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# Application of Long-run Network Charging to Large-scale Systems

Chenghong Gu[1], Furong Li[1], and Lihong Gu[2]

*Abstract*-- **Charging methodology is one important scheme in the deregulated environment in the way that it can be utilized to recover the investment cost from network users according to their different impact on the network. The long-run incremental cost (LRIC) pricing methodology developed by University of Bath in conjunction with Western Power Distribution (WPD, UK) and Ofgem (the office of gas and electricity markets, UK) has drawn lots of attention from industry and academic circles and found its application in practice. Compared with the existing long-run cost pricing methodologies, this charging model can produce forward-looking charges that reflect both the extent of the network needed to serve the generation/demand and the degree to which the network is utilized.**

**This paper examines the practical issues concerning implementation of this charging model in order to assist its utilization in the future. Firstly, the calculation and selection of the parameters, load growth rate, contingency factor, asset costs, that would impact charge evaluation are discussed, followed by the focus on some particular issues concerning them. Thereafter, the technical problems which might appear while applying this charging model to large-scale practical systems are dressed and a few feasible solutions are provided. This charging model, at last, is demonstrated on a practical system taken from the U.K. network.**

*Index Terms*-- **Long-run network charging, load growth rate, contingency analysis, discount rate**

## I. NOMENCLATURE

NETWORK charges are charges against network users for their use of a network in order to recover the costs of capital, operation and maintenance of a network and provide forward-looking, efficient messages to both consumers and generators[1]. Network charges, therefore, should be able to truly reflect the extent of the use of the network by network users. Efficient charges can help to release constraints and congestion in the network, deferring prospective network expansion or reinforcement [2, 3].

The present pricing methodology adopted by the majority of the distribution network operators (DNOs), the distribution reinforcement model (DRM) in the U.K., however, cannot provide locational economic signals as the costs of network assets are averaged at each voltage level[4]. Long-run cost charging methodologies, due to its merits of being able to reflect the cost of future network reinforcement caused by the nodal increment are recognized as more economically efficient. Most long-run cost pricing methods evaluate costs associated with projected demand/generation pattern and subsequently allocate the costs among new and existing customers. These approaches, however, can only passively react to a set of projected patterns of future generation or demand, failing to proactively influence the patterns of future generation or demand through economic incentives. Up to 2005, investment cost-related pricing (ICRP) utilized in the U.K., which works based on distance or length of circuits, is the most advanced long-run pricing model[5].

One recent development in long-run cost pricing methodology is the long-run incremental cost (LRIC) pricing methodology developed by the University of Bath in conjunction with Western Power Distribution (WPD, U.K.) and Ofgem (the office of gas and electricity markets, U.K.)[6]. This charging approach examines how a nodal increment of generation/demand might impact the time to reinforce system assets and then translate the time change into charges. The decision concerning of being penalty or reward is based on whether the nodal perturbation advances future investment or defers it. This method, compared with existing long-run cost pricing approaches, can produce cost-effective charges that reflect both the extent of the network needed to serve the generation or demand and the degree to which the network is utilized[7]. As being able to send forward-looking signals to influence prospective network connections, this charging model has been adopted by WPD in its EHV network and is being under consideration by several other DNOs in the U.K.

In this charging model, the time to reinforce is evaluated by assessing the time for a loading level to reach the full capacity of system components under a certain load growth rate with and without the nodal injection. The proper modeling and calculation of load growth rate, as a result, is essential for this charging model. Furthermore, in order to cater N-1 security principle, part of components’ spare capacity should be reserved for contingency case. This is achieved in the LRIC model by defining a contingency factor to assess the maximum allowed power flow the component can carry in normal conditions[8]. In addition, while applying this charging model to large-scale systems, some technical problems might appear, such as time consumption, connectivity of network in contingency analysis, computational time. All these modeling and technical issues are the targets of this paper.

