A Frame Work for Cost of Reactive Energy for Generators in Deregulated Electricity Market

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Abstract

In India presently there is no mechanism to account for the reactive energy supported by the generators during its operation outside the prescribed power factor range. However a flat rate tariff for a unit of reactive energy is introduced in the year 2010 by Central Electric Regulatory Commission (CERC). The flat rate tariff for reactive energy is in action only during the violation of Indian Electricity Grid Code (IEGC) for restriction of system voltage and operating power factor of generators. The generators are not allowed to participate in dynamic reactive energy allocation.

This indicates that the generators are remunerated sufficiently for their availability to produce active power under 'Availability Based Tariff' (ABT) mechanism but the same generator receives no or restricted remuneration to produce / absorb reactive power.

This paper presents a hypothetical frame work to evaluate the cost of generation of reactive energy outside the power factor range. The method aims at removing generators from their restriction to participate in dynamic reactive energy allocation. The proposal is partly similar to drawl / return of active energy during Unscheduled Interchange (UI) under ABT mechanism in India[3].

*Keywords—Reactive energy cost, Power factor, Dynamic reactive energy, In-phase currents***.**

1. Introduction

The National Load Dispatch Center (NLDC) under Power System Operation Corporation Ltd (POSOCO), India mentions that: Reactive power compensation should ideally be provided locally, by generating reactive power as close to the reactive power consumption as possible. The Regional Entities except Generating Stations are therefore expected to provide local Volt Ampere Reactive (VAr) compensation/generation such that they do not draw VArs from the EHV grid, particularly under low-voltage condition.
To discourage VAr drawls by Regional Entities except Generating Stations, VAr exchanges with Inter State Transmission System (ISTS) shall be priced as follows:

- The Regional Entity except Generating Stations pays for VAr drawl when voltage at the metering point is below 97%
- The Regional Entity except Generating Stations gets paid for VAr return when voltage is below 97%
- The Regional Entity except Generating Stations gets paid for VAr drawl when voltage is above 103%
- The Regional Entity except Generating Stations pays for VAr return when voltage is above 103%, Provided that there shall be no charge/payment for VAr drawl/return by a Regional Entity except Generating Stations on its own line emanating directly from Inter State Generating Station (ISGS).

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The commission also says: The producer should not be compensated for reactive power when operating within its power factor range of 0.95 leading and 0.95 lagging but the transmission provider must compensate the producer for reactive power during an emergency. The charge for reactive energy shall be at the rate of 10 paisa/kVArh w.e.f. 01st April, 2010, and this will be applicable between the Regional Entity, except Generating Stations, and the regional pool account for VAr interchanges. This rate shall be escalated at 0.5paisa/kVArh per year hereafter, unless otherwise revised by the Commission. This tariff is applicable at all times when ever there is a violation of IEGC for system voltage [1].

There is no indication that this tariff structure during reactive energy transactions is reflecting the actual cost of production and or partly the capacity charge towards reactive energy commitment. This is a price based on a pricing formula announced in advance and the method is also currently used in United Kingdom.

In British system, the generator's cost of producing reactive power is recovered from a reactive power capacity payment (majority of the cost) and the rest from the actual reactive power production.

In some other parts of the world the reactive power and voltage support is procured through long term contracts with Reliability Must-Run (RMR) units, In most markets, Independent System Operators (ISOs) compensate generators that provide reactive power and voltage support. These countries include England and Wales, Australia, Belgium, the Netherlands, and certain provinces of Canada. Sweden follows a different policy. Reactive power in Sweden is supplied by generators on a mandatory basis without compensation. In the province of Alberta, Canada, generators are penalized for failing to produce or absorb reactive power and in Argentina, such penalties are imposed not only on generators, but also on transmission operators, distribution operators and large loads. Finally, in Japan, Tokyo Electric Power Co., gives its retail customers a financial incentive to improve their power factors through discounts of the base rate [2].

