

# A Novel Procurement Market Model Approach of Reactive Power in Deregulated Electricity Market

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**Abstract**— This paper discusses various issues in Reactive power Management along with its pricing in deregulated electricity market. Reactive power procurement model is proposed which ensure secure and reliable operation of deregulated electricity market. A two-level frame for the operation of a competitive market of reactive power services is considered. It is argued that the first-level, i.e., reactive power procurement, be on a seasonal basis with objective like minimization of reactive generation cost, determined by ISO while the second-level, i.e., reactive power dispatch, be close to real-time operation. This framework may be adopted for any type Competitive Electricity market including Indian restructuring electricity Market.

**Index Terms**—Reactive Procurement Model, Societal Advantage Function, Reactive Power Pricing, Reactive Power Dispatch.

## I. INTRODUCTION

Sufficient reactive power support need to be provided in the system in order to maintain the power flow limits on transmission lines and voltage limits at bus bars. Also, since it is not desirable to transport reactive power over the network, it should be procured at different locations in the system depending upon perceived demand conditions, mix of the load and availability of reactive support devices. The US –Canada Power System outage states in its report that insufficient reactive was the reason in the August 2003 blackout, and recommended to strengthen the reactive power and voltage control practices in all North American Electric Reliability Council (NERC) Regions [1].

Reactive Power management differ in each deregulated power systems of different Countries. Often the independent generators or local suppliers own the resources for reactive power such as synchronous generators, synchronous condensers, capacitor banks, reactors, static VAR compensators and FACTS devices and the ISO needs to enter into contracts with them for such provision. The reactive power management and payment mechanisms as an Ancillary Services vary for each deregulated electricity market of various Countries in the way the contracts are framed and the markets are operated [2].

An integrated framework considering the issues of reactive power planning along with reactive power pricing is analysed. The Reactive planning criteria is of optimal placement and sizing of capacitors at load centres

in a network so that operating and investment costs are minimum. A two part reactive power spot pricing scheme is formulated in which one is fixed part to account for investment costs of new capacitor at a bus and another is variable spot price to account for the operating costs incurred in supplying the additional reactive power from generating units [3].

Cost based reactive power dispatch is determined which minimizes the total cost of reactive power support which includes the explicit and opportunity cost from various generation sources, such as generators and the explicit cost from various transmission sources, such as reactive compensators, tap-changing transformers and the cost of transmission losses [4].

The overall production cost of Active and reactive power is minimised which included Active power production cost of generators, reactive power production cost of generators and capital cost of capacitors. The cost of network management and system maintenance are assumed constant and not included in the objective function of the paper [5].

The pattern of optimal load dispatch is taken as bi-level problem consisting of an upper and lower part, the upper level problem is that of satisfying the demand functions where the prices are determined by the lower level problem which is basically the optimal power flow problem which has the objective of minimizing the total cost of operating the spatially separated generating units subject to the set of equations that characterize the flow of power throughout the system and all operational constraints [6].

A cost based Novel pricing modified OPF scheme is formulated for reactive power with assumption that the total reactive power can be divided into two parts, one is for real power transportation when there are no reactive loads in the system and other part is for reactive power consumption which is deemed as the responsibility of reactive loads [7].

## II. REACTIVE POWER MANAGEMENT IN VARIOUS COMPETITIVE ELECTRICITY MARKETS

Reactive power management and payment mechanisms differ from one electricity market to another, and no uniform structure or design has yet evolved. In most cases, the ISO enters into contracts with the reactive power providers for procurement of their services. These contracts are usually bilateral agreements based on ISO

experience and traditional practices used for reactive power support, rather than through well formulated competition mechanisms.

In North America, according to NERC's Operating Policy 10[8], only synchronous generators are compensated for reactive power provision. The New York ISO (NYISO) follows an embedded cost based pricing to compensate generators for their reactive power services, and also imposes a penalty for failing to provide reactive power [9]. Generators are also compensated for their lost opportunity costs if they are required to produce reactive power by backing down their real power output. Such opportunity cost payments also exist in the PJM Interconnection[10] and California ISO (CaISO). Provision of reactive power services in the California system is based on long-term contracts between CaISO and reliable must-run generators; generators are mandated to provide reactive power within a power factor range 0.9 lagging to 0.95 leading. Beyond these limits, the generators are paid for their reactive power including a loss opportunity cost payment.

