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Reactive Power Generation Curve

[1,]Sergio B. Barragán Gómez, [2,]Yoram Astudillo Baza,[3,]Manuel A. López Zepeda
[1,2,3,]Instituto Politécnico Nacional Escuela Superior de Ingeniería Mecánica y Eléctrica
Departamento de Ingeniería Eléctrica Av. Instituto Politécnico Nacional s/n, Unidad Profesional "Adolfo López Mateos"Edif. 2, Col. Lindavista, Del. Gustavo A. Madero, D.F. C.P. 07738

--**ABSTRACT**--

In this paper we propose a curve to determine the cost of reactive power generation; this cost consists of a fixed cost and a variable cost. The fixed cost is set with a recovery factor of annual capital invested in the generator. The variable cost is calculated depending on operating conditions of the generator. It's proposed to determine this variable cost from a τ variable, which is a function of active and reactive power generated, considering the capability curve. The simulations are performed in 30-node IEEE test system.

Keywords – Capability curve, generation costs, fixed and variable costs, reactive power.

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1. INTRODUCTION

Independently from the scheme of the electric system the reactive power is a very important parameter and it has direct link with the voltage magnitude of the system, however in a horizontal structure the reactive power is defined as a part of the set of the auxiliary services and has a commercial aspect in the system. The generators, condensers and compensators are considered as dynamic devices and are used for the voltage regulation and also to maintain the reactive power reserves and could support any contingency in the system [1]. Unless the reactive power compensation in an electric system has to be done in a local way, because the transmission of reactive power flows from the generators provoking an increment in the losses of the transmission system;

however although the principal function of the synchronous generators is the generation of the active power, in an implicit way these generate reactive power under certain operating conditions. To determine the generation of reactive power cost is not easy to model because [2]: the own reactive power generation, the behavior of the reactive power in the transmission system and the function that develops is of the reactive support in the operation of system.It had been developed works to determine the cost for reactive power markets [2, 3, 4, 5], they define that the payment structure for this service is composed by a payment for capability and a payment for consume, the payment for consume could be determined with the measurement of the reactive power generation in each machine or through the quadratic function that represents the reactive power generation in each generator.

The analysis of the cost for this service has motivated the use of optimal power flow (OPF), [6, 7] uses the traditional statement of the OPF and establishes that with the reactive power marginal prices the users make a payment just for the reactive power consumed quantity instead of the use of penalization in base of the power factor of the loads. In [8, 9] combine the classical problem of the OPF, with the installation cost of capacitors, analyzing the variation of the reactive power marginal prices in the presence of changes in the demand, the limits in the voltage magnitudes and de power factor of the loads. In [10] also combine the statement of the OPF with designing problems and the installation of capacitors in the system, defining only a structure to recover the installation cost This study determines the cost of reactive power generation, considering a fixed cost and a variable cost. The fixed cost is calculated from the annual recovery factor of capital invested in the generator. The variable cost is a dependent cost on operating conditions.

2. REACTIVE POWER GENERATION

Normally the dispatch term is oriented to the active power dispatch, however the reactive power dispatch has economic significance and it's considered an important part to the system operation. The reason for which the reactive dispatch assumes a secondary role is because of the politics about the reactive compensation. Even with the implementation of this kind of actions, there exist some actions of diverse controls or devices whose action is related directly with the problem of reactive [11]. The resources that are used to control the reactive power flows are the generators, synchronous condensers, static compensators, capacitors, reactors and autotransformers. Although it exists a division between the devices that are employed for the voltage regulation as the elements in derivation and transformers. Therefore there exists the necessity to determine the generation of reactive power cost, because this action is considered as an auxiliary service and is reward in an independent way.