2. General Definition of the Problem

As per the CERC to bring discipline in the voltage profile the following are the code of conduct and is enumerated in Table-1. The agreement between the Transmission System Operators (TSO) and generator /producers is highlighted below. The ancillary service of reactive power support can be provided basically by generators, static VAR compensators, synchronous condensers and capacitors / reactors banks connected to the transmission system. The reactive support is divided into two categories: static and dynamic. The voltage at various points on the power network is tightly related to reactive power at those points. Sufficiency or surplus reactive power generation at a point may raise the voltage above nominal value and deficiency or lack of reactive power generation at a point will pull down the voltage below the nominal value.

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Table-1: Summary of reactive energy transaction scheme as per IEGC

Voltage status at Metering point	TSO	Generator/Producer
0.97 < V < 1.03	Pays nothing for reactive energy transactions	Receives no payment and generator is obligated to produce, irrespective of its power factor status. However gets compensation during emergency (Tariff not mentioned).
V < 0.97	Pays for Var drawl at 10paisa/Kvarh	Receives no payment for producing if the generator is in agreed power factor range of 0.95lag and 0.95lead. Receives no additional payment for generating outside the agreed range of power factor.
	Gets paid for Var return at 10paisa/Mvarh	
V > 1.03	Gets paid for Var drawl at10paisa/Kvarh	Receives no payment for absorbing if the generator is in agreed power factor range of 0.95lag and 0.95lead. Receives no additional payment for absorbing outside the agreed range of power factor.
	Pays for Var return at 10paisa/Kvarh	

The generators, static VAR compensators, synchronous condensers provide dynamic reactive power support and the capacitors / reactors banks supply and consume reactive power. These devices are used for base loads

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and have little value in satisfying the fluctuations in the reactive power requirement. On the other hand dynamic reactive power support quickly changes the Mvar level independent of voltage level [5] [6].

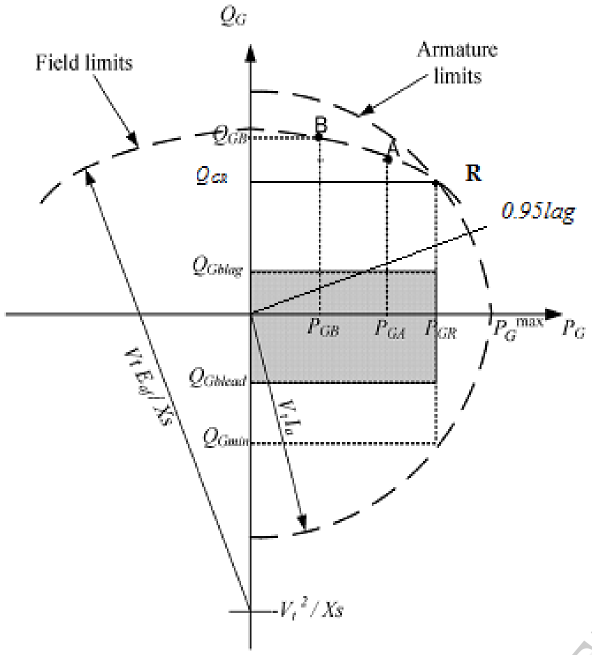

Fig.1 Synchronous generator capability curve

Many studies have revealed that cost of dynamic reactive power is higher than those of producing through static means. But one of the factors that empower the TSO to go for dynamic reactive power support is reliability of dynamic reactive support. The reactive power by static method cannot always produce as reliably as necessary [2]. Generally the The reactive power price for its production by generators should have three parts based on reactive power output according to generators ability curve shown in fig.1[7]:

a. A fixed component to account for capital cost that can be attributed to reactive power production.
b. Cost of loss to account for the increased winding losses as reactive power output increases.
c. Opportunity cost to recover the forgone power during generator obligation to increase its reactive power.

