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Improved Version of Long-Run Incremental Cost (LRIC) – Voltage Network Charges

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ABSTRACT:- *An improved version of LRIC-Voltage network charges is proposed. This emanates from the premise that, for simplicity, respective nodal voltage degradation rates were considered to be constants when determining the LRIC-Voltage network charges. However, the respective nodal voltage degradation rates consequent upon a constant annual growth rate for any particular network follow the respective nodal P-V curves which are in fact of quadratic nature. It was against this background that it became imperative to determine these rates using the most representative approximate behavior along the P-V curve. Since it is a daunting task to accurately formulate this aforementioned behaviour, therefore it became obvious to approximately express this behaviour in simple terms, the issue being to provide a reasonable compromise between accuracy and simplicity in determining these aforementioned nodal voltage degradation rates. Thereafter, improved LRIC-V network charges were sought from these newly determined rates and, ultimately, these charges were compared to LRIC-V network charges to make a clear distinction of their differences. This improved version is demonstrated on the IEEE 14 bus test network.*

***Index Terms*:-** Improved LRIC-Voltage Network Charges, LRIC-Voltage Network Charges, Linear Relationship, Network Lower Nodal Voltage Limit, Network Upper Nodal Voltage Limit, Piecewise Linear Relationship, P-V Curve and Quadratic Equation.

I. INTRODUCTION

IN the new era of deregulation and privatization as regard to electrical power industry, one of the fundamental needs is that the network operators (NOs) should at all times maintain and uphold the required prescribed statutory standard of network security and quality of supply. One precise way is to always ensure that the network nodal voltages are within the required preset limits. As a result, the associated network charges should exactly reflect the true loading burden in the network in the context of the extent of the use of associated network assets (VAr compensation assets) alongside the corresponding costs equitable to this network asset usage, under all possible prevailing conditions [1].

It is for that reason that it can be seriously reasoned that reactive power is the main commodity to be distributed evenly throughout the entire network to ensure that the overall network voltage profile is within the required prescribed limits. To that end, reactive power can be best understood to be a resource that supports real power shipment, caters for reactive power loads and reserved for maintaining voltage profiles under steady state and following credible contingencies. In a nutshell, NOs are charged with the responsibility to secure adequate reactive power support to assist real power shipment and, consequently, maintain the required level of network security and reliability. The reactive power resource in a network comes from three sources: 1) networks for carrying and generating reactive power for maintaining the security and quality of supply 2) suppliers who affect consumers' reactive power consumption 3) generators those produce reactive power [2]. Significant research in reactive power pricing [3]-[14] reflects the benefits from the third source – generation, reflecting the operational cost related to reactive power due to new customers, i.e. how they might affect network losses. Network reactive power pricing also generated significant research interests into methodologies to reflect investment costs incurred in network when supporting nodal reactive and real power withdrawal/injection [2], [15]-[34], but the network investment costs are confined to the circuits and transformers triggered by thermal limits. The pioneering approach to charge for the cost of supporting network voltages [35] was developed and extended in the work in [36] – [40]. However, all these [35] – [40], are inadequate in that they assume that the respective nodal degradation rates are constant consequent to constant annual network growth rate. In reality, the nodal voltage degradation rates closely follow the P-V curve which is of quadratic nature.

This paper addresses the issue of relating nodal voltage degradation rates to the respective nodal P-V curves which are of quadratic nature. In that regard, an approximate approach was sought which was a tradeoff between complexity and simplicity.

This paper is organized as follows: Section II details the mathematical models of the LRIC-voltage network charging and the approximate behavior of the nodal voltage change owing to nodal power change. Section III covers the implementation of this principle in that percentage voltage errors at each node given various load increments are computed and, eventually, improved LRIC-V network charges are determined and, finally, are compared to the LRIC-V network charges [35]. 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 LONG-RUN INCREMENTAL COST PRICING BASED ON NODAL SPARE CAPACITY

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 compensation device will be placed 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.

