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Long-Run Incremental Costs (Lric) – Voltage Network Charges Considering Different Demand Growth Rates

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***ABSTRACT**: The LRIC-voltage network charging pricing approach is meant to reflect the investment cost of a network to ensure that the quality and reliability of supply is maintained - ensuring that network nodal voltages are within required prescribed statutory limits. This charging approach is premised upon the spare nodal voltage capacity or headroom of an existing network (distribution and transmission systems) to provide the time to invest in reactive power (VAr) compensation assets. A nodal reactive power withdrawal/injection will impact on network-wide voltages, which as a result advance or defer the future network investment costs, the LRIC-voltage network charge aims to reflect the impact on network voltage profiles as the result of nodal reactive power perturbation. This approach also provides forward-looking economically efficient signals that reflect both the voltage profiles of an existing network and the indicative future cost of VAr compensation assets. The correct forward-looking LRIC-voltage charges can be utilized to influence the location of future demand/generation for bettering the network quality and reliability.The LRIC-voltage network charges are different for different demand growth rates. The results show that the more the LRIC-voltage network costs/credits are the descending load growth rates.This paper analyses the trend of LRIC-voltage network charges on different demand growth rates (1%, 1.6% and 2% rates), providing insights into how charges will vary given those aforementioned kinds of different scenarios. Ultimately, these charges would provide correct economic signals to potential network users, which will help them to make informed decisions as to whether to invest in reactive power devices or pay for the network for reactive power provision. Consequently, this will guide towards the efficient and effective usage of the network's reactive power sources. This study is carried-out on an IEEE-14 bus test network.*

***INDEX TERMS**: Correct forward-looking economic signals, demand growth rates, LRIC-voltage network charging principle, spare nodal voltage capacity and VAr compensation assets.*

I. INTRODUCTION

Uder the current climate of deregulation and privatization of respective electricity power industries around the globe, the most fundamental issue is that the network assets (generators, transformers, lines, e.t.c.) should be utilized effectively and efficiently. On the other hand, an appropriate pricing approach to recover the aforementioned network costs is needed which should be reflective of the impact caused on the network by the wheeling of the real and reactive powers. Network operators (NO's) are charged with the responsibility to maintain the network security and quality of supply at all times, in that, the network voltages should be within prescribed statutory limits. This can be achieved by employing the use of reactive compensation devices in supporting the network nodal voltages whilst transporting real power, thereby improving the efficiency of the network. Thus, reactive power is a commodity that has to be adequately availed throughout the entire network by the NO's to ensure that the system voltage profile is satisfactory in the context of the appropriate statutory instrument. In addition, to enhance this voltage control on the network, an economic charging paradigm could be developed to price towards the improvement of the network voltage profile and this was first developed and reported by authors in [1]. Most research in reactive power pricing has been focused on reflecting the operational cost due to new customers - how they might change network losses as reported by authors in [2]-[13]. Other network pricing approaches generated significant research interest to reflect investment costs incurred in network when supporting nodal reactive and real power withdrawal/injection [14]-[34], but the network investment costs are mainly focused on the circuits and transformers. It was against this background that the authors in [1] proposed a framework to charge towards the improvement of the network voltage profile. However, this approach in [1] fail to assess these charges given different demand growth rates as practically, different networks have variable demand growth rates.

This paper is concerned about LRIC-voltages network charges given different demand growth rates to provide some insights into how these changes given those different scenarios which are a practical reality. The used approach employs the use of the unused nodal voltage capacity or headroom within an existing network to provide an economically efficient forward-looking pricing signal to influence the siting of future demand and generation for bettering network voltage profiles. A nodal withdrawal/injection of reactive power will impact on the nodal voltage, which will be further propagated over the entire network. The impact on the nodal voltage will affect the investment horizon of network VAr compensation devices. As the LRIC aims to give indicative future investment cost in maintaining voltage profiles, each study node is a candidate for a reactive power compensation device. Depending on the headroom of each study node, the investment horizon for each node can be inferred. For a nodal reactive power perturbation, there will be a related benefit if the system-wide investment can be deferred, otherwise, there will be a cost if it can be advanced. Then, the LRIC-voltage (LRIC-V) network charges are the sum of the difference in the present value of the future investment with and without the nodal reactive power injection or withdrawal. This paper is organized as follows: Section II details the mathematical model of the LRIC-voltage network charging principle. Section III provides a demonstration of the study carried-out on an IEEE 14-bus test network. The paper's conclusions are drawn in Section IV. Section V provides for Appendix which outlines the loading condition of the test system while References are depicted in Section VI.