Also the Mvar output of a generator is thought of exercising two purposes: One is to support the shipment of its own generated power into the grid and the second is to support the system voltage [5]. It is difficult to operate the generator always in the limited range of power factor for the scheduled load cycle. In Fig.1 shows the capability curve of a generator. The operating point B is in the region of point where the power factor is outside the power factor range [4].

3. Analytical Model for Evaluation

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S	3 Phase rating of the Generator [MVA]
V	Voltage rating of the Generator Line-Line [KV]
I_a	Rated current of the Generator [Amps]
I_f	Field current [Amps]
Φ	Phase angle between phase voltage **& I_a**
$Cos\Phi$	Power Factor of the Generator
SCR	Short circuit ratio
X_s	Synchronous reactance per phase
I_{ao}	Active current component of I_a [Amps]
I_{ro}	Reactive current component of I_a [Amps]
I_{ai}	In-Phase active current component of I_a [Amps]
I_{ri}	In-Phase reactive current component of I_a [Amp
$I_{ri}\_I_a$	Ratio to I_{ri} to I_a
$I_{ai}\_I_a$	Ratio to I_{ai} to I_a
$I_{ri}\_I_{ai}$	Ratio to I_{ri} to I_{ai}
P_a	Armature power loss due to I_{ao} [MW]
P_r	Armature power loss due to I_{ro} [MW]
P_{loss}	Total armature power loss due to I_a [MW]
$P_r\_P_a$	Ratio of P_r to P_a
$P_a\_P_{loss}$	Ratio of P_a to P_{loss}
$P_r\_P_{loss}$	Ratio of P_r to P_{loss}

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The IEGC reactive energy transaction scheme reveals that the generator / producer receive no payment for serving outside the range of agreed power factor. The generator under this condition is not remunerated and therefore receives no payment from the TSO if the voltage is as per IEGC. On the other hand if the system voltage is below 0.97pu then TSO pays for the reactive power service rendered by generators / producers at the rate of 10paisa/Kvarh with effect from 01st April 2010. Every year the cost per reactive unit is escalated by 0.5paisa.

The cost of reactive energy is uniform irrespective of the power factor falling out of range. The authors' is of the opinion that, the uniform cost for different operating power factor outside the agreed range for such generator operations outside the agreed power factor range is irrational and therefore makes an attempt to propose a frame work for tariff structure to recover the cost mentioned in part 'b' of reactive power pricing mentioned in [7].

The following points are worth mentioning to introduce a cost structure for reactive energy referring to fig 1. which gives the information of the capability of the generators.

- Region I, where $0 \leq Q_G \leq Q_{Gblag}$: In this region the generator is not to be remunerated because it is producing reactive power for its own use. Therefore the generator is not injecting reactive power to the grid.

- Region II, where $Q_{Gblag} \leq Q_G \leq Q_{GR}$: Part of this region is prescribed by IERC (up to 0.95lag line). In this region the generator injects reactive power into the grid without sacrificing active power P_G. There is definitely increase in active power losses in the generator which is not accounted.

- Region III, where $Q_{GR} \leq Q_G \leq Q_{GB}$: In this region the power factor of the generator falls outside the agreed power factor range. The generator is subjected to severe stator and rotor heating (due to over excitation) which is not addressed in the present remuneration structure. Over heating demands efficient cooling system to remove excess heats and so on. Also the generator has to give-up some portion of active power generation to accommodate demand in reactive generation. Presently the IEGC demand the generator not to shed portion of active power. This means the generators should invariably be in the power factor range irrespective of reactive demand. In other words since the present remuneration is weak to support this region the CERC insists the generators not to participate. Generator not supporting to produce reactive power to support voltage shall certainly deteriorate the security of the operating condition in this region.

- Region IV, where $Q_{Gmin} \leq Q_G \leq 0$: In this region the generator is under excited and absorbs reactive power. At some points the generator may have to shed active power to absorb reactive power. More importantly the generator is close to its stability limit. It is seen that a power factor of about 0.5lead can move the generator to the verge of instability. This suggests the producers to avoid absorbing the reactive generation demanded by TSO.