The Independent Electric System Operator (IESO) in Ontario, Canada, requires generators to operate within a power factor range of 0.9 lag to 0.95 lead and within a +/- 5% range of its rated terminal voltage. The IESO signs contracts with generators for reactive power support and voltage control, and generators are paid for the incremental cost of energy loss in the windings due to the increased reactive power generation. The generators are also paid if they are required to generate reactive power levels that affect their real power dispatch, receiving an opportunity cost payment at the market clearing price for energy for the power not generated [11],[13].

The Transmission System Operator (TSO)-National Grid Company (NGC) of UK invites half-yearly tenders for "obligatory reactive power services" which correspond to the reactive power each generator is required to provide, and "enhanced reactive power services" for generators with excess reactive power capabilities [12].

1.NGC maintains the voltage of super grid system ,to meet Transmission License Requirements for secure and stable power transmission and to ensure quality of Power to customers .

2.Generating Units provide reactive power and have the ability to vary their reactive power output, as per requirement of Grid code.

3.Dynamic reserves of reactive power are essential for system operation. NGC considers reactive capability as it gives rise to increased confidence in the availability of post fault service.

4.NGC which carries out the functions of the ISO invites tenders for reactive support services. The generators can bid for reactive power support through bids composed of capacity components (price per MVar and quantity on offer) and an utilization component (MVar-h price curve).

Among other international practices, in Australia, synchronous condensers also receive payments for providing reactive power apart from generators [14].

The Payment Mechanism as follows.

- Availability Payments: All reactive support providers are eligible for the *availability payment component* for their preparedness to provide the service when called for.
- Enabling Payment: Synchronous compensators also receive the *enabling payment component*- paid when their service is activated by the ISO for use.
- Usage Payment: Based on actual use. Such as rapid loading and unloading services of generators.
- Compensation Payment: On the other hand a generator receives the *compensation payment component*- which is based on its opportunity cost.

On the other hand, Sweden follows a policy wherein reactive power is supplied by generators on a mandatory basis and without any financial compensation.

As per Indian Electricity Grid Code, reactive power compensation and or other Facilities, should be provided by SEBs/ STUs and distribution Licensees as far as possible in the Low Voltage systems close to the load points.

Procurement of reactive power services through long-term contracts between the ISO and service providers (generators) is an alternate way for reactive power management in deregulated electricity markets[15]-[18].

From the brief review of management of reactive power in various deregulated electricity markets of different countries, it is clear that there are no universally accepted reactive power management practices .In some country reactive power pricing is based on fixed contractual payments and in some other countries based on gross system (embedded cost) usage.

In this paper, the main objective is to present streamline reactive power management in deregulated electricity markets.

### III.PROPOSED REACTIVE POWER PROCUREMENT MODEL

The synchronous generator's MVA rating is the point of intersection of the two curves formed with armature and field winding heating limits as shown in figure1.

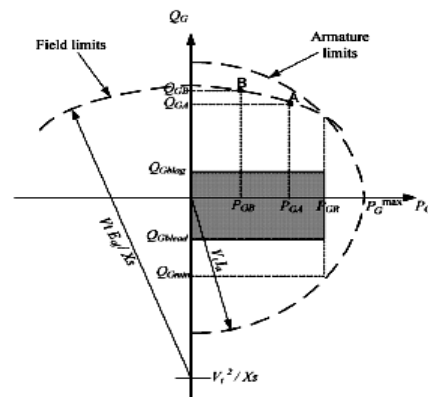


Figure 1. Determination of Reactive Power limits from Generators

For an operating point A where real power output  $P_{GA}$  such that  $P_{GA} < P_{GR}$  the limit on  $Q_G$  is imposed by the generator's field heating limit; whereas, when  $P_{GA} > P_{GR}$ , the limit on  $Q_G$  is imposed by the generator's armature heating limit. The armature heating limit is a circle centered on the origin and given by,

$$P^2 + Q^2 \leq (\sqrt{V_t I_a})^2 \tag{1}$$

The field heating limit is also a circle centered at  $(0, V_t^2 / X_s)$  and given by (2) (shown in fig1.)