3. GENERATION COST

This study aims to determine a total cost *CQ* of reactive power generation in the short term, which is the sum of all costs that are incident during a production process. Inside the total costs there are costs that must be covered although the production is equal to zero, in other words, they are independent of the production levels and are defined as fixed costs. Also there are variable costs that are dependent of a productive index. Therefore the total costs in the short term are the sum of the fixed and variable costs. The fixed costs are also named as explicit or direct and are related with the inversion, maintenance and administration costs. The variable costs identified as implicit or indirect are the costs involved around the production process, as well as the set of the necessary energetic [12].

i. **Fixed Cost (*I)*).** The principal function of the generators is to produce active power however, they also can absorb or generate reactive power, this function in an electric deregulate system is known as an auxiliary service; hence the fixed cost of the generators to provide support of reactive power is estimated from the retrieval factor of the capital. This factor is used to determine the annual retrieval of the invested capital in the generator from an established economic interest and in a period of time [13]:

$$\sigma_{gi} = I_{gi}\frac{i_{gi}\left(1+i_{gi}\right)^{n}}{\left(1+i_{gi}\right)^{n}-1} \qquad i \in ng \qquad (1)$$

where:

σ_{gi} : is the retrieval factor of the capital of the generator *i*.
I_{gi}: is the invested capital in the generator *i*.
i_{gi}: is the annual interest in the generator *i*.
n: is the useful life of the generator.
ng: generation node.

Therefore, the fixed cost for the support of reactive power is estimated with the annual retrieval of the invested capital in terms of the generated MVA and used in the power triangle to obtain the proportional part of MVAr [12, 13]. The equation is

$$Cf_{gi} = \frac{Q_{gi}\,\sigma_{gi}\,\sin\theta_{gi}}{8760\,S_{gi}} \qquad i \in ng \qquad (2)$$

where:

Cf_{gi}: is the fixed cost of the generator *i* in $[\$/\mathrm{hr}]$.
σ_{gi} : is the retrieval factor of the capital of the generator *i*.
θ_{gi}: is the power factor angle of the generator *i*.
Q_{gi} : is the reactive power of the generator *i*.
S_{gi}: is the apparent power in the generator *i*.
ng: generation node.

ii. **Variable Cost ($I)$).** The variable cost for reactive power generation is formed by operating outside its nominal conditions. Normally it is called the capacity load diagram or operating machine map. This one shows the normal operating conditions of the generator. The operating limits can be reached when it is operated in the maximum temperature allowed in any element of the generator. The temperature elevation depends on the losses in core and in the windings. The losses in the core are practically constants, wherefore the limit of temperature and in consequence the limits of capacity depend on the losses of the windings in the generator [1]. The synchronous generators are designed not only to produce active power, since through the exciting system it can modified the reactive power generated and its generation point. Because of these characteristics the synchronous machine generates reactive power from: (*a*) its nominal conditions$I)$ $[P_{g(a)}, Q_g$, (*b*) when varying the current excitation of the machine $I)$ $[P_{g(b)}, Q_g$ and (*c*) to reduce its active power generation, passing from point (*a*) to (*c*) $I)$ $[P_{g(c)}, Q_g$. These three different types of operation are shown in *figure 1*.

This one is only applied when the generator does not operate under its nominal conditions most of it is calculated in an equivalent way of the fixed cost (equation 2) however, this component of the variable proposed cost will be in terms of τ.

As you can see in fig. *2*, a τ is defined as a quadratic function dependant of the power factor angle of the generator, regardless this one operates in an overexcited or underexcited way. The τ variable is the absolute value of the quotient between the reactive power and the active power generated. The absolute value is considered because when the generator operates in the underexcited conditions the power factor angle and the reactive power generated are negative; hence to obtain the quadratic curve this consideration is realized.

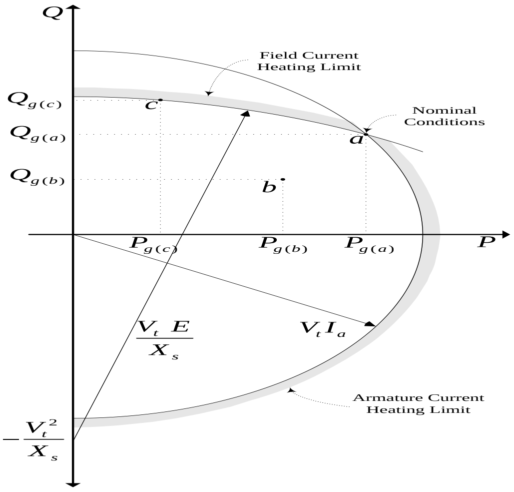

Figure 1. Capability Curve of the Synchronous Machine.