II. MATHEMATICAL FORMULATION OF LRIC-VOLTAGE NETWORK CHARGING PRINCIPLE

The LRIC-V network charging principle is based upon the premise that for an assumed nodal generation/load growth rate there will be an associated rate of busbar voltage degradation. Given this assumption the time horizon for a busbar to reach its upper /lower voltage limit can be evaluated. Once the limit has been reached, a VAr compensation device will be sited at the node as the future network reinforcement to support the network voltage profiles. A nodal demand/generation increment would affect the future investment horizon. The nodal voltage charge would then be the difference in the present value of the future reinforcement consequent to voltage with and without the nodal increment.

The following steps outlined below can be utilized to implement this charging model:

1) Evaluating the future investment cost of network VAr compensation assets to support existing customers

If a network node b, has lower voltage limit, V_L and upper voltage limit V_H, and holds a voltage level of V_b, then the number of years for the voltage to grow from V_b to V_L/V_H for a given voltage degradation rate v can be evaluated from (1.a) or (1.b).

If V_L is critical, i.e, bus voltage is less than target voltage, 1 pu :

$$V_L = V_b \times (1 - v)^{n_{bL}} \tag{1.a}$$

On the other hand if V_H is critical, i.e, bus voltage is more than target voltage, 1 pu :

$$V_H = V_b \times (1 + v)^{n_{bH}} \tag{1.b}$$

where: n_{bL} *and* n_{bH} are the respective numbers of years that takes V_b to reach V_L/V_H.

Reconfiguring equations (1.a) and (1.b) constitute:

$$(1 - v)^{n_{bL}} = \frac{V_L}{V_b} \tag{2.a}$$

$$(1 + v)^{n_{bH}} = \frac{V_H}{V_b} \tag{2.b}$$

Taking the logarithm of equations (2.a) and (2.b) on both sides gives

$$n_{bL} x \log(1 - v) = \log V_L - \log V_b \tag{3.a}$$

$$n_{bH} x \log(1 + v) = \log V_H - \log V_b \qquad 3.b)$$

then the values of n_{bL} / n_{bH} are

$$n_{bL} = \frac{\log V_L - \log V_b}{\log(1-v)} \tag{4.a}$$

$$n_{bH} = \frac{\log V_H - \log V_b}{\log(1+v)} \tag{4.b}$$

The assumption is that when the node is fully loaded the reinforcement will take effect. This means that investment will be effected in n_{bL} / n_{bH} years when the node utilization reaches V_L / V_H, respectively. At this point an installation of a VAr compensation asset is regarded as the future investment that will be needed at the node to support the voltage.

2) Determining the present value of future investment cost

For a given discount rate of d, the present value of the future investment in n_{bL} / n_{bH} years will be:

$$PV_{bL} = \frac{Asset_{CbL}}{(1+d)^{nbL}} \tag{5.a}$$

$$PV_{bH} = \frac{Asset_{CbH}}{(1+d)^{nbH}} \tag{5.b}$$

where $Asset_{CbL}$ and $Asset_{CbH}$ are the modern equivalent asset cost to cater for supporting voltage due to lower voltage limit and upper voltage limit violations.

3). Deriving the incremental cost as a result of an additional power injection or withdrawal at node N

If the nodal voltage change is ΔV_{bL} / ΔV_{bH} consequent upon an additional ΔQ_{In} withdrawal/injection at node N, this will bring forward/delay the future investment from year n_{bL}/n_{bH} to n_{bnewL}/n_{bnewH} and when V_L is critical

for withdrawal

$$V_L = (V_b - \Delta V_{bL}) \times (1-v)^{n_{bnewL}} \tag{6.a}$$

or

for injection

$$V_L = (V_b + \Delta V_{bH}) \times (1-v)^{n_{bnewL}} \tag{6.b}$$

and when V_H is critical

for withdrawal

$$V_H = (V_b - \Delta V_{bL}) \times (1+v)^{n_{bnewH}} \tag{6.c}$$

or

for injection

$$V_H = (V_b + \Delta V_{bH}) \times (1+v)^{n_{bnewH}} \tag{6.d}$$

Equations (7.a), (7.b), (7.c) and (7.d) give the new investment horizons as

$$n_{bnewL} = \frac{\log V_L - \log(V_b - \Delta V_{bL})}{\log(1-v)} \tag{7.a}$$

or

$$n_{bnewL} = \frac{\log V_L - \log(V_b + \Delta V_{bH})}{\log(1-v)} \tag{7.b}$$

$$n_{bnewH} = \frac{\log V_H - \log(V_b - \Delta V_{bL})}{\log(1+v)} \tag{7.c}$$

or

$$n_{bnewH} = \frac{\log V_H - \log(V_b + \Delta V_{bH})}{\log(1+v)} \tag{7.d}$$

then the new present values of the future investments are

$$PV_{bnewL} = \frac{Asset_{CbL}}{(1+d)^{nbnewL}} \tag{8.a}$$

$$PV_{bnewH} = \frac{Asset_{CbH}}{(1+d)^{nbnewH}} \tag{8.b}$$

The changes in the present values as consequent of the nodal withdrawal/injection ΔQ_{In} are given by (9.a) and (9.b)