A. Base LRIC-Voltage Network Charging Principle

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_r 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 :

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

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

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

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:

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

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

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

$$n_{bL} = \frac{\log V_L - \log V_b}{\log(1 - v_r)} \quad (3.a)$$

$$n_{bH} = \frac{\log V_H - \log V_b}{\log(1 + v_r)} \quad (3.b)$$

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:

$$PV_{bL} = \frac{Asset_{CbL}}{(1+d)^{nbL}} \quad (4.a)$$

$$PV_{bH} = \frac{Asset_{CbH}}{(1+d)^{nbH}} \quad (4.b)$$

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, respectively.

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

If the nodal voltage change is $\Delta V_{bL}/\Delta V_{bH}$ 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 $$V_L = (V_b - \Delta V_{bL}) \times (1 - v_r)^{n_{bnewL}} \quad (5.a)$$

or

for injection $$V_L = (V_b + \Delta V_{bH}) \times (1 - v_r)^{n_{bnewL}} \quad (5.b)$$

and when V_H is critical

for withdrawal $$V_H = (V_b - \Delta V_{bL}) \times (1 + v_r)^{n_{bnewH}} \quad (5.c)$$

or

for injection $$V_H = (V_b + \Delta V_{bH}) \times (1 + v_r)^{n_{bnewH}} \quad (5.d)$$

Equations (6.a), (6.b), (6.c) and (6.d) give the new investment horizons as

$$n_{bnewL} = \frac{\log V_L - \log(V_b - \Delta V_{bL})}{\log(1 - v_r)} \quad (6.a)$$

or

$$n_{bnewL} = \frac{\log V_L - \log(V_b + \Delta V_{bH})}{\log(1 - v_r)} \quad (6.b)$$

$$n_{bnewH} = \frac{\log V_H - \log(V_b - \Delta V_{bL})}{\log(1 + v_r)} \quad (6.c)$$

or

$$n_{bnewH} = \frac{\log V_H - \log(V_b + \Delta V_{bH})}{\log(1 + v_r)} \quad (6.d)$$

then the new present values of the future investments are

$$PV_{bnewL} = \frac{Asset_{CbL}}{(1+d)^{nbnewL}} \quad (7.a)$$

$$PV_{bnewH} = \frac{Asset_{CbH}}{(1+d)^{nbnewH}} \quad (7.b)$$

The changes in the present values as consequent of the nodal withdrawal/injection ΔQ_{In} are given by (8.a) and (8.b)

$$\Delta PV_{bL} = PV_{bnewL} - PV_{Lb} \qquad (8.a)$$

$$\Delta PV_{bH} = PV_{bnewH} - PV_{bH} \qquad (8.b)$$

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

$$IV_{bL} = \Delta PV_{bL} * annuityfactor \qquad (9.a)$$

$$IV_{bH} = \Delta PV_{bH} * annuityfactor \qquad (9.b)$$

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:

$$LRIC\_V_{N,L} = \frac{\sum_{bL} IV_{bL}}{\Delta Q_{In}} \qquad (10.a)$$

$$LRIC\_V_{N,H} = \frac{\sum_{bH} IV_{bH}}{\Delta Q_{In}} \qquad (10.b)$$

B. Approximating Behavior Of The Nodal Voltage Change Given *Nodal Power Change*

The P-V curve correlates the nodal voltage variation due to nodal power (MVA) change in a quadratic form, as shown in **Fig. 1** below.

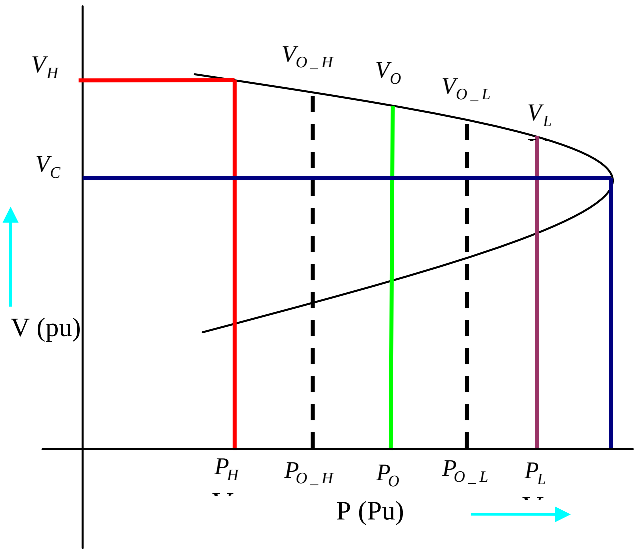

Fig. 1: Nodal P-V curve

The P-V curve approach was used by authors in [41]-[42] to approximate the respective nodal voltage collapse points at the corresponding specific load points, among other things. Here, this P-V curve formulation is extended to also feature buses without load. Ultimately, the nodal voltage variations consequent to the corresponding nodal load variations for all buses would be sought.

