Implementation of Reactive Power Markets to Enhance the Power System Network

Madhuvanthani Rajendran* and L. Ashok Kumar

Abstract — **Reactive power is an important component which plays a critical role in maintaining grid reliability, especially voltage stability. The report presents an analysis of the current compensation strategies followed by different independent system operators (ISOs) in US and identifies the drawbacks in the present compensation schemes. The properties of reactive power which poses an impediment to setup a reactive power market has been compared with the need of a reactive power market. Finally, a possible spot market structure has been considered along with bid formulation and its different components as applicable to different reactive power producing equipment.**

Index Terms—**ACOPF, Herfindahl-Hirschman Index, sensitivity matrix, expected payment function, lost opportunity cost.**

I. Introduction

Reactive power is a very important component of the electric power system. Some of the reasons why reactive power is needed in the system are discussed below. Reactive power is very essential for reliably operating the electric transmission system. For reliable operation of the electric power system, a good voltage profile needs to be maintained during both emergency and normal operating conditions. Reactive power support becomes very essential for this purpose. When the voltage in a system goes below its nominal value, the current increases in order to maintain the power supplied to the load. The decrease in system voltage may cause overheating of generators and motors. Reactive power support also improves real power transfer capability, when power transfer is constrained due to low bus voltages. Injection of reactive power into the system at certain locations can alleviate transmission bottlenecks and allow cheaper real power to be transferred to the loads. Inadequate reactive power in the system can lead to voltage collapse. When voltage in the system reduces, further reactive power is absorbed into the system leading to further reduction in the system voltage.

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A cascading effect occurs leading to voltage collapse, if reactive power is not injected into the system to mitigate the effect of the low voltage levels.

Reactive power being very important for the reliable operation of the electric transmission system, has to be procured and priced adequately and efficiently. The independent system operators (ISO) in the United States are responsible for reliable operation of the electric transmission system. Reactive power due to its unique features, becomes very difficult to price. Reactive power cannot travel long distances due to significant losses on the wires. Thus reactive power has to be purchased locally when needed leading to market power issues. Reactive power can be obtained from various sources like generators, synchronous condensers, static var compensators (SVCs), capacitors and static compensators [1]. There are different compensation strategies and pricing policies that exist today for reactive power procurement. The regulatory policies need to be sound to ensure efficient procurement of reactive power from the cheapest sources available in order to maximize economic benefits.

Procurement and pricing of reactive power should be designed in a way that encourages investment in the infrastructure needed to provide reactive power and in turn maintain reliability in the system. Also, incentives should be provided for efficient production and consumption of reactive power form the existing infrastructure. A reactive power market structure promotes the above mentioned goals and also provides the operator with real time control over the resources. Currently there are no market structures that exist for reactive power procurement like the spot markets that exist today for real power. The real power markets are solved using a direct current optimal power flow (DCOPF), which works on various assumptions made in order to make it a linearized version of the actual AC model. This ignores various constraints like the reactive power balance constraint and thus the DCOPF model does not always hold true due to the non-convexities that are present in the market [2]. Thus in order to solve a reactive power market it becomes necessary to run an alternating current optimal power flow (ACOPF) which is complex and thus lies as a challenge in incorporating a reactive power market.

In this paper the various aspects of why reactive power markets are needed is discussed along with the current compensation strategies that are followed by the various ISOs. Different market structures are also being analyzed and proposed. This paper also deals with the issues related to reactive power markets like market power and price volatility. The computational complexities of solving an ACOPF is also elaborated.