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In this paper, we will discuss the selection and calculation of load growth rate, contingency factor, and asset costs that would to great extent impact charge evaluation and examine the technical issues of applying the LRIC charging model to practical large-scale systems. The modeling and selection of the those major parameters are firstly examined by focusing on the underlying information they carry for LRIC charging model, followed by the discussion on some particular problems concerned. Thereafter, the potential technical issues appearing while applying this charging model to large-scale system are dressed and some feasible solutions are presented. Lastly, this charging model is demonstrated on a practical large-scale system with over 2000 busbars taken from the U.K. network.

The rest of the paper is organized as follows: section II gives a brief introduction to LRIC charging approach. In section III, the parameters affecting LRIC charging are presented and discussed. Section IV presents some potential technical problem of implementation LRIC charging model and their feasible solutions. An example is provided in section V. Finally, some conclusions are drawn in section VI.

## II. LONG-RUN NETWORK CHARGING MODEL

In the original LRIC pricing model[6], for components in network that are affected by a nodal injection, there will be a cost or a credit associated for the injection according to whether the network investment is accelerated or deferred. The LRIC model has the following three implementation steps.

### A. Present Value of Future Investment

If a circuit $l$ has a maximum allowed power flow of $C_l$, supporting a power flow of $P_l$, the number of years it takes $P_l$ to grow to $C_l$ under a given LGR, $r$, can be determined with

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

Where, $n_l$ is the number of years taking $P_l$ to reach $C_l$.

Rearranging (1) and taking the logarithm of it gives

$$n_l = \frac{\log C_l - \log P_l}{\log(1+r)} \tag{2}$$

Assume that investment will occur in the $n_l$-*th* year when the circuit utilization reaches $C_l$ and with a chosen discount rate of $d$, the present value of future investment will be

$$PV_l = \frac{Asset_l}{(1+d)^{n_l}} \tag{3}$$

Where, $Asset_l$ is the modern equivalent asset cost.

### B. Cost Associated with Power Increment

If power flow change along line $l$ is $\Delta P_l$ as a result of a nodal injection, the time horizon of future reinforcement will change from year $n_l$ to year $n_{lnew}$, defined by

$$C_l = (P_l + \Delta P_l) \cdot (1+r)^{n_{lnew}} \tag{4}$$

Equation (4) gives the new investment horizon $n_{lnew}$

$$n_{lnew} = \frac{\log C_l - \log(P_l + \Delta P_l)}{\log(1+r)} \tag{5}$$

The new present value of future reinforcement becomes,

$$PV_{lnew} = \frac{Asset_l}{(1+d)^{n_{lnew}}} \tag{6}$$

The change in present value as a result of the injection is given by

$$g(r) = \Delta PV_l = Asset_l \cdot \left( \frac{1}{(1+d)^{n_{lnew}}} - \frac{1}{(1+d)^{n_l}} \right) \tag{7}$$

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

$$\Delta IC_l = \Delta PV_l \cdot AnnuityFactor \tag{8}$$

### C. Long-run Incremental Cost

The nodal LRIC charges for a node are the summation of incremental cost over all circuits supporting it, given by

$$LRIC_i = \frac{\sum_l \Delta IC_l}{\Delta PI_i} \tag{9}$$

Where, $\Delta PI_i$ is the size of power injection at node $i$, and here we assign it to be 1MW.

### D. Flowchart of LRIC

The flowchart for LRIC charge evaluation can be summarized in Fig. 1, the core of which is contingency analysis, incremental power analysis and charge assessment.

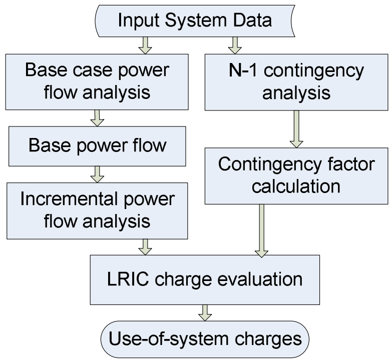

Fig.1. Flowchart of LRIC charging model

In the following sections, the major issues concerning charges evaluation will be discussed.

## III. PARAMETERS INFLUENCING LRIC CHARGING

### A. Load Growth Rate and Circuit Load Growth Rate

Demand growth represents the increase in energy demand over time, occurring through natural growth of a service territory resulting from the increased prosperity, productivity or population. Load growth rate is an averaged index derived by annuitizing the load growth in a particular time span. In the U.K., for example, National Grid Company (NGC, UK) forecasted electricity demand met via the Western Power Distribution (WPD, UK) network to increase to 15TWh by 2013-14, an average growth rate of 1.4% per year [9].

