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Network Charging Principle for Pricing Existing Network SVCs Considering MW and MVAr Perturbations

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Abstract*— A simplistic novel approach is instituted in that the initial LRIC – voltage network charging principle is modified and utilised to price for the existing network SVCs. Originally, this approach was used to price for the future network SVCs and in the process does not make the grade in catering for the existing network SVCs since it hinges its strength on the varying network nodal voltages. In this regard, the SVC VAr minimum and maximum limits were mapped to the network lower and upper nodal voltage limits, respectively. To that end, the current SVC VAr loading capacity was appropriately transformed to a corresponding voltage level within the context of the said mapping exercise. What makes this novel approach to be a cut above the rest is that it offers forward-looking efficient economic signals which also reflect the true loading burden on the existing network SVCs. In addition, it penalizes those network users who advance the investment horizons of the existing network SVCs and, otherwise, incentivize those that defer the investment horizons of the existing network SVCs. Moreover, this charging paradigm integrates the network nodal MW and MVAr withdrawals/injections. This novel charging methodology is demonstrated on the IEEE 14 bus network.

***Index Terms*— Existing Network SVCs, LRIC-Voltage Network Charges, Network Lower Nodal Voltage Limit, Network Upper Nodal Voltage Limit, SVC VAr Minimum Limit and SVC VAr Maximum Limit**

I. INTRODUCTION

In a deregulated and privatized electrical power industry setup, one of the fundamental requirements is that the network operators should maintain, at all times, the required prescribed statutory standard of network security and quality of supply. One way to deal with this is to always ensure that the network nodal voltages are within the required preset levels. Consequently, 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) under all possible prevailing conditions [1].

Given the above, it can be rigorously argued that reactive power is the main factor to be balanced throughout the entire network to ascertain that the network voltage profile is within the required limits. In simple terms, reactive power can correctly be treated as 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 short, network operators are required to secure adequate reactive power support to assist real power shipment and as a result 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 generators those produce reactive power 2) suppliers who affect consumers' reactive power consumption 3) generators those produce reactive power [2]. Most 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 first approach to charge for the cost of supporting network voltages [35] was developed and associated research was carried-out in [36] – [40] as the approach evolved and propagated. However, all these [35] – [40], are inadequate to charge for the use of existing network SVCs and only charge for future network SVCs.

This paper is addresses the development of network charges that account for the use of existing network SVCs. This charging paradigm employs the use of the unused nodal voltage capacity or headroom within an existing network to gauge time to invest in reactive power compensation device for each node in the system. A nodal withdrawal/injection of reactive power will impact on the nodal voltage, which in turn impact on the time to

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reinforce reactive power compensation devices. LRIC-v network charges are the difference in the present value of future Var compensation devices with and without the nodal perturbation, providing an economically efficient forward-looking pricing signal to influence the siting and/or reactive power consumption of demand and generation for bettering network voltage profile. This aforementioned LRIC-v network charging principle was modified to be able to be used to price for the use of the existing network SVCs. This owes to the fact that an SVC would be usually preset to a certain voltage level so as to maintain a constant voltage level at the bus at which it is sited. Given that the pricing approach in question depicts its strength from varying nodal voltage and unless a modification to it was effected, this approach would not apply in this case. It should be noted that an SVC while maintaining a constant network nodal voltage would have to supply or draw varying reactive power to or from the network to accomplish its mission. It was then this varying reactive power character by the SVC that was used, in that, the SVC VAr minimum limit was mapped to the network lower nodal voltage limit and the VAr maximum limit mapped to the network upper nodal voltage limit, at the bus this particular SVC was sited. Finally, the present SVC VAr loading was duly converted to a corresponding voltage level in the context of the mapping exercise. The above mentioned mapping exercise is detailed in section II.

This paper is organized as follows: Section II details the mathematical models of the LRIC-voltage network charging and the mapping of SVC VAr limits to network nodal voltage limits. Section III covers the implementation of this principle and the resulting LRIC – voltage network charges to price for existing network SVCs. 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

In this section, the nodal base LRIC-V network charging principle formulation would be outlined. Thereafter, the formulation to reflect the nodal voltage impact on buses resulting from N-1 contingencies would be shown. Finally, this effect of N-1 contingencies would be factored into the former charging principle to constitute CF (contingency factor) LRIC-voltage network charges.

