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Pricing for Generators under Lost Opportunity Cost for Suppling of Reactive Power

[1*]Raghavendra L , [2]Shreeshayana R, [3]Sathish K R, Parthasarathy L**

[1] Research Scholar and Associate Professor, Department of Electrical and Electronics Engineering, ATME College of Engineering, Mysuru and Visvesvaraya Technological University, Belagavi-590018, Karnataka, India.
[2]Assistant Professor, Department of Electrical and Electronics Engineering, ATME College of Engineering, Mysuru and Visvesvaraya Technological University, Belagavi-590018, Karnataka, India.
[3] Professor, Department of Electrical and Electronics Engineering, ATME College of Engineering, Mysuru and Visvesvaraya Technological University, Belagavi-590018, Karnataka, India.

* Corresponding Author; Raghavendra L, Department of EEE, ATME College of Engineering, Mysuru, Karnataka, India.

Abstract: The importance of doing a thorough evaluation of the expenses associated with reactive power is paramount within the framework of energy markets that are becoming more competitive. The evaluation should include cost factors that enable the recovery of the Lost Opportunity Cost (LOC) component. This component emerges when a generator approaches its field limits and requires reactive power to accommodate increasing demand. At present, there is a prevailing belief that the pricing framework of 0.10₹/kvarh, as established by the Central Electricity Regulatory Commission, is insufficient in terms of adequately remunerating for services rendered outside the power factor range. This phenomenon is a consequence of the reduction in power factor, leading to an escalation in heat generation and consequently requiring a higher energy expenditure for its dissipation. The current cost structure fails to account for this factor. There is a clear association between the amount of effort spent in heat removal and the in-phase reactive current that is responsible for generating heat. To address this issue, a proposed pricing scheme has been put forth for reactive units generated by the generator, which considers various Power Factor scenarios and LOC.
Keywords: Reactive Power, Lost Opportunity Cost, Tariff Structure.