Observing the behavior of the generator in different regions, the authors develop a cost structure that can suitably remunerate the generator while it operates in region III and part of region II. The regions I, IV and part of region II are not considered for remuneration in the discussion.

The following steps are used to propose a new tariff structure to compensate for generators while they operate in region III and part of region II:

i. The MVA of the generator is direct indication of its capacity or capability to inject the both active and reactive power to the grid. At rated voltage, the generator current containing both active and reactive component produces active and reactive powers respectively and supply to grid. These components are 90 electrical degrees out of phase and produce heat in the armature independently with a very brief time lag in milli-seconds for a frequency of 50Hz.

$$I_a = I_{ao} + jI_{ro} \quad .... \quad (1)$$

$$I_{ao} = I_a * Cos\Phi \quad .... \quad (2)$$

$$I_{ro} = I_a * Sin\Phi \quad .... \quad (3)$$

ii. The authors recommend considering the in-phase components: active and reactive currents of the armature current. These currents exists simultaneously and share the cross sectional area of the armature conductors. Their magnitudes decide the relative space in conductors and hence produce heat accordingly.

$$I_{ai} = I_a * Cos^2\Phi \quad .... \quad (4)$$

$$I_{ri} = I_a * Sin^2\Phi \quad .... \quad (5)$$

$$I_a = I_{ai} + I_{ri} \quad .... \quad (6)$$

iii. The information about the content of $\%I_{ri}\_I_a$ in-phase reactive current in the armature for different power factors outside the range is used to frame the cost per reactive unit.

$$I_{ri}\_I_a = \frac{I_{ri}}{I_a} \quad .... \quad (7)$$ also

$$I_{ai}\_I_a = \frac{I_{ai}}{I_a} \quad .... \quad (8)$$

iv. When the operating power factor is out of the range, there will be an increase in the in-phase reactive component and the corresponding heating. The additional effort used in cooling the

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stator and rotor (due to increase in field current) is to be reflected in the cost structure.

v. The present cost structure seems to be too weak to recover the efforts to cool the generator. The 10paisa per reactive unit is taken as datum to propose the new cost structure. The contribution of in-phase reactive component is 9.75% for operating power factor of 0.95lag. According to CERC no charges are levied for this power factor informs that only 9.75% of heating is allowed and any increase in the reactive contribution of heating invites 10paisa per reactive unit.

vi. The authors propose that there should be an increase in cost per reactive unit for ramping up of %increase in the in-phase reactive current. If 10paisa is charged for about 10% contribution of heat due to in-phase reactive current then for every further 10% contribution of heat a 10paisa increase in cost can be framed. Thus if there is 50% increase in the in-phase reactive current which directly contributes to 50% heating should invite charges of about 50paisa per reactive unit for corresponding power factor of the generator.

vii. Ramping up the cost per reactive unit can be used to recover the cost towards corresponding heating due to in-phase reactive current. This structure penalizes heavily for TSO if they demand reactive power outside the power factor range of the generator. TSO is forced to see other alternatives before deciding on the procurement. On the other hand the generator is compensated proportionately based on the heating due to in-phase reactive current.

4. Comparison and Discussions

To demonstrate the proposed method for the new tariff structure for reactive units generated by the generator under different power factor conditions, let us consider the following generator and its data in table-2:

Table-2

Data	**Calculated Values**
S = 137.5MVA	P = 110MW
V = 11KV	Q = 82.5Mvar
pf = 0.8lag	I_a = 7220A
I_f = 1500A	X_s =2.0pu
SCR = 0.5	

We also have:

$$I_{ri}\_I_{ai} = \frac{I_{ri}}{I_{ai}} \quad .... \quad (9)$$

$$P_r\_P_a = \left(\frac{I_{ro}}{I_{ao}}\right)^2 \quad .... \quad (10)$$

In table-3, the sum of in-phase currents for different power factors and are yielding the same armature current magnitude. It is evident that the out of phase currents do not give directly the armature current magnitude. The **%$I_{ri}\_I_{ai}$** increase in the in-phase reactive component over active component indicates the dominancy of reactive current over heating of the armature for power factors smaller than 0.82lag.