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 :

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

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

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

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:

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

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

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

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

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

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:

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

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

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 $$V_L = (V_b - \Delta V_{bL}) \times (1-v_r)^{n_{bnewL}} \tag{5.a}$$

or

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

and when V_H is critical

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

or

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

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

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

or

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

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

or

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

then the new present values of the future investments are

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

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

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

$$\Delta PV_{bL} = PV_{bnewL} - PV_{Lb} \tag{8.a}$$

$$\Delta PV_{bH} = PV_{bnewH} - PV_{bH} \tag{8.b}$$

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

$$IV_{bL} = \Delta PV_{bL} * annuityfactor \tag{9.a}$$

$$IV_{bH} = \Delta PV_{bH} * annuityfactor \tag{9.b}$$

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:

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

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

B. Mapping SVC Limits to Network Nodal Voltage Limits

Since the existing network SVC is meant to continuously adjust its reactive power output to regulate the voltages at the controlled bus to a preset value (e.g. 1 pu), therefore, the bus voltage at which this SVC exists remain constant and, only, the device's reactive power output varies accordingly. Owing to this factor, the LRIC-voltage network charging approach can not be applied without any modification, therefore, this aforementioned approach is modified as detailed below to accommodate the behaviour of the existing network SVC.

If a network node *b*, has a lower voltage limit, V_L and an upper voltage limit, V_H , and on this bus if there exist an SVC having minimum reactive power capacity, Q_{min} and maximum reactive power capacity, Q_{max}. Then Q_{min} can be mapped to V_L while Q_{max} can be mapped to V_H and, therefore, the relation below by equation (11) holds

$$V_{b_{SVC}} = \left(\frac{V_H + V_L}{2}\right) + \left(\frac{\left(V_H - \left(\frac{V_H + V_L}{2}\right)\right)}{\left(Q_{\max} - \left(\frac{Q_{\max} + Q_{\min}}{2}\right)\right)}\right) * \left(Q_{gen} - \left(\frac{Q_{\max} + Q_{\min}}{2}\right)\right) \tag{11}$$

With the mapped voltage , V_{bSVC} known, then V_b in equations ((1) – (3)) and ((5) – (6)) can be replaced by the voltage to price the contribution of the existing network SVC at the node where it is sited.

III. IMPLEMENTATION

A. *Test System*

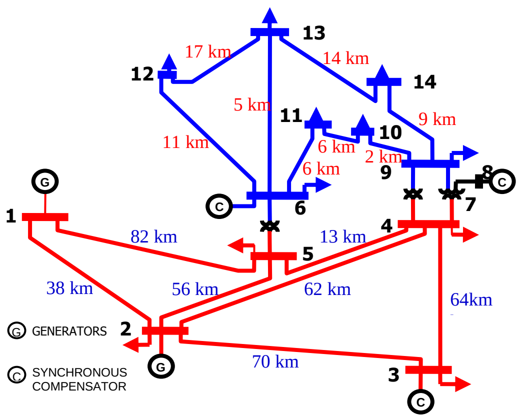

Fig. 1: IEEE 14 Bus System

The test system shown above in **Fig. 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 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%.

Also, on the above test system, there are two SVCs, one existing at bus 4 and the other at bus 12. These SVCs were randomly installed to exist at these respective buses. It is emphasized that, the reactive power planning (RPP) exercise determines the optimal allocation of VAr compensation assets through-out the entire power system to ensure network security and reliability at the least possible costs. To this end, it can be said that, the random existence of SVCs at the aforementioned buses is just meant to demonstrate the concept of charging for the use of these existing network SVCs.

Both the SVCs at buses 4 and 12 have the same specification of maximum and minimum VAr capabilities of 100 MVAr and -50 MVAr, respectively. Both these SVCs have their voltages preset at 1 pu, so as the voltage settings for synchronous condensers at buses 3, 6 and 8. The nodal lower and upper voltage limits remain to be 0.94V and 1.06V, respectively.

B. *LRIC-Voltage Network Charges to Price for Existing Network SVCs*

Figs. 2 and 3 show the 1 MVAr and 1 MW nodal withdrawals to reflect the LRIC-V network charges for the use of these existing network SVCs. On the other hand, Figs. 4 and 5 show the 1 MVAr and 1 MW nodal injections to reflect the LRIC-V network charges for the use of the above mentioned existing network SVCs.