1. Introduction

Maintaining power system security largely depends on the implementation of effective reactive power management strategies. This approach reduces dependence on generators for reactive power supply, improves voltage profile stability, improves PF, and eliminates the need for high KVA values. The increasing number of negotiated transactions has caused power systems to move closer to the security perimeter. This proximity can potentially lead to voltage instability if there is a supply of reactive power. The issue of managing reactive power poses significant challenges within the competitive electricity sector. Hence, researchers, and system operators are interested in examining the economic implications of reactive power within a competitive market. The system is capable of efficiently meeting the reactive power demands of electric motors and other industrial loads. The patterns of reactive power demand exhibited by these loads bear resemblance to the patterns of real power consumption. Synchronous generators and condensers are widely recognized as the primary producers of reactive power. The fulfilment of local reactive power demands can be achieved by the installation of capacitor banks. Generators are capable of supplying active power only within specific limits of reactive power demands, wherein an increased requirement for reactive power is met by sacrificing active power. A reduction in active power output leads to a decline in generated revenue. To ensure the sustainability of auxiliary service providers in competitive power markets, it is imperative to account for the cost associated with missed opportunities. The primary duty of the ISO is to efficiently oversee, produce, and distribute commercial activities. To accomplish this, the management and allocation of reactive power have become imperative [1]. Industrial clients are subject to penalties imposed by suppliers when their power factors are low, as this allows suppliers to recoup the expenses associated with reactive units. Additionally, many utilities determine the charges for industrial users based on their KVA demand. In the context of competitive market environments, the current method of recovering fixed costs for reactive units is deemed inadequate and may fail to provide reliable pricing signals to additional suppliers [2]. Ref. [3,4] has analyzed the limitations associated with the utilization of power factor penalties as a means to establish pricing for reactive power. The adoption of economic principles based on marginal theory has been recommended as a response. Accessing the cost characteristics of reactive power is challenging due to the presence of typical equipment that generates reactive power, the local reactive power characteristics of loads, and the behavior of the transmission system [5]. Hao and Papalexopoulos (6) assert that network restrictions exert a substantial influence on the reactive power marginal price, often representing a fraction of the active power marginal price, typically less than 1%. Several authors have put forward different approaches for determining the expenses associated with reactive power. Dandhachi and Choi, together with their colleagues, introduced a real-time reactive power pricing technique based on the notion of optimal power flow (OPF) [7]. Choi J. Y. introduced a theoretical framework that addresses the pricing and compensation of reactive power costs. Nevertheless, accurately determining the possible expenses associated with reactive support from generators poses a significant challenge [8]. The process of determining the potential cost associated with reactive support from generators is a complex undertaking. As indicated by the citation provided [9], researchers have utilized many alternative goal functions within the framework of optimal power flow-based approach to ascertain the marginal prices of reactive power. The authors of [10] developed an interior point approach for the decomposition of spot pricing. Zhao and Erving (year) proposed a recommendation in their study [11]. Matteo Troncia has developed two market-oriented solutions that are specifically tailored to local contexts. These solutions aim to foster the participation of innovative service providers in the domain of voltage management. In contrast to existing practices, the cost-based incentive program and weighted auction presented in this study aim to enhance economic efficiency and transparency in the acquisition and compensation of reactive power capacity for voltage management [12]. The utilization of a distribution market-clearing model is recommended for the determination of prices for active and reactive power. This model can be further extended to incorporate the inclusion of operating reserves [13]. The study conducted in [14] examined the significance of reactive power in the preservation of voltage stability inside electric power grids. This study examines several pricing strategies and market structures that facilitate the provision of sufficient reactive power. This study examines variations in worldwide market strategies and underscores the significance of establishing competitive, stable, and efficient markets for reactive power. Ref. [15] in their comprehensive study, undertook a meticulous analysis of the markets for reactive power auxiliary services. The researchers also analyzed the difficulties associated with the implementation of these services and evaluated the efficacy of current methodologies. The primary objective of this work is to expand understanding of the present circumstances while offering valuable insights for the advancement and enrichment of these markets. Fixed costs, often referred to as investment costs, and variable costs are the two distinct classifications that can be assigned to reactive power generation expenses. The category of variable costs encompasses running costs, such as those associated with gasoline and maintenance expenses. Opportunity expenses are encompassed inside this particular category as well. The primary factor contributing to the subsequent increase in costs is the decline in active electricity generation. The implementation of a reactive power pricing mechanism that adequately accounts for the generator's lost opportunity cost is of utmost importance. The efficient collection of reactive power costs would ensure the financial viability of auxiliary service providers in the electrical markets. The cost estimate is contingent upon the capabilities of the generators at each operating point due to the fluctuation in load and power factor. This study presents a novel pricing model for reactive units generated by the generator, considering different PF scenarios and LOC, utilizing MATLAB software.

2. Generator Capability

Multiple techniques are employed to maintain the continuity of reactive power, such as the utilization of capacitor banks, generators synchronous condensers, and static var compensators. These devices possess the ability to both provide and absorb reactive power. These electrical appliances serve as base loads and exhibit little capability to respond to variations in the demand for reactive power. Nevertheless, the dynamic provision of reactive power support, regardless of the voltage level, enables swift adjustments to the level of reactive

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power in Mvar. Based on the generator ability curve illustrated in Figure 1, the pricing structure for the production of reactive power by generators generally has three distinct portions, as indicated by reference [7].

a. A fixed component designed to account for the capital expenses associated with the production of reactive power.

b. The increase in reactive power output is correlated with the escalation of winding losses, as indicated by the price tag.

c. The cost related to the generator's capacity to restore the depleted power through the enhancement of its reactive power.

Considering the generators' capacities as shown in Figure 1, the following issues must be addressed to create a reactive power cost structure.