The issue is to approximate the most reasonable behavior of the nodal voltage variation due to the nodal power variation along the P-V curve. The P-V curve is represented by the quadratic equation, below, over the limits ranging from $V = V_0$ to $V = V_L$,, assuming that load would grow from V_0 to V_L over the years:

$$P_1 = a_1V^2 + b_1V + c_1 \qquad (11)$$

Then, the behavior of the nodal voltage change to nodal power change can be approximated along the P-V curve by the use of the linear relationship, below, over the limits ranging from $V = V_O$ to $V = V_L$:

$$P_2 = a_2V + b_2 \qquad (12)$$

Also, the behavior of the nodal voltage change to nodal power change can be approximated along the P-V curve by the use of the piecewise linear relationship, below, over the two separate limits, ranging from $V = V_O$ to $V = V_{O\_L}$ and from $V = V_{O\_L}$ to $V = V_L$:

$$P_3 = a_3V + b_3 \quad V_O \le V_{O\_L} \qquad (13)$$

$$P_4 = a_4V + b_4 \quad V_{O\_L} \ge V_L \qquad (14)$$

The quadratic representation of the nodal voltage degradations consequent to load growth rate would be the most accurate approach to adopt but it would be most complex to construct and, therefore, a need to seek for other options of constructing a compromise between accuracy and simplicity to represent this mentioned behaviour, namely, piece-wise linear approximation. In that light, the resulting calculated charges consequent to utilizing improved nodal voltage degradation rates would be better in terms of accuracy than the earlier charges achieved with the linear approach, since this approximation would follow the P-V curve more closely than the linear dispensation.

III. IMPLEMENTATION

1. Test System

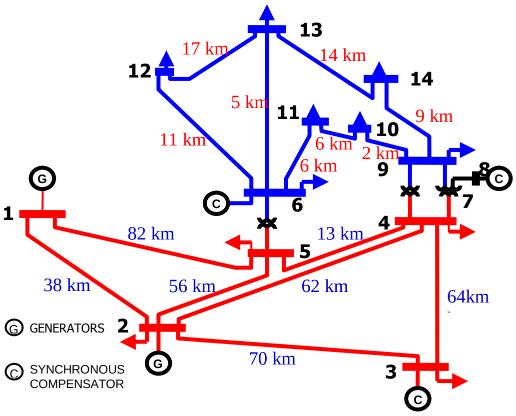

Fig. 2: IEEE 14 Bus System

The test system shown above in **Fig. 2** 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 sub transmission voltage level shown in red and the 132kV distribution voltage level shown in blue. There are two generators and three synchronous compensators as depicted in the diagram. The line distances between the buses are depicted in blue and red for the sub transmission 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 annual load growth for this test network is assumed to be 1.6% while the discount rate is assumed to be 6.9%.

A. Percentage Voltage Errors at Each Node Given Various Load Increments

It should be noted that, in this work, a revised version of the nodal voltage degradations resulting from nodal load growth rate would be sought, based on the nodal P-V curves. These new nodal voltage degradation rates will be employed to determine the improved LRIC-V network charges.

Firstly, to ensure that all nodes are within voltage limits, the power loadings along the respective nodal P-V curves of the IEEE 14 test system were increased arbitrarily, in steps of 3.5%, from initial loading levels, up to 14%. This assumption was adopted since all the buses remained within their voltage limits and the idea was to view how the nodal voltages considering the linear, piece-wise linear and quadratic approaches varied in comparison to the simulated results. Therefore, as a result, while performing the respective load increments, the resulting voltages due to the aforementioned quadratic, piecewise and linear curves were noted. Thereafter, the aforementioned voltages were compared to the simulated results, which were used as a benchmark, to establish the respective nodal percentage voltage errors. These percentage errors are shown in **Figs.** 3(a)-3(d). The nodal voltage degradation rates would be calculated from the curve that would offer a good compromise between accuracy and simplicity and, thereafter, these would be also used in determining the improved LRIC-V network charges.