$$P^2 + \left( Q + \frac{V_t^2}{X_s} \right)^2 \leq \left( \frac{\sqrt{V_t E_{af}}}{X_s} \right)^2 \tag{2}$$

$V_t$  is the voltage at the generator terminal bus,  $I_a$  is the steady state armature current,  $E_{af}$  is the excitation voltage and  $X_s$  is the synchronous reactance.  $P$  and  $Q$  are real and reactive power generation from the machine, respectively.

The shaded area of figure 1 represents the obligatory base reactive power provision range set by the system operator. Any reactive power provision required by the operator beyond this area is eligible for payment due to the increased cost of losses in its windings.

Reactive power provisions can be considered as two classes of problems in the context of deregulated electricity markets, namely,

- A. Reactive power procurement
- B. Reactive power dispatch.

Reactive power procurement is basically a long-term issue, i.e., a seasonal problem; in this case, the ISO obtains optimal reactive power "allocations" from possible suppliers that would be best suited to its needs and constraints in a given season. This optimal set would be determined based on forecasts of the demand and system conditions expected over the planning horizon. The criterion for such procurement could be varied, but would essentially take into consideration the cost/price offers of reactive power provision.

Based on reactive power procurement versus its real time dispatch, a reactive power management scheme is proposed that comprises two major time-based steps (shown in figure2).

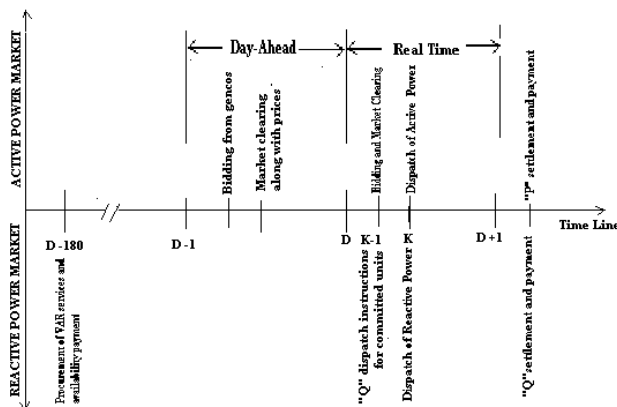


Figure 2. Active and Reactive market clearing and dispatch at day D hour k.

Figure.2 describes how active and reactive power markets could be decoupled from each other, keeping these two markets in entirely different operating time frames, so that the ISO does not entertain reactive power management in the same time frame as that of real power auctions. This basically minimizes the risk that might arise from price volatility of real power, and thus help reduce market inefficiencies.

The decoupling of active and reactive power implies that the OPF problem can be separated into two parts: an active power sub-problem that provides the active power dispatches and prices in real-time based on a cost minimization (social welfare maximization) market settlement model; and a reactive power sub-problem, operating on different time frames, that provides reactive power levels and prices based on a taken optimization criterion.

A. Reactive Power Procurement

The ISO in long term procurement, first calls for reactive power offer from the reactive power providers, and on the basis of the received bids, it solves an optimization model that maximizes a social welfare function subject to system constraints. The solution of this optimization model yields the required reactive power service "reserves" for each generator, as well as the price components of reactive power. The selected providers would have a long-term obligation for reactive power provision receiving an availability payment for these reserves. The schematic representation of the long-term reactive power management mechanism is depicted in Figure 3.