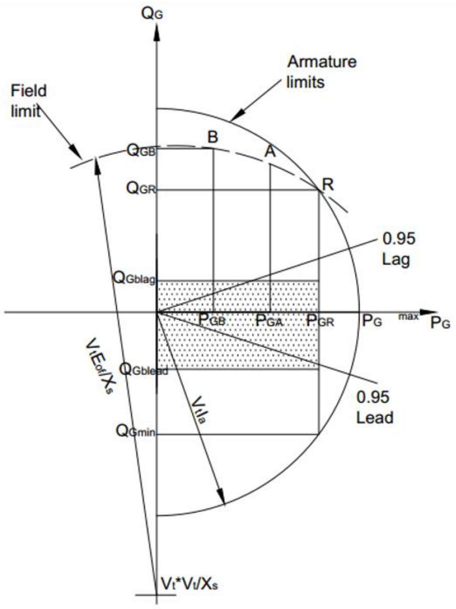

Fig.1; Generator Ability Curve

- **Region-I, where $0 \le Q_G \le Q_{Gblag}$:** The generator located in this particular region operates without the need for payment, as it is solely responsible for producing reactive power for internal usage. As a result, the generator is failing to provide the grid with reactive power.
- **Region-II, where $Q_{Gblag} \le Q_G \le Q_{GR}$:** The Indian Electricity Regulatory Commission has established specific limits for a certain region up to a lag line of 0.950. Within this particular region, the generator is capable of injecting reactive power into the grid without diminishing the quantity of active power, denoted as P_G. There is undoubtedly a rise in the generator's active power losses which is unaccounted for.
- **Region-III, where $Q_{GR} \le Q_G \le Q_{GB}$:** The PF of the generator in this region exceeds the prescribed PF range. The current compensation scheme does not currently manage the substantial heating of the generator's stator and rotor caused by overexcitation. To mitigate excessive heat and other contributing variables, the issue of overheating necessitates the employment of an efficient cooling system. To satisfy the need for reactive power generation, the generator must consequently relinquish a portion of its active power generation. Currently, the International Electrotechnical Commission (IEGC) mandates that generators must not incur any active power losses. This implies that the generators should consistently operate within the power factor range, irrespective of any changes in reactive demand. The CERC asserts that the generators should abstain from participation due to the inadequacy of the present compensation to sustain this region. If the generator is unable to supply reactive power to maintain voltage, the security of the operating conditions in this region will certainly degrade.

- **Region-IV, where $Q_{Gmin} \leq Q_G \leq 0$:** The generator within this particular area is currently functioning in a state of under-excitation, resulting in the active consumption of reactive power. In specific cases, the generator may be required to release active power to absorb reactive power. The generator has reached its stability threshold, a matter of significant concern. A PF of roughly 0.5 lead has been seen to push the generator close to instability. This implies that the producers avoid taking on the reactive generation that TSO requires.

After conducting a thorough analysis of the generator's performance in different regions, a cost structure has been devised to adequately remunerate the generator for its operation outside the grid code.

3. Lost Opportunity Cost

The generator must once operate at a PF that is lower than the prior operating condition due to a situation that requires it to reduce active power by value ΔP and supply additional ΔQ (Since generators are designed to provide active power, they are typically not encouraged to reduce active power). Region III might experience this. The inability to produce ΔP causes the generator to lose money. It is referred to as the LOC. It's also true that not enough fuel is being burned for ΔP to be produced. Other generators in the area supply the missing value of ΔP. However, if the generator were required to create more ΔQ at the expense of ΔP, it would refuse. This necessitates providing sufficient compensation or incentives to influence the generation of ΔQ and lower ΔP.

The subsequent paragraph outlines the minimal remuneration necessary under different operational conditions. The minimum level of compensation required for generating additional ΔQ should be established such that it exceeds or equals the cost associated with producing ΔP. Furthermore, it is imperative to consider the extra time and resources required for the production of ΔQ.

$$C_{gQm} = \frac{C_{gp} * \Delta P.x}{\Delta Q} \qquad \dots (1)$$

C_{gQm}	Minimum Remuneration for Reactive Energy of Generator in ₹/Mvarh
C_{gP}	Cost of Active Energy of Generator in ₹/MWh
χ	Profit Margin
ΔP	Active Power not supplied in MW
ΔQ	Additional Q supplied in Mvar