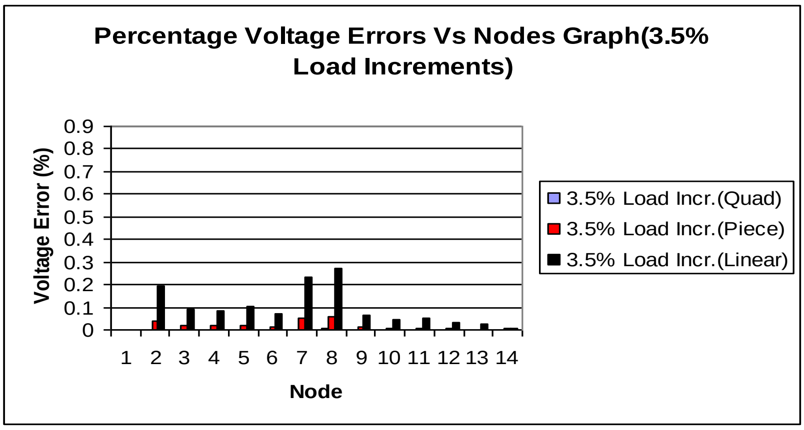

Fig. 3(a): Percentage voltage errors against nodes graph resulting from 3.5% Load increments on IEEE-14 bus test system

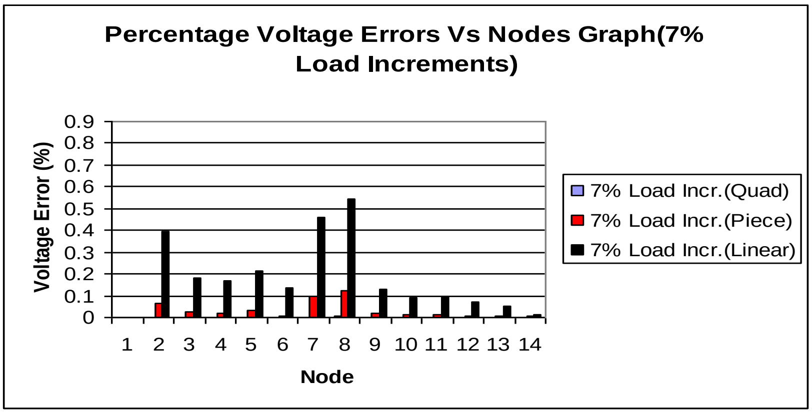

Fig. 3(b): Percentage voltage errors against nodes graph owing to 7% load Increments on IEEE-14 bus test system

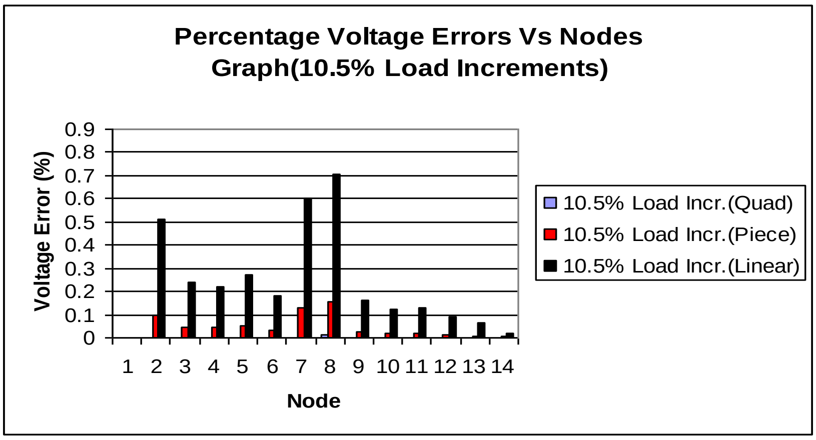

Fig. 3(c): Percentage voltage errors against nodes graph owing to 10.5% load Increments on IEEE-14 bus test system

