances.
2) As demonstrated in the examples, marginal prices for both interruptible and uninterruptable loads are significantly reduced compared with those from the original LRIC model. At the same loading levels and with the same load compositions, charges for the interruptible loads are significantly lower compared with those for the uninterruptible loads as their security levels are relatively low, but both of them are smaller than charges produced by the original model. The resultant locational charges can influence the potential energy use behaviors of network users for overall network efficiency. They are financially rewarded if they choose a lower security level and thus reduce the otherwise needed network investment, but they have to weigh the financial gain from a lower security level with the consequential costs from potential energy loss.

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