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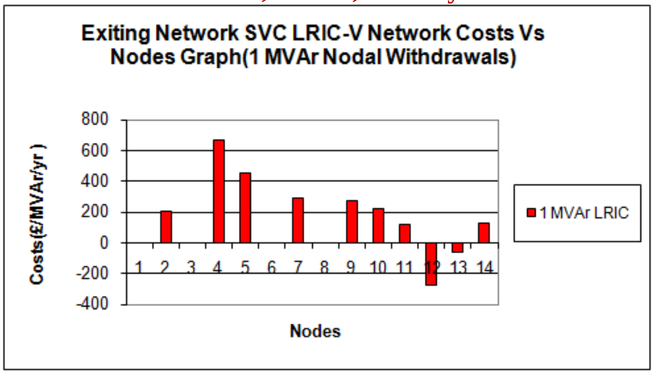

Fig. 2: LRIC-voltage network costs resulting from 1 MVAr nodal withdrawals to reflect the use of existing network SVCs

It should be noted that, the initial VAr loadings of SVCs at buses 4 and 12 were 40.987 MVAr and 11.365 MVAr, respectively. These VAr loadings translated to 1.013V and 0.989V for buses 4 and 12, respectively, owing to the SVC VAr limit/nodal voltage limit mapping exercise. In this regard, during nodal withdrawals, bus 4 was attracting a cost since reactive power had to be injected into the network and that represented a voltage increase in the mapping exercise context and, therefore, a degradation of this bus upper voltage limit margin. This latter effect meant the investment horizon of the concerned SVC was brought closer and, therefore, a penalty imposed in the context of a cost. On the other hand, for bus 12, the reverse was true and hence a credit during nodal withdrawals as its already critical bus lower voltage margin (voltage from the context of transforming node SVC VAr loading to node voltage) is increased and, therefore, its investment horizon was deferred as a result.

Specifically, during 1 MVAr nodal withdrawals (fig. 2), it can be observed that buses 3, 6 and 8 attract no charges as the synchronous condensers at these buses absorbed all the shock resulting from these particular withdrawals, by supplying reactive power into the network. However, bus 2 attracts a cost even though a generator is connected at this bus since this connected device has reached its VAr capacity. It can be observed that bus 4 attracts the most cost as during MVAr withdrawal at this bus, the existing SVC there makes up all for the withdrawal.

Elsewhere, other than buses 12 and 13, the costs reduce as these buses distances from bus 4 increase, owing to the reduced perturbations impacted on bus 4 and increased perturbations impacted on bus 12 which is attracting credits. On the other hand, bus 12 attracts a credit since it absorbs all the impact resulting from the withdrawal on it. Bus 13 also attracts a credit, since, due to its closeness to bus 12, during MVAr withdrawal at the former bus the voltage at the latter bus is offset only to be restored by the action of the SVC at bus 12 in putting more capacitive reactance into the network.

On the other hand, during 1 MW nodal withdrawals (fig. 3), all buses (excluding slack bus) attract costs since the slack bus has to support these buses with real power as the synchronous compensators and the SVCs do not have their own real power supplies. Also, buses 4 and 12 attract cost and credit for these perturbations, respectively. The costs increase as the bus distances increase from bus 4 and once again decrease when their relative distances decrease with relation to bus 12 which is attracting a credit. As such bus 9 is attracting the most cost. In this case, bus 12 attracts a cost since during withdrawal at it, it attracts a credit but because the real power has to flow from the slack bus, bus 4 attracts a larger cost resulting in the overall being a cost at bus 12. Due to the latter factor, bus 13 attracts a cost as well. Bus 4 attracts the least credit because it is closer to both slack bus and bus 4.

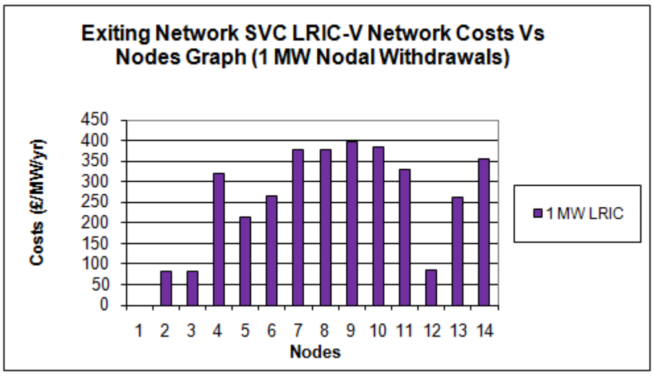

Fig. 3: LRIC-voltage network costs resulting from 1 MW nodal withdrawals to reflect the use of existing network SVCs