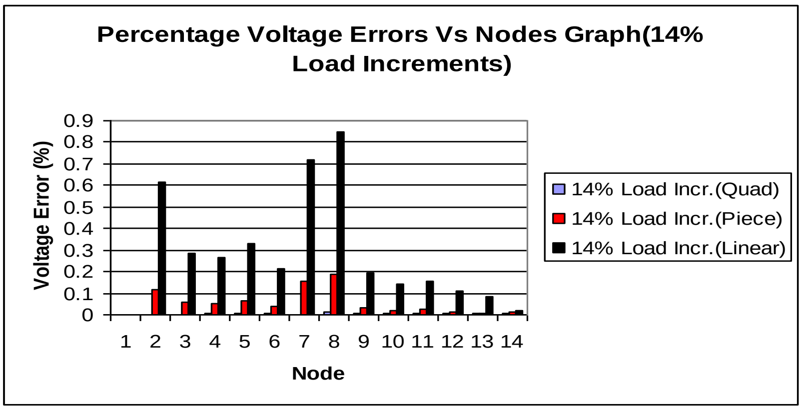

Fig. 3(d): Percentage voltage errors against nodes graph resulting from 14% load Increments on IEEE-14 bus test system

The results in **Figs**. 3(a)-3(d), show that the nodal voltage variations closely resemble the PV curves in that percentage voltage errors owing to the quadratic function are all very small. The piece-wise linear curves come second and linear curves offer the worst percentage voltage errors. The voltage percentage errors, throughout the cases, are considerable at buses 8, 7 and 2 since their initial voltages were 1.048 pu, 1.008 pu and 1.006 pu, respectively. This is due to the fact that, the less closer the initial bus voltages to the lower bus limit, the more the error during load increments. In constrast, the closer the initial bus voltages to the lower bus limit the less the percentage voltage errors. It is against this background that the initial voltage at bus 14 was 0.954 pu which is closer to the lower bus voltage limit, 0.94 pu. It is quiet apparent that the results show that piecewise linear function provides the second best approximation to the nodal voltage changes while the linear function provides the worst approximation. This is backed by the fact that, during 3.5% load increment, the percentage voltage error at bus 8 is 0.0125, 0.05 and 0.28 for piecewise linear, linear and quadratic functions, respectively. These errors keep on increasing following that pattern owing to the load increments, for these respective functions, such that during 14% load increments the errors became 0.025%, 0.2% and 0.84% for piecewise linear, linear and quadratic functions, respectively. This shows that, the percentage voltage errors increased as the load deviated, increasing from the initial loading level to 14% load increments. It should be notes across all cases, bus 1 registered 0% voltage errors for all the functions since the voltage at this bus does not change because this bus is the slack bus. Also, it should be noted that, the rest of the buses other than buses 2, 7 and 8 have their initial voltages less than 1 pu, hence, they have less percentage voltage errors than buses 2, 7 and 8. Since the piecewise linear function offers a good compromise between accuracy and simplicity, it would be used as a reasonable approximation in determining the nodal voltage degradation rates given the load growth rates and, consequently those would be used to calculate the improved nodal LRIC-voltage network charges in the next phase as earlier stated.

B. Nodal Comparison of LRIC and Improved LRIC –Voltage Network Charges

Ultimately, to show the value of the improved LRIC-voltage network charges two cases have been selected to demonstrate the effects to the network when integrating different loads and generations at each node. Case 1 covers a withdrawal of 1 MW at each node while case 2 covers an injection of 1 MW at each node.

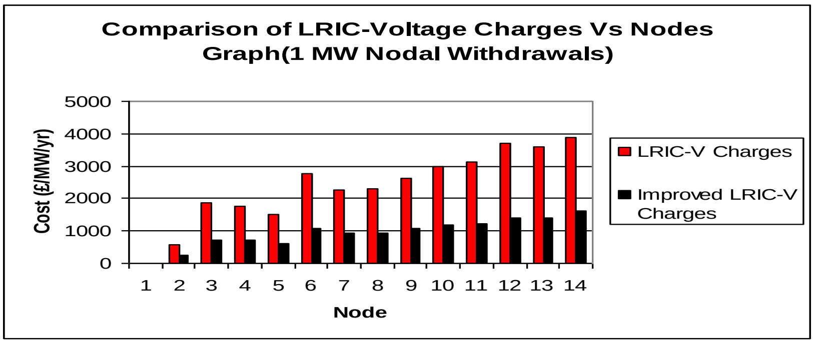

Fig. 4: Comparison of LRIC-V and Improved LRIC-V network charges resulting from 1 MW nodal withdrawals on the IEEE 14 bus test system.