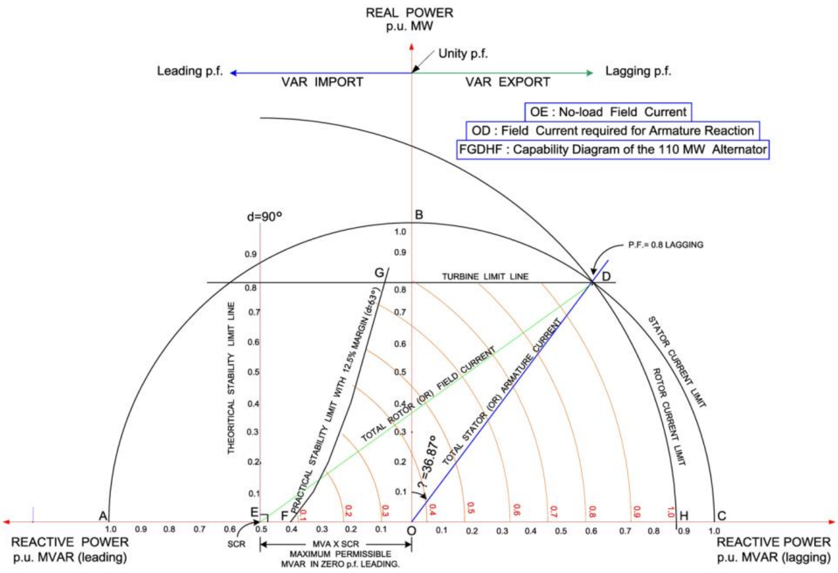

Fig.2: Capability diagram of a 110 MW Alternator

The approach offered for the innovative tariff structure pertaining to reactive power produced by the generator is demonstrated by analyzing the data presented in Table 1, which encompasses various PF conditions and LOC. A capability diagram has been developed, as seen in Fig.2. The "Kolubara Power Plant" of the Brazilian Electric System, an electrical engineering institute, developed this generator.

Table 1: Kolubara Generator Details

Data	S = 137.5MVA	V = 10.5 kV	cosΦ = 0.8lag	I_f = 1335A	X_s =2.0pu
Calculated Values	I_a = 7560A	SCR = 0.5	P = 110MW	Q = 82.5Mvar	-

Nomenclature

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

$$I_a = I_{ao} + jI_{ro} \qquad \ldots(2)$$
$$I_{ao} = I_a * \cos\emptyset \qquad \ldots(3)$$
$$I_{ro} = I_a * \mathrm{SIN}\,\emptyset \qquad \ldots(4)$$
$$I_{ai} = I_a * cos^2\emptyset \qquad \ldots(5)$$
$$I_{ao} = I_a * sin^2\,\emptyset \qquad \ldots(6)$$
$$I_a = I_{ai} + I_{ri} \qquad \ldots(7)$$
$$I_{ri}\_I_a = \frac{I_{ri}}{I_a} \qquad \ldots(8)$$
$$I_{ai}I_a = \frac{I_{ai}}{I_a} \qquad \ldots(9)$$
$$I_{ri}\_I_{ai} = \frac{I_{ri}}{I_{ai}} \qquad \ldots(10)$$

Table 2: Performance of Generator For PF between 1.0 & 0.8 Lag

e	δ	I_f	I_a	cosΦ	I_p	I_q	I_{ai}	I_{ri}	$\%I_{ri}/I_a$
1.8868	57.9946	0.9434	0.8000	1.0000	0.8000	0	0.8000	0	0
1.9416	55.4915	0.9708	0.8016	0.9981	0.8000	0.0500	0.7984	0.0031	0.3891
2.0000	53.1301	1.0000	0.8062	0.9923	0.8000	0.1000	0.7938	0.0124	1.5385
2.0616	50.9061	1.0308	0.8139	0.9829	0.8000	0.1500	0.7863	0.0276	3.3962
2.1260	48.8141	1.0630	0.8246	0.9701	0.8000	0.2000	0.7761	0.0485	5.8824
2.1932	46.8476	1.0966	0.8382	0.9545	0.8000	0.2500	0.7636	0.0746	8.8968
2.2627	45.0000	1.1314	0.8544	0.9363	0.8000	0.3000	0.7491	0.1053	12.3288
2.3345	43.2643	1.1673	0.8732	0.9162	0.8000	0.3500	0.7329	0.1403	16.0656
2.4083	41.6335	1.2042	0.8944	0.8944	0.8000	0.4000	0.7155	0.1789	20.0000
2.4839	40.1009	1.2420	0.9179	0.8716	0.8000	0.4500	0.6973	0.2206	24.0356
2.5612	38.6598	1.2806	0.9434	0.8480	0.8000	0.5000	0.6784	0.2650	28.0899
2.6401	37.3039	1.3200	0.9708	0.8240	0.8000	0.5500	0.6592	0.3116	32.0955
2.7203	36.0274	1.3601	1.0000	0.8000	0.8000	0.6000	0.6400	0.3600	36.0000