Table-3

CosΦ	**Out of Phase Currents**		**In-Phase Currents**		**$I_{ri}\_I_{ai}$ %**
	I_{ao}	**I_{ro}**	**I_{ai}**	**I_{ri}**	
0.65	4693	5487	3050	4170	136.69
0.66	4765	5424	3145	4075	129.57
0.67	4837	5360	3241	3979	122.77
0.68	4910	5294	3339	3881	116.26
0.69	4982	5226	3437	3783	110.04
0.70	5054	5156	3538	3682	104.08
0.71	5126	5084	3640	3580	98.37
0.72	5198	5010	3743	3477	92.90
0.73	5271	4934	3848	3372	87.65
0.74	5343	4856	3954	3266	82.62
0.75	5415	4776	4061	3159	77.78
0.76	5487	4692	4170	3050	73.13
0.77	5559	4607	4281	2939	68.66
0.78	5632	4518	4393	2827	64.37
0.79	5704	4427	4506	2714	60.23
0.80	5776	4332	4621	2599	56.25
0.81	5848	4234	4737	2483	52.42
0.82	5920	4132	4855	2365	48.72
0.83	5993	4027	4974	2246	45.16
0.84	6065	3917	5094	2126	41.72
0.85	6137	3803	5216	2004	38.41
0.86	6209	3684	5340	1880	35.21
0.87	6281	3560	5465	1755	32.12
0.88	6354	3429	5591	1629	29.13
0.89	6426	3292	5719	1501	26.25

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0.90	6498	3147	5848	1372	23.46
0.91	6570	2993	5979	1241	20.76
0.92	6642	2830	6111	1109	18.15
0.93	6715	2654	6245	975	15.62
0.94	6787	2463	6380	840	13.17
0.95	6859	2254	6516	704	10.80

Table-4 gives, for a constant load current the ***%I_{ri}_I_a*** in-phase reactive component for different power factors. We find the content is 9.75% for 0.95lag and this reactive content increases to 57.76% for 0.65lag. As discussed earlier an approximate of 10% rise in reactive content calls for 10paisa rise in the cost structure. It is seen that for 0.65lag, 57.76paisa will be charged for 136.69% of reactive heating which is caused by 57.76% of in phase reactive current.

Table-4

CosΦ	**In-Phase Currents**		**P_r_P_a %**
	I_{ai}_I_a %	**I_{ri}_I_a %**	
0.65	42.24	57.76	136.69
0.66	43.56	56.44	129.57
0.67	44.89	55.11	122.77
0.68	46.25	53.75	116.26
0.69	47.60	52.40	110.04
0.70	49.00	51.00	104.08
0.71	50.42	49.58	98.37
0.72	51.84	48.16	92.90
0.73	53.30	46.70	87.65
0.74	54.76	45.24	82.62
0.75	56.25	43.75	77.78
0.76	57.76	42.24	73.13
0.77	59.29	40.71	68.66
0.78	60.84	39.16	64.37
0.79	62.41	37.59	60.23
0.80	64.00	36.00	56.25
0.81	65.61	34.39	52.42
0.82	67.24	32.76	48.72
0.83	68.89	31.11	45.16
0.84	70.55	29.45	41.72
0.85	72.24	27.76	38.41

0.86	73.96	26.04	35.21
0.87	75.69	24.31	32.12
0.88	77.44	22.56	29.13
0.89	79.21	20.79	26.25
0.90	81.00	19.00	23.46
0.91	82.81	17.19	20.76
0.92	84.64	15.36	18.15
0.93	86.50	13.50	15.62
0.94	88.37	11.63	13.17
0.95	90.25	9.75	10.80

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The ratio ***%P_r_P_a*** is rising much rapidly for decreasing power factors. This is also nothing but ***%I_{ri}_I_{ai}*** the ratio of in phase reactive current to in phase active current. Also we find for power factors close to 0.95 an approximately 1.88% increase in reactive content for every 0.01 fall in power factor and 1.32% for power factor close to 0.65lag. Thus the variation is non-linear. The authors approximate this curve to a linear one with negative slope to account for cost per reactive unit of CERC and the authors proposed cost per reactive unit for lagging power factors in the range 0.65 < CosΦ < 0.99.