In fig. *2* it is shown that the τ variable is increased forth in agreement that the power factor angle increases. This variable tends to the infinity when $\theta \to 90^{\circ}$, taking in consideration that a minimum limit of active power generation exists $\tau \neq \infty$ and it will have a maximum value that will be established by the inferior limit of the active power generation. On the other hand, also $\tau \to 0$ when $\theta \to 0^{\circ}$ y $\tau = 0$ only when the reactive power generated is equal to zero. The component of the variable cost for operating outside its nominal conditions is proposed to be determined form the following equation

$$Cv_{gi} = \frac{Q_{gi}\,\sigma_{gi}\,\sin\theta_{gi}}{8760\,S_{gi}}\tau_{gi} \qquad i \in ng \qquad (3)$$

where:

Cv_{gi}: is the variable cost of the generator *i* in $[\$/\mathrm{hr}]$.
σ_{gi} : is the retrieval factor of the capital of the generator *i*.
θ_{gi}: is the power factor angle of the generator *i*.

Q_{gi} : is the reactive power of the generator *i*.

S_{gi}: is the apparent power in the generator *i*.
τ_{gi}: is the relation of generated powers $\left|\frac{Q_{gi}}{P_{gi}}\right|$.
ng: generation node.

Therefore this component of the variable cost is $Cv_{gi} \cong 0$ always and when the power factor is approximately equal to the nominal. To maintain the nominal conditions of operation of the generator and $Cv_{gi} = 0$, the increases of reactive power generation and the active power must be equal to τ.

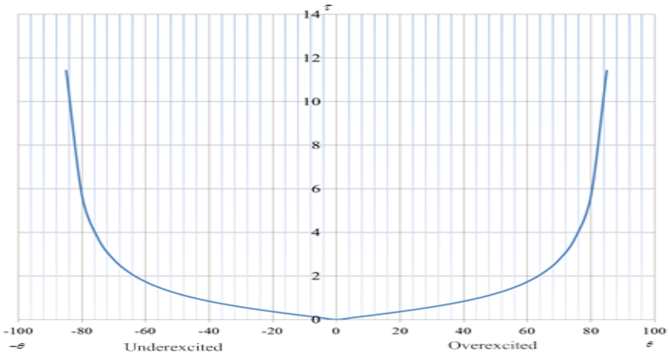

Figure 2. Relation of the Generated Powers and the Power Factor Angle.

4. RESULTS

Two cases studies are performed in the 30-node IEEE test system. Data from this system, the production cost of active power and the investment cost of each generator is detailed in the appendix. The operating conditions are determined by solving the system power flows. Table 1 presents the generated power and their respective costs. Fig. 3 shows that the *CP* active power generation costs in two machines activated is greater than the costs of *CQ* reactive power generation, however, the *CQ* in generators 3 and 4 is greater than *CP*, also in machines 5 and 6 these are almost equal.

Table 1. Generated Powers and Costs.

i	*Generation*		*Costs*			
	P_{qi} MW	Q_{qi} MVar	CP_i [$/hr]	CQ_i [$/hr]	Cf_{qi} [$/hr]	Cv_{qi} [$/hr]
1	129.10	9.59	320.71	0.726	0.532	0.194
2	33.62	23.09	78.63	26.588	16.325	10.263
3	15.00	32.55	29.07	80.340	24.986	55.354
4	10.00	31.20	33.33	80.365	19.356	61.009
5	10.00	15.32	32.50	32.756	11.986	20.770
6	12.00	17.88	39.60	42.021	16.892	25.129

Fig. 4 shows the components of *CQ*, which are the fixed cost and the variable cost for operating outside of nominal conditions, wherein five of the six generators of the system have these two components. We can also note that the four generators contributes most reactive power generation system, the variable cost represents almost half of the *CQ*. This is because the generators work away from their nominal conditions and variable t reaches important values.

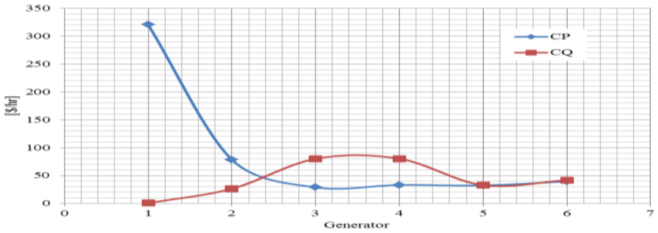

Figure 3. Operations Costs.