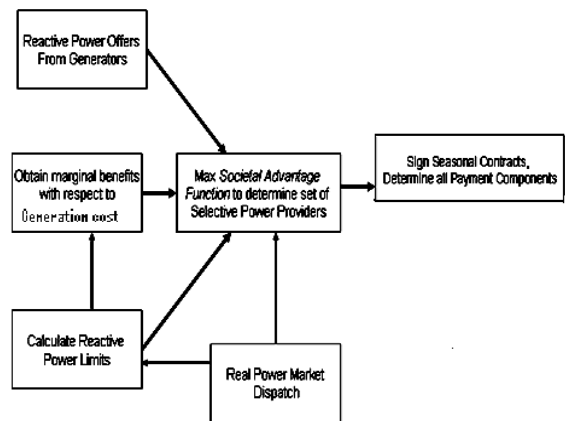


Figure 3. Long term Management for Reactive Power Services

1) Reactive Power Limits of Generator

When real power and terminal voltage are fixed, the armature and field winding heating limits determine the reactive power capability of a generator.

Regions for reactive power generation (shown in fig4.)

Region-1:  $(Q_{Gmin} \leq Q_G = Q_{G1} \leq 0)$

Mandatory leading reactive power is from 0 to  $Q_{Gblead}$ .

Any reactive power support beyond  $Q_{Gblead}$  is recognized as an ancillary service eligible for an under excitation payment component.

Region-2:  $(0 \leq Q_G = Q_{G2} \leq Q_{GA})$

Mandatory lagging reactive power is from 0 to  $Q_{Gblag}$ .

Any reactive power support beyond  $Q_{Gblag}$  is recognized as an ancillary service eligible for a payment for the increased losses in the winding (Cost of loss component).

Region-3:  $(Q_{GA} \leq Q_G = Q_{G3} \leq Q_{GB})$

Any reactive power support beyond  $Q_{GA}$  will require decreasing in active power generation eligible for a loss of opportunity cost payment.

2)-Marginal Benefits of Reactive Power Supply with respect to Generation Cost

Based on this optimization of reactive power which gives Lagrange multipliers that represent the marginal benefit /contribution of each reactive source, SAF is maximized. The classical concept of social welfare from economic theory is extended to formulate a reactive power SAF (Societal Advantage Function) which is basically determination of aggregate system benefits accrued from reactive power services minus the expected payment by the ISO.

3) The Reactive Power Offers from Generators:

The reactive power offers are shown in figure 4.

- Availability price offer ( $m_0$ , \$): A fixed component to account for that portion of a supplier's capital cost that can be attributed to reactive power production.
- Cost of loss offer ( $m_1, m_2$ , \$/Mvar): An assumed linearly varying component to account for the increased winding losses as reactive power output increases, in the under- and over- excitation ranges, respectively.
- Opportunity offer ( $m_3$ , \$/Mvar/Mvar): A quadratic component to account for the lost opportunity cost when a supplier is constrained from producing its scheduled real power in order to increase its reactive power production.

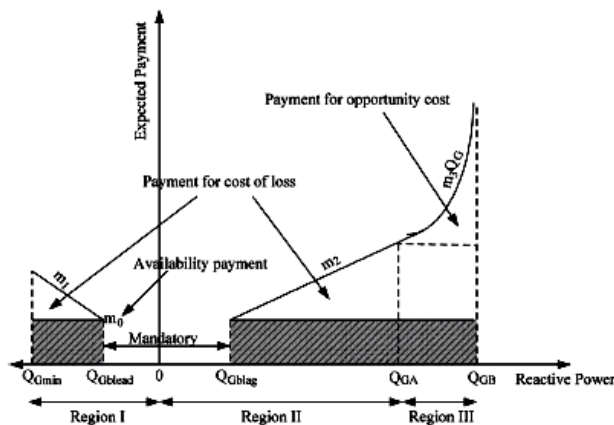


Figure 4. Reactive Power Offers from Generators

4) Societal Advantage Function Maximization

Once the reactive power ancillary service limits and the marginal benefits of each provider with respect to system security are determined, and reactive power offers are received, the ISO is in a position to carry out a procurement market settlement where its sole objective is to maximize a societal advantage function. The proposed SAF is formulated on a zonal basis and can be expressed as follows:

$$SAF_K = - \sum_{g \in K} \rho_{ok} - \sum_{g \in K} (C_L \mu_g - \rho_{1k})(Q_{G1g} - Q_{Gblead_g}) + \sum_{g \in K} (C_L \lambda_g - \rho_{2k})(Q_{G2g} - Q_{Gblag_g}) + \sum_{g \in K} ((C_L \gamma_g - \rho_{2k})(Q_{G3g} - Q_{Gblag_g}) - 0.5 \rho_{3k} (Q_{G3g} - Q_{GA_g})^2). \quad (3)$$

In (3), the subscript g denotes a generator in the system, while K refers to the set of generators in zone k, considering that the system is divided into voltage control zones.