$$\Delta PV_{bL} = PV_{bnewL} - PV_{Lb} = Asset_{CbL}\left(\frac{1}{(1+d)^{n_{bnewL}}} - \frac{1}{(1+d)^{n_{b}L}}\right) \tag{9.a}$$

$$\Delta PV_{bH} = PV_{bnewH} - PV_{bH} = Asset_{CbH}\left(\frac{1}{(1+d)^{n_{bnewH}}} - \frac{1}{(1+d)^{n_{bH}}}\right) \tag{9.b}$$

The annualized incremental cost of the network items associated with component *b* is the difference in the present values of the future investment due to the reactive power magnitude change ΔQ_{In} at node N multiplied by an annuity factor

$$IV_{bL} = \Delta PV_{bL} * annuityfactor \tag{10.a}$$

$$IV_{bH} = \Delta PV_{bH} * annuityfactor \tag{10.b}$$

4) Evaluating the long-run incremental cost

If there are a total of *bL* busbars' lower limits and *bH* busbars' high limits that are affected by a nodal increment from N, then the LRIC-V network charges at node N will be the aggregation of the changes in present value of future incremental costs over all affected nodes:

$$LRIC\_V_{N,L} = \frac{\sum_{bL} IV_{bL}}{\Delta Q_{In}} \tag{11.a}$$

$$LRIC\_V_{N,H} = \frac{\sum_{bH} IV_{bH}}{\Delta Q_{In}} \tag{11.b}$$

III. IMPLEMENTATION

A. Test Network

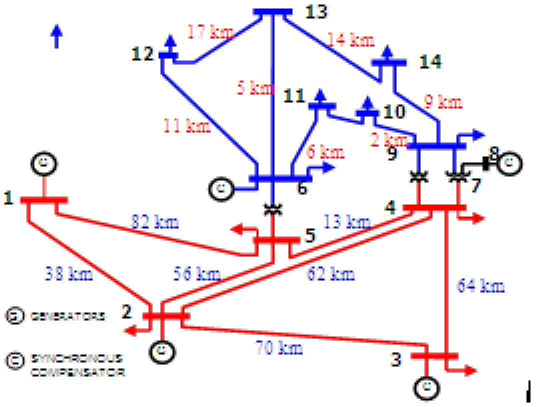

Figure 1: IEEE 14 Bus Test System

The test system shown above in figure 1 is the IEEE 14 Bus Network, the load and generation data of this network are shown in the appendix section. This network consists of 275kV subtransmission voltage level shown in red and the 132kV distribution voltage level shown in blue. There are two generators and three synchronous compensators. The synchronous compensators boost the voltage at buses 3, 6, 8 since the subtranmission lines are fairly long. It is also worthwhile to note that, these synchronous compensators have reached their full capacities and, therefore, they can not maintain the respective bus voltages at pre-set voltage levels and, as such, during withdrawals/injections, voltage changes are experienced at the buses where these are connected. The line distances between the buses are depicted in blue and red for the subtransmission and distribution levels, respectively. The compensation assets (SVCs) have the investment costs of £1, 452,000 and £696, 960 at the 275-kV and 132-kV voltage levels, respectively. Bus 1 is the slack bus. The voltage limits are assumed to be1 ± 6% pu. The use of power flow was employed to capture the nodal voltages while performing nodal withdrawals/injections on the system. The annual load growth for this test network is assumed to be 1.6% while the discount rate is assumed to be 6.9%.

B. RESULTS AND ANALYSIS

Case 1: Figure 2 shows the LRIC-voltage network costs owing to 1 MVAr nodal withdrawals considering 1%, 1.6% and 2% demand growth rates, respectively.

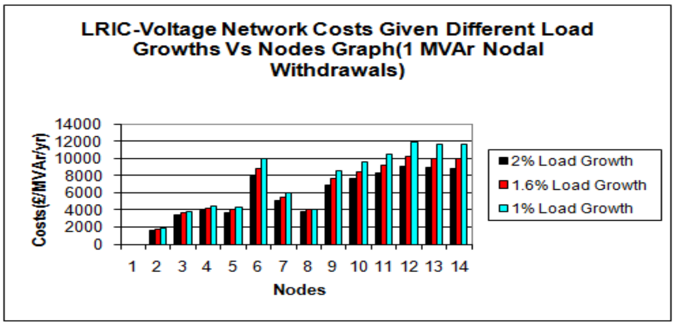

Figure 2: LRIC-voltage network costs owing to 1 MVAr nodal withdrawals considering different load growth rates on IEEE 14 bus test system.