In the LRIC charging model, in order to simplify the process of assessing time to reinforce without and with nodal injection, (1) and (4) assume uniform loading growth rate along each circuit. In reality, however, loads at different buses may grow at quite different rates, leading to relatively diversified loading growth rate for each circuit. In this case, the uniform loading growth rate is no longer practical. In order to cope with this problem, a two-run power flow strategy can be used to assess the true circuit loading growth rate caused by the different load growth rate at each busbar. In the first run, a basic power flow analysis is executed to compute the base flow along each circuit. In the second run, all loads are scaled up/down according to their growth rates and then calculate all circuit flow. The desired circuit loading growth rate can subsequently be derived with

$$r = \frac{P_l}{P_{l,0}} \tag{10}$$

Where, $P_l$ is the power flow along circuit $l$ in the second run and $P_{l,0}$ is the base case flow along it.

Further, it can be found that the majority of the previous work concerning LRIC charging model is limited on the assumption that a fixed LGR can be predicted [5, 6, 10]. For developed regions/countries, it is less likely for load growth to have huge variations over long term since load growth has already saturated and become relatively steady. But for medium developing regions/countries, load growth might have a range of plausible values varying considerably with time, leading to uncertain load growth rate, which, in turn, would impose great difficulties on charge evaluation. Paper [11] proposed a novel LRIC charging methodology for evaluating charges with consideration of uncertainty in load growth through fuzzy set theory. The uncertain LGR is modeled by a range of potential values, each with its own confidence level. Then, the fuzzy model is mapped into charging method based on fuzzy extension principle method that respects the relationship between LGR and long-run network charges. Thereafter, defuzzificaion approach can be employed to derive crisp charges. Results show that the proposed fuzzy load growth rate model can effectively capture the uncertainty in future load growth and the defuzzified charges still maintain the economic signals sent to network users to guide their potential connections.

### B. Contingency Factor

In practice, all networks are designed to withstand credible contingencies, which is also compulsory for LRIC pricing. It is important for it to recognize the level of spare capacity reserved for catering N-1 contingency to ensure network security, although this might come at significant costs for network development.

Paper [8] proposes a new approach that can establish a direct link between nodal generation/demand increment and change in investment costs while ensuring network security. The investment cost is reflected by the change in the spare capacity of a network asset from a nodal injection, which is then translated into investment horizon, leading to the change in the present value of future investment. The security is reflected in the pricing model through conducting a full N-1 contingency analysis to decide the maximum allowed power flow along each circuit, from which the time horizon of future investment is determined accordingly. In the paper, contingency factor is defined as the ratio of the maximum contingency flow along a circuit over its base flow in normal condition [8]. The maximum allowed power flow for each circuit to carry considering the additional power flow it has to carry in contingency situation is given by

$$C_l = \frac{Rated\ Capacity_l}{Contingency\ Factor_l} \tag{11}$$

For a given load growth rate, the time horizon of future investment will be the time taking the load to grow from current loading level to the maximum or requirement of reinforcement loading margin (under contingency), instead of the full loading level (rated capacity), given by

$$\frac{C_l}{CF} = D \times (1+r)^n \tag{12}$$

With the contingency factor term, LRIC can make sure that sufficient spare capacity is allocated to ensure network security under contingent situation.

### C. Component Reinforcement Cost

Generally, the reinforcement costs of circuits or transformers need to be recovered though LRIC charging model. Based on their different functions or ownerships, these branches can be roughly divided into two different categories: i)transformer/circuit branches which have certain reinforcement costs; ii) transformer/circuit branches which have no costs (zero-cost branches). Those zero-cost branches are mainly branches, whose costs have been recovered from network users, or branches which are owned by network users, or branches which are used to connect different part of the substations, such circuit breaker, and switches.

All the components' costs are annuitized through annuity factor into annuity costs, which are the actual amount of reinforcement costs that are recovered each year.