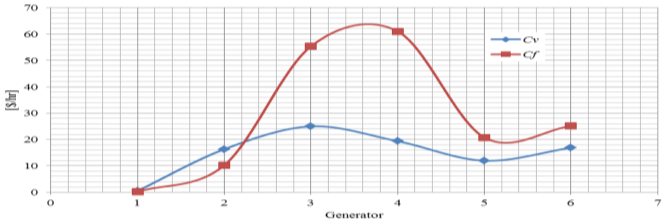

Figure 4. Relation of the Generated Powers and the Power Factor Angle.

Table 2. Reactive Power Generated, Power Factor Angle and τ factor.

i	Operation Conditions		
	Q_{gi}	θ_{gi}	τ_{gi}
1	9.59	4.251	0.0743
2	23.09	34.485	0.6869
3	32.55	65.257	2.1699
4	31.20	72.228	3.120
5	15.32	56.879	1.5328
6	17.88	56.140	1.4904

In fig. 5 and Table 2, we can see the power factor angle of the generators and the constant τ_{gi}, which show that the *CQ* generators 1 and 2 is low, because of both generators operate near theirs nominal condition. However we note that, generators 3 and 4 are contributing more reactive power in the system, and these are the ones with the largest values of the constant τ, as θ values are close to 90°.

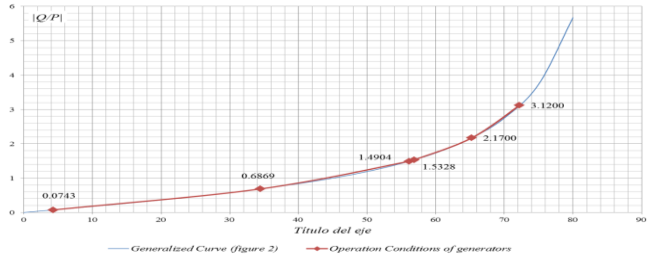

Figure 5. Relation of Generated Powers and Generalized Curve.

5. CONCLUSIONS

Considered τ to establish the *Cv* is crucial, mainly because this variable cost gets to be a key component of the cost of the service, because of the generators that reach considerable value of τ get much of the *CQ* total obtained. The operating conditions of the generators are taking into account the variable τ as well, as these can operate outside their nominal conditions still remaining within its boundaries. With the approach to determine the *CQ*, this depends on the generation of reactive power but mainly of the operating conditions of each generator.

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BIOGRAPHIES

Manuel Alejandro López-Zepeda. He received BsC and Masters in Electrical Engineering from ESIME-IPN and SEPI-ESIME-IPN, Mexico in 2002 and 2006. He's currently a Computer Science professor at ESIME-IPN. His research interests span state estimation in electric power systems, intelligent control and neuronal networks.

Yoram Astudillo-Baza. He's graduated of the Instituto Tecnológico de Acapulco of Electromechanical Engineer in 2000. Master of Science in Electrical Engineering from the Escuela Superior de Ingeniería Mecánica y Eléctrica del Instituto Politécnico Nacional (IPN). Currently a professor of mathematics at the department of Electrical Engineering of the ESIME Zacatenco del IPN. His research and interest are: Analysis and Control of Electrical Power Systems, Electrical Machines, Intelligent Control, Adaptive and Robust, Power Generation, Cogeneration.

Sergio Baruch Barragán-Gómez. He received Masters in Electrical Engineering from SEPI-ESIME- IPN, Mexico in 2004. He is currently a electric power systems professor at Department of Electrical Engineering of ESIME-IPN. His research interests: open software, analysis and optimization of electrical power systems.

APPENDIX

Table 3. IEEE 30 Bus Test System.

*Generador**	*a*	*b*	*c*	*Investment*
				$US
1	0.0	2.0	0.00375	10,150,000
2	0.0	1.75	0.01750	4,060,000
3	0.0	1.0	0.06250	2,537,000
4	0.0	3.25	0.00834	1,776,250
5	0.0	2.1	0.01750	1,522,500
6	0.0	3.0	0.02500	2,030,000

* 30 ages useful life & 10% economic interest.