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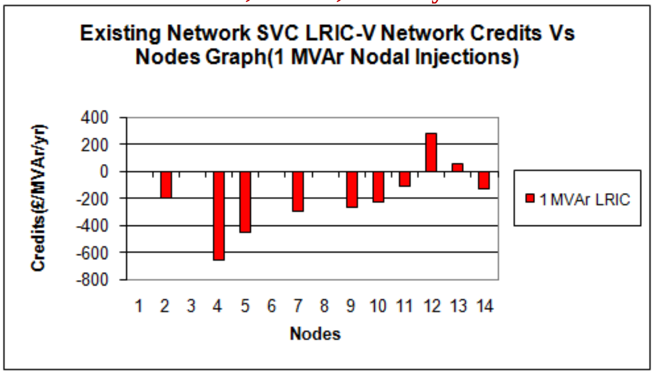

Fig. 4: LRIC-voltage network costs resulting from 1 MVAr nodal injections to reflect the use of existing network SVCs

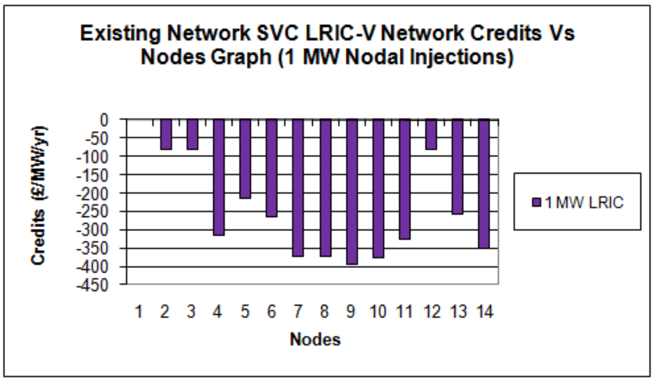

Fig. 5: LRIC-voltage network costs resulting from 1 MW nodal injections to reflect the use of existing network SVCs

In the contrary, during nodal injections, buses 4 and 12 attract credit and cost, respectively. The trend in this case is the same as the earlier case, for both MVAr and MW perturbations, but in the opposite sense. The same reasons as advanced above hold in this case and, therefore, for MVAr nodal injections (fig. 4) bus 4 attracts the most credit while buses 12 and 13 attract costs. On the other hand, for MW perturbations (fig. 5), bus 9 attracts the most credit while bus 2 attracts less credit.

IV. CONCLUSION

This paper offers a novel long-run incremental cost (LRIC) pricing approach to cater for the use of existing network SVCs in pricing terms. The initial and original approach is based upon the spare nodal voltage capacity or headroom of an existing network to reflect the impact to the network wide voltage profile and the cost of future network VAr compensation resulting from a nodal injection/withdrawal, i.e. whether they accelerate or delay the need for future network compensation assets. In that regard, the paradigm is inevitably cost-reflective and able to provide forward-looking economic signals to drive network users to minimize the cost of future investment in VAr compensation. This original LRIC-voltage network pricing principle fails to price for the use of existing network SVCs in its original form. To that end, this original pricing approach was modified, in that, the SVC VAr minimum and maximum limits were mapped to the network lower and upper nodal voltage limits, respectively. Finally, the current SVC VAr loading level is able to be transformed into any corresponding voltage level within the context of the already mentioned mapping exercise.

This study was tested on a 14-bus network. The major findings from this undertaking are summarized as follows:

1) This novel network pricing principle reflects both the true loading burden on the existing network SVCs and the associated indicative forward-looking economic signals.

2). This pricing approach penalizes those network users who advance the investment horizons of the existing network SVCs and, otherwise, incentivize those that defer the investment horizons of the existing network SVCs.

3) Finally, this approach integrates the MW and MVAr network nodal withdrawals/injections.

The next phase would be to integrate this pricing approach with the one for pricing for future network VAr compensation assets following the reactive power planning (RPP) exercise.

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APPENDIX

The used IEEE 14 bus network is described in detail in [41]. The loading and the generation conditions of this used network are shown below in TABLES, I and II, respectively.

TABLE I. 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 II. 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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