## IV. PRACTICAL ISSUES OF IMPLEMENTING LRIC CHARGING

### A. Sensitivity Analysis

In order to evaluate charges for one single node, two-run load flow analysis is executed in order to assess the effect from the nodal injection imposed on system assets. The shortcoming of this simulation approach is that it would spend much longer time on calculating charges for large-scale systems. The computational time rises exponentially with the increasing number of busbars in the network.

In paper[12], a sensitivity-based charging model is proposed following the same principle of [6], but utilizes sensitivity analysis to significantly reduce the computational burden for large systems. In the proposed approach, the change of present value of future reinforcement due to a nodal power increment is represented by three partial differentiations: i) sensitivity of circuit loading level with regard to nodal injection, ii) sensitivity of time to reinforce with respect to circuit loading level, and iii) sensitivity of the present value of future reinforcement with respect to time to reinforce, given as

$$\frac{\partial PV_l}{\partial PI_n} = \frac{Asset_l}{P_l} \cdot \frac{\log(1+d)}{\log(1+r)} \cdot \frac{1}{(1+d)^{n_l}} \cdot \frac{\partial P_l}{\partial PI_n} \tag{13}$$

As demonstrated in the example, in terms of accuracy, the proposed approach yields quite similar results compared with LRIC when the nodal injection for LRIC is small. The biggest difference appears when circuits are highly loaded and LGR is small. When the injection becomes large, the discrepancies between the two approaches become apparent and the biggest difference shows up when circuits are lightly loaded and LGR is very high. In terms of speed, the original LRIC needs to run power flow analysis for each nodal injection twice in order to examine the effects of the injection on the long-term development costs. The proposed method, on the other hand, working through sensitivity analysis, can save significant computational time especially for large-scale networks.

Conclusively, the proposed charging calculation method is a promising supplement to LRIC method not only because of its computational efficiency but also because of the additional insights that the interim results can offer for the understanding of the charging problems and the consequential charges.

### B. *Contingency Analysis*

Another problem is with contingency analysis, which is the most heavily time-consuming part in LRIC. Further, when or more components are out of service, in quite few cases, the system might be split into one more parts. In order to tackle theses problems, some special techniques should be taken.

In the LRIC, the contingency factor utilized to assess the spare capacity reserved for security purpose of each component is obtained by performing contingency analysis. The contingency level is usually chosen according to the desired security level. For distribution network, in most case, *N*-1 level contingency would be enough to secure the network according to the P2/6 document (U.K.). While in some special cases, high level security might be required, which means that, *N*-2 or even higher level of contingency ($N$-$x$, $x$>2) should be considered. In this condition, a man-picked contingency list is needed for the contingency analysis and in order to find out the most serious contingency case for each component, all the contingency cases are assessed.

One potential problem appearing at this stage is network islanding caused by the outage of certain network components. When these components are out of service, the network might be split into more than one part, leading to the non-convergence of power flow analysis. In this case, a scheme that can detect network connectivity is required in order to determine the true structure of the network. Generally, a two-step method can work properly to cope with the network islanding problem: i) if the islanding part does not have any generators or power sources, all the components are flagged as out to be moved out; ii) if the islanding part has generators or power sources, the bus with the biggest size of generator is chosen as the slack bus for the part to run contingency analysis.

Another problem at this stage is with time consumption. For a large-scale system, the number of considered contingency cases can be huge, leading to great computational burden. In some particular cases, voltage regulation might also be considered in order to improve network voltage profile and consequently, more runs of power flow should be executed. The ultimate effect is soaring computational time, which increases with the rise in the number of network busbars. One feasible solution is to initialize each contingency case analysis with the base power flow results, since the states of most components in the network do not divert too far from their base states, especially for large-scale system. As a result, power flow would need less times of iteration to reach to the preset resolution. Other potential strategies are to use PQ decoupled load flow analysis if the precision in contingency factors is not the primary concern. The PQ decoupled power flow strategy can dramatically reduce computational time, while still providing acceptable results for contingency analysis.