The variables  $\rho_{1k}$  (in \$/Mvar) and  $\rho_{2k}$  (in \$/Mvar) are the under- and over-excitation prices for reactive power in zone k, respectively; similarly  $\rho_{3k}$  (in \$/Mvar/Mvar) is the zonal uniform opportunity price component. The variable  $\rho_{ok}$  (in \$) is the zonal availability price component. The constant  $C_L$  is a "loadability" cost parameter (in \$/MWh) denoting the economic worth of increasing the system loadability.  $\lambda, \gamma$  and  $\mu$  are the Lagrange multipliers obtained from optimization model of marginal benefits of reactive power supply with respect to generation cost.  $Q_{Gblag}$ ,  $Q_{Gblead}$  are the mandatory lagging and leading reactive power provided by generator.  $Q_{G1g}$ ,  $Q_{G2g}$  and  $Q_{G3g}$  are regions of reactive power as shown in fig4.

B. Reactive Power Dispatch

The second level in the proposed hierarchical approach to reactive power management is the short-term management function, which takes place one to half hour ahead of real-time. The real-time dispatch of reactive power only takes into account the current operating conditions, with the ISO arriving at the optimal dispatch via an OPF (shown in figure 5).

The cumulative payment to supplier is calculated post real time operation, based on actual usage and dispatch requested by the ISO aggregated over a period of time.

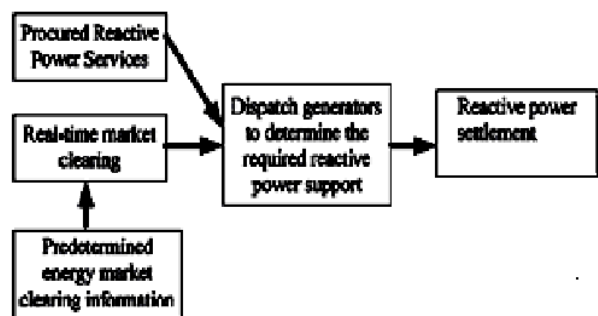


Figure 5. Reactive power dispatch (short term management)

C. Comparison of Zonal Reactive Power Pricing with Uniform Reactive Power Pricing

It is advantageous to use Zonal pricing in place of Uniform pricing as it is found that zonal pricing mechanism not only reduces the risk of power market ,but it also reduces the payment burden on ISO. In uniform price market where are selected participants are paid uniform price, which is the price of the highest accepted offer. The issues of market power associated with the limited number of providers in reactive power markets, it would be more pertinent to disaggregate the uniform price of reactive power into zonal components. Zonal price mechanism for reactive power markets would reduce the impact of market power exercised by certain gaming generators and should hence restrict them only to their Zones.

#### D. Other Sources of Reactive Power Supply

If other sources like capacitor banks, SVCs, Statcom can be considered into Reactive Power Procurement Model then a more liberal reactive power ancillary service provision structure will be ready as there would be more competition due to increased number of providers which leading to a reduction in reactive power prices and improved system reliability.

#### IV. CONCLUSION

Based on the current practices for reactive power provision by various ISOs in competitive electricity markets, this paper has proposed a streamline reactive power market structure. The proposed market design consists two stages, namely, procurement of reactive power resources on a seasonal basis, and a real-time reactive power dispatch. The proposed procurement market model, which is the main focus of this paper, is based on at first level with two-step optimization process; the first step consists of the determination of the marginal benefits of reactive power with respect to generation cost, which are then used in the second step to maximize a reactive power societal advantage function (SAF) considering bids from service providers. In the second level, reactive power dispatch which is basically short term management is considered based on first result.

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