The performance of the generator-exciter for various power factors, as well as its variation in armature current, in-phase active and reactive currents, and relative components of active and reactive armature currents, are shown in Table 2.

For Regions, I and II as well as changes in PF from UPF to 0.8 lag, the performance quantities listed in Table 2 are detailed. All figures are in per unit. Table 3 and Table 4, respectively, contain information on various quantities for other PFs in regions III and IV.

Table 3: Generator Exciter Performance for PF between 0.8000 lag and 0.6420 lag

e	δ	I_f	I_a	cosΦ	I_{ao}	I_{ro}	I_{pi}	I_{qi}	$\%I_{qi}/I_a$
2.7203	36.0274	1.3601	1.0000	0.8000	0.8000	0.6000	0.6400	0.3600	36.0000
2.7203	35.4544	1.3601	0.9960	0.7921	0.7890	0.6079	0.6249	0.3711	37.2557
2.7203	34.8815	1.3601	0.9921	0.7841	0.7778	0.6158	0.6099	0.3822	38.5263
2.7203	34.3085	1.3601	0.9882	0.7758	0.7666	0.6235	0.5948	0.3934	39.8110
2.7203	33.7355	1.3601	0.9843	0.7674	0.7554	0.6311	0.5797	0.4046	41.1092
2.7203	33.1626	1.3601	0.9805	0.7588	0.7440	0.6386	0.5646	0.4159	42.4199
2.7203	32.5896	1.3601	0.9767	0.7501	0.7326	0.6460	0.5495	0.4272	43.7423
2.7203	32.0167	1.3601	0.9730	0.7411	0.7211	0.6533	0.5344	0.4386	45.0757
2.7203	31.4437	1.3601	0.9693	0.7320	0.7095	0.6604	0.5194	0.4499	46.4190
2.7203	30.8708	1.3601	0.9657	0.7227	0.6979	0.6675	0.5044	0.4613	47.7713
2.7203	30.2978	1.3601	0.9621	0.7132	0.6862	0.6744	0.4894	0.4727	49.1317
2.7203	29.7248	1.3601	0.9586	0.7036	0.6744	0.6812	0.4745	0.4841	50.4991
2.7203	29.1519	1.3601	0.9551	0.6937	0.6626	0.6879	0.4596	0.4954	51.8725
2.7203	28.5789	1.3601	0.9516	0.6837	0.6507	0.6944	0.4449	0.5067	53.2509
2.7203	28.0060	1.3601	0.9482	0.6735	0.6387	0.7009	0.4302	0.5180	54.6331
2.7203	27.4330	1.3601	0.9449	0.6632	0.6266	0.7072	0.4156	0.5293	56.0181
2.7203	26.8600	1.3601	0.9416	0.6527	0.6145	0.7134	0.4011	0.5405	57.4045
2.7203	26.2871	1.3601	0.9384	0.6419	0.6024	0.7195	0.3867	0.5517	58.7914