As it can be observed, from figure 2, the results show that the more the load growth rate the less are the charges. For a higher load growth rate, the present values before and after MVAr withdrawals are more than the corresponding present values before and after MVAr withdrawals with a less load growth rate. The former present values are such that their differences are smaller than the corresponding differences in the latter present values (PVs), for buses with bus voltage loadings before withdrawals in excess of 66.5% with respect to the lower voltage limit. These buses are 6, 9, 10, 11, 12, 13 and 14 with bus voltage loadings of 66.6%, 67.8%, 74.8%, 73.6%, 79.5%, 83% and 90.9%, respectively, which also have very high charges. Elsewhere, the few buses with critical lower voltage limits (buses 3, 4 & 5) and having voltage loadings less than 66.5%, the reverse is true as their respective differences in (PVs) are more for the more load growth rate. Buses 2, 7 and 8 have critical upper voltage limits and they attract credits during their respective nodal withdrawals, but since the lower bus voltage limits dominate and these tend to influence the results and hence resulting costs at nodes. The overall result is, the more the LRIC-voltage network costs are the descending load growth rates.

Case 2: Figure 3 shows the LRIC-voltage network credits owing to 1 MVAr nodal injections considering 1%, 1.6% and 2% demand growth rates, respectively.

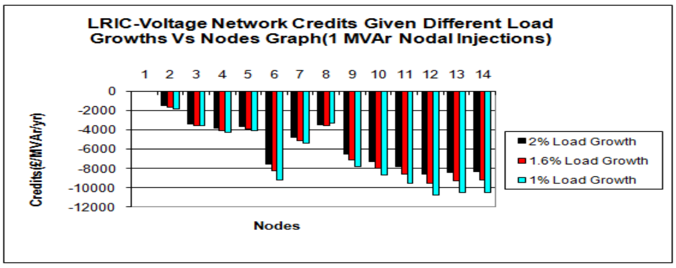

Figure 3: LRIC-voltage network costs owing to 1 MVAr nodal injections considering different load growth rates on IEEE-14 bus test system.

It can be observed, from figure 3, that the credits follow the same pattern as the above case, in that, the less the demand growth rate the more are the LRIC-voltage network credits, the same reasons as outlined in the above case hold.

IV. CONCLUSIONS

This paper analyses the trend of LRIC-voltage network charges given different demand growth rates, specifically, 1%, 1.6% and 2% load growth rates. This provides insights into how these charges will change since in reality different networks/systems have different demand growth rates, therefore, it would be imperative to be able to have an idea of scale as regard to the correct economic signals reflected by variable demand growth rates. The long-run incremental cost (LRIC)-voltage network charging principle is utilized to price the cost of the network ensuring that network nodal voltages are within prescribed statutory limits. This charging approach is premised upon the spare nodal voltage capacity or headroom of an existing network (transmission/distribution system) to reflect the time instance to invest in reactive power (VAr) compensation assets. The consequent LRIC-voltage network charging model is able to propagate correct forward-looking economic signals, reflecting the extent of the impact to busbar voltages by a connected party expressing whether they accelerate or delay the need for future network VAr compensation assets. These economic signals will, in turn, influence generation/demand in order to minimize the cost of future investment in VAr compensation assets.This study was performed on an IEEE 14-bus test network. The major finding is that, the more the LRIC-voltage network costs/credits are the descending load growth rates. The conclusions drawn from this analysis can be utilised in future, particularly, in the next stage of LRIC-voltage network charging approach which would consider the integration of the reactive power planning (RPP) problem with this pricing model (LRIC-voltage network charging principle) as the ultimate practical approach to employ. Furthermost, the analysis has provided insights into how the LRIC-voltage network charges would vary given different demand growth rates.

V. APPENDIX

The used IEEE 14- bus test network is pronounced in detail in [35]. The generation and loading conditions of this utilized system are shown below in tables, 1 and 2, respectively.

TABLE 1
IEEE 14 NETWORK LOAD DATA

Bus	MW	MVAr
1	0	0
2	21.7	12.7
3	94.2	19
4	47.8	-3.9
5	7.6	1.6
6	11.2	7.5
7	0	0
8	0	0
9	29.5	16.6
10	9	5.8
11	3.5	1.8
12	6.1	1.6
13	13.5	5.8
14	14.9	5

TABLE 2
IEEE 14 GENERATOR DATA

Bus	Real Power(MW)	Max VAr(MVAr)	Min Var(MVAr)	Voltage pu
2	40	50	-40	1.045
3	0	40	0	1.01
6	0	24	-6	1.07
8	0	24	-6	1.09

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BIOGRAPHIES

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