### C. *Incremental Power Flow Calculation*

Incremental power flow analysis is executed to determine how the future network users would affect the existing network components, which can be calculated either by simulation approach or sensitivity analysis forehead mentioned. The method for calculating the incremental flows should be carefully selected in order to ensure that the incremental flows along each component with and without nodal injection are accurate enough to reflect network users' effect on those components.

Normally, nodal injection is chosen as 0.1MW, which means that power flow analysis approach should be able to capture the change in incremental flows due to the injection. As discussed in section IV, simulation approach is more accurate than sensitivity analysis, but its shortcoming is time consumption especially for large-scale systems. Sensitivity method, although not as accurate as simulation approach, can save computational time dramatically and produce acceptable results and is a quite good alternative to simulation method.

## V. TEST SYSTEM DEMONSTRATION

The LRIC charging model is demonstrated on a large-scale system taken from WPD network, which consists of more than 2000 nodes. Fig. 2 is the geographical map of the UK network and the chosen system is located in its southeast.

Fig. 2. Geographical map of the UK network.

In the calculation, load growth rate is taken as 1% uniformly, discount rate is chosen as 6.9. The contingency factors for all components are calculated by running the contingency list chosen by the network operator. It takes simulation approach about 12 seconds to calculate charges for one single node and approximately 400minutes in total. By contrast, it takes sensitivity only 0.5 second to compute charges for a single node and in total takes barely 17 minutes to calculate charges for all load busbars. In order to simply the analysis, this example considers only the basic situation for charge evaluation with simulation method.

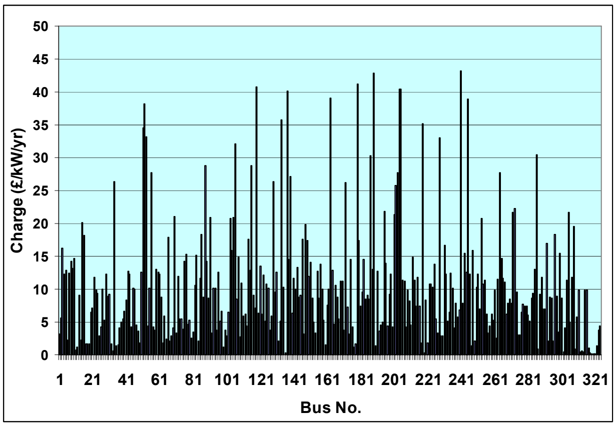

Fig. 3. Long-run incremental charges for the test system

Fig 3 demonstrates the charges for all the load busbars. It can be observed that charges for the all the load busbars vary greatly, depending on the impact on system assets supporting the busbar imposed by nodal injection from this busbar. The maximum charges is 43.153 £/kW/yr for busbar 241, which is served with quite heavily loaded components.

If non-uniform load growth rate is taken into consideration, the circuit load growth rate can be computed by running two times of load flow analysis, with the base one and the one with all loads scaled up/down according to their load growth rate. As 0.1MW nodal injection is taken for the simulation method, the resultant charges from sensitivity analysis should not deviate too much from those from the simulation.

The varying charges can effectively reflect the effect of network users putting on the system components, and in addition, these charges can be sent to potential network users to influence their prospective connection sites and sizes. As can be seen, no matter the sizes of the networks, LRIC is an effect charging algorithm to recover the investment in the network from DNOs, and make the development of the network towards more reliable and efficient direction.

## VI. CONCLUSION

Long-run incremental cost (LRIC) pricing methodology is one of the most advanced charging models, which cannot only reflect the impact from network users imposed on the network but also to influence potential network connections. Ofgem in the UK has successfully pushed charging scheme reform through the evidence given by this charging model.

In this paper, we focused on the selection of load growth rate, contingency factor, and asset costs, which would affect the resultant charges. The discussion of potential problems concerning them can be helpful while utilizing LRIC to actual networks. In addition, the technical issues which might be confronted while applying this charging model to large-scale system are dressed and a few of valuable solutions are provided. The demonstration of this model a practical system with more than 2000 busbars shows its effectiveness. The obtained charges, diversifying greatly in amount, are able send economic cost-effective signals to prospective network users to influence their connections.

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## VIII. BIOGRAPHIES

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