Table 4: Generator- Exciter Performance for P=0.3 and -0.2<Q<0

E	δ	I_f	I_a	cosΦ	I_{ao}	I_{ro}	I_{pi}	I_{qi}	$\%I_{qi}/I_a$
1.1662	30.9638	0.5831	0.3000	1.0000	0.3000	0	0.300	0	0
1.0817	33.6901	0.5408	0.3041	0.9864	0.3000	-0.0500	0.2959	0.0082	2.700
1.0000	36.8699	0.5000	0.3162	0.9487	0.3000	-0.1000	0.2846	0.0316	10.00
0.9220	40.6013	0.4610	0.3354	0.8944	0.3000	-0.1500	0.2683	0.0671	20.00
0.8485	45.0000	0.4243	0.3606	0.8321	0.3000	-0.2000	0.2496	0.1109	30.77

For the generator's remuneration, the cost per reactive unit is defined as follows:

- **In Region I: UPF ≤ PF ≤ 0.950 Lag:** The generator must meet any demand in Q as well as the rating P without reducing the supply of P. In this region, the generator is not compensated, and the suggested cost structure does not apply.
- **In Region II: 0.951 Lag ≤ PF ≤ 0.80 Lag:** The generator must meet a specified demand in Q and the rating P without affecting the supply of P. The generator will be compensated in this area in accordance with the suggested cost structure. The cost structure exceeds the flat rate of compensation of 0.1₹/Mvar. It goes up when operating power factors are below IEGC-recommended levels.
- **In Region III: 0.80 Lag ≤ PF ≤ 0.70 Lag:** The generator is asked to supply more reactive power (ΔQ) while forgoing a specific quantity of active power (ΔP). According to the specified pricing structure, the generator will be rewarded in this area. This cost structure is more expensive than the minimal amount of reactive power needed to pay off the LOC by selling ΔP. The least expensive reactive generation for LOC in this region is shown in Table 5.
- **In Region IV: UPF ≤ PF ≤ ZPF lead:** The stability of the generator is the major factor controlling this area. The operating point must not cross the stability requirement's region.

Such calculated results are presented in Table 5 for generators that participate outside of grid code by skipping active power ΔP. This calculation is implied by the proposed cost structure, which also includes the LOC. If the operating PF is higher than 0.95 lead, the generator will not be compensated. We discover LOC as well as the crucial stability margin that needs to be adjusted for PF less than 0.95 lead. As a result, the cost structure of the relevant lagging PF is also applicable to this area. The proposed values shown in Table V and CgQ are based on the assumption that the generator is entrusted with supplying reactive power in Region II. There exists a disparity in the CgQ between Region II and Region III. When ΔQ is greater than ΔP in Region II, the values of CgQ are lower; nevertheless, when ΔP is typically bigger than ΔQ in Region III, the values of CgQ are higher.

Table 5: LOC Calculation for PF 0.8000 to 0.7040 lag

Operating Point	PF	P pu	Q pu	ΔP pu	ΔQ Pu	C_{gQm} ₹/kvarh	C_{gQ} ₹/kvarh
From	0.950	0.800	0.260	-	-	-	-
To	0.759	0.744	0.639	0.056	0.380	0.038*	0.40
To	0.704	0.674	0.681	0.126	0.421	0.076	0.49
From	0.800	0.800	0.600	-	-	-	0.36
To	0.759	0.744	0.639	0.056	0.039	0.368	0.40
To	0.704	0.674	0.681	0.126	0.043	0.399	0.49
From	0.759	0.744	0.639	-	-	-	0.40
To	0.704	0.674	0.681	0.070	0.043	0.428	0.49

4. Conclusion

At present, there is a prevailing belief that the pricing framework of 0.10₹/kvarh, as established by the Central Electricity Regulatory Commission, is insufficient in terms of adequately remunerating for services rendered outside the power factor range. The results obtained are the basis for calculating the unit cost of reactive power. The operating capacity of the field circuit is optimized by selecting a power factor of 0.65 lag, considering the given constraints. The existing framework provides incentives for adopting alternative methods of obtaining reactive power, while also preventing the TSO from excessively relying on generating services moreover, the generator is duly remunerated, encompassing LOC. Generators are invited to engage in the provision of this service based on the proposed pricing framework, the enhanced reliability of dynamic reactive support, and the reinforcement of system security.

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