During 1 MW nodal withdrawals, it can be observed from **Fig. 4**, that the Improved LRIC-V network charges follow the same pattern as the LRIC-V network charges. The only difference is that the LRIC-V charges are more than those of the improved version as the nodal voltage degradation rates are smaller than the corresponding nodal voltage degradation rates of the improved version.

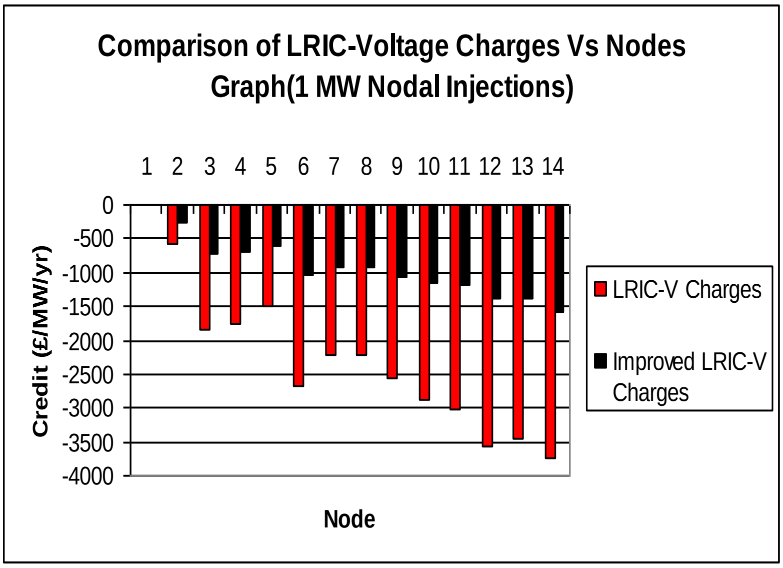

Fig. 5: Comparison of LRIC-V and Improved LRIC-V network resulting from 1 MW nodal injections on the IEEE 14 bus test system.

During 1 MW nodal injections, it can also be observed from **Fig. 5**, that the Improved LRIC-V network credits follow the same pattern as the LRIC-V network credits. Once again, the LRIC-V charges are more than those of the improved version since the nodal voltage degradation rates are smaller than the corresponding nodal voltage degradation rates of the improved version.

IV. CONCLUSIONS

In this paper, the improved version of the LRIC-V network charges is presented. This work emanates from the premise that the voltage change at a node and its corresponding nodal power (MVA) change are related to each other by the P-V curve. Ultimately, the piecewise linear instance provided a good tradeoff between accuracy and simplicity and, in that regard, it was used to calculate the nodal voltage degradation rates resulting from the load growth rate and, lastly, the Improved LRIC-V network charges were sought and compared to those of the earlier proposed LRIC-V network charging version [35]. This formulation was tested on the IEEE 14 bus test system.

Overall, it is observed that improved LRIC-V network charges are smaller than the earlier computed LRIC-V network charges [35] as the nodal voltage degradation rates for the latter are smaller than those of the former. This is consequent to the fact that the final nodal voltages, resulting from 1.6% system load growth rate, are more for the LRIC-V network charge case than the other case. Also, it should be noted that the nodal voltages, before the system loads are increased at a rate of 1.6%, are equal. Further, it can be concluded that, the more nodal voltage degradation rates the less are the LRIC-V charges for this system at this particular initial network loading level. Furthermost, this improved version provided best results since the charges were premised upon nodal voltage degradation rates computed to reflect the more representative physical relationship of the nodal voltages consequent to the system load growth rate.

V. APPENDIX

The used IEEE 14 bus network is described in detail in [43]. The loading and the generation conditions of this used network 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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