Fig.2 shows the per unit in-phase currents, armature current and ***I_{ri}_I_{ai}*** the in-phase reactive to in-phase active ratio.

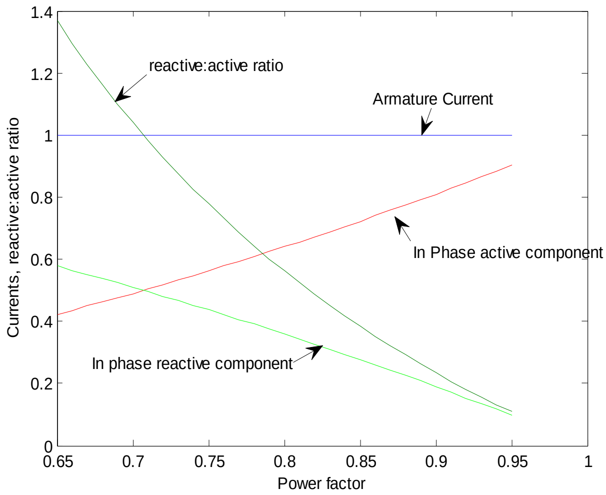

Fig.2

Fig.3 shows the proposed cost structure curve for reactive unit and existing cost per reactive unit as per CERC. It is seen that the cost per reactive unit is 10paisa for power factor 0.94 lag and ramp up to a value of 58paisa for power factor of 0.65.These values are in correspondence with in-phase reactive current contribution and its participation in heat generation. To get present cost / Kvarh one has to add 1.5paisa per reactive unit for the reading for proposed cost structure obtained from fig2.

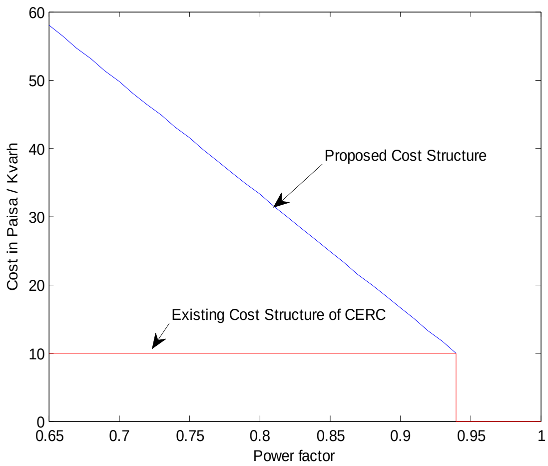

Fig.3

4. Conclusions

An adequate effort in a rational way is made to arrive at a frame work to introduce the cost per reactive energy when the operating power factor of a generator is out of the agreed range. Present cost structure of 10ps/Kvarh issued by CERC is seen to be inadequate to recover the cost for the service outside the power factor range. This is of the fact being that the heat generated escalates which needs additional effort to evacuate it as power factor becomes poor. This is not addressed in the present cost structure. Direct relations among the in-phase reactive current that involves in producing heat and cost needed to evacuate heat with additional effort are established. This is used as the basis to frame the cost per reactive energy.

Power factor of 0.65 lag is taken considering the maximum participation possible by the field circuit without crossing its limits. The frame work discourages the TSO to overdraw the services from generators and also encourages using alternate methods to procure reactive energy. Also the generator is suitably remunerated while generating reactive power outside power factor range. Dynamic reactive support is more reliable and support the system security hence the proposed cost structure invites the participation of generator for dynamic reactive support service.

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