II. Need For Reactive Power Markets

This section provides various reasons as to why a reactive power market is needed. A critical analysis of the current compensation strategies and pricing policies is done. At present there are no consistent compensation and pricing policies that are followed by the ISOs throughout the United States. Currently the different ISOs have different compensation strategies and pricing policies for reactive power. Some of the compensation strategies have been discussed below. PJM compensates all generators with a payment equal to the generation owner's monthly revenue requirement and also provides lost opportunity costs when there is a reduction in real power output [3]. MISO compensates transmission owned generators with rates that are localized and does not provide lost opportunity costs [4]. NYISO provides compensation for all generators that provide reactive power but have different compensation strategies for generators owned by utilities and nonutility generators. NYISO also provides for lost opportunity costs but penalizes the generators for failing to produce reactive power. ISO-NE compensates selected reactive power resources based on capacity cost, lost opportunity cost, cost of energy consumed, and cost of energy produced [5]. Lack of consistent policies make it difficult for central organizations like the Federal Electric Regulatory Commission (FERC) to implement regulatory standards. A market for reactive power may answer these problems efficiently.

Reactive power sources can be classified as static and dynamic sources. Static sources like capacitors and inductors have no active control of the reactive power output in response to the system voltage. These sources provide blocks of reactive power. Dynamic sources like synchronous generators, synchronous condensers, static compensators, Static Var Compensators (SVCs) and static compensators are capable of changing the output in response to the changing system voltages [6]. According to North American Electric Reliability Council (NERC) interconnected operations service policy-10: Only reactive power from a synchronous generator is considered an ancillary service. What about reactive power that comes from synchronous condensers, SVCs, STATCOMs and capacitors? What about their incentives? A reactive power market can be a solution to such problems. The reactive power produced by dynamic sources is more reliable than the reactive power produced by static sources. This gives rise to an issue of whether owners of both static and dynamic sources should be given the same compensation. However in a market, when reactive power is bought and sold in real time, the price of reactive power faced by all the providers will be the same at any given location and time, irrespective of the source. Thus a market structure also gives rise to a transparent and non-discriminatory pricing structure.

The current compensation strategies provide no incentives for providers to invest in the infrastructure needed to provide reactive power. In order to produce reactive power, real power output has to be reduced accordingly. This in turn leads to a decrease in profit and therefore generating units are reluctant to provide reactive power. A market structure provides efficient procurement of reactive power from the cheapest available sources and also provides incentives for generating units to provide reactive power when needed. It also provides a platform for healthy competition enabling the identification of the most competent resources thereby increasing the efficiency of the overall system and also providing efficient discovery of reactive power capability. In a market structure the ISOs have real time control over all the available sources of reactive power and this in turn decreases the losses by effective pricing and control of reactive power. So far in this paper the importance of reactive power and the need for reactive power markets have been discussed. In the forthcoming sections, various market structure designs, pricing of reactive power, issues with reactive power markets and computational complexities will be dealt with in detail.

III. Issue With Market Power

In a uniform pricing model for reactive power, generator and other equipment providing reactive power are required to submit bids to the independent system operators. These bids usually consists of several components such as the availability, loss and lost opportunity cost component (as mentioned in section). The availability component is the cost that accounts for the willingness of the unit to provide reactive power. The loss component represents the power loss due to heating losses in the field and armature winding and is usually determined from the generator's capability curve. The lost opportunity cost component represents the opportunity cost that is lost in terms of real power output when the generator produces reactive power output by restraining its real power production at the request of the independent system operator. The lost opportunity cost is typically determined from the generator's capability curve.

Uniform pricing model is expected to work fairly well under steady state conditions with capacitors supplying the major part of the base reactive power demand. However, under certain load conditions and contingencies there is a short-term need for reactive power from large generator units. As reactive power does not travel well; during contingencies many generators which provide reactive power support have distinct advantages over other reactive power providing units due to their strategic location. It is very likely that under such a scenario these units might alter the prices away from competitive levels to make profit, thus exercising market power and creating a situation where transparent and competitive market operation is hindered. It is thus imperative to identify the generators with formidable market power.

A common index to quantify market power is the Herfindahl-Hirschman Index (*HHI*). The HHI is the sum of the squares of the market share of all the market participants and is expressed as follows:

$$HHI = \sum_{i=1}^{i=N} s^2$$

where's' represents the market share of each participant and 'N' represents the number of participants in a particular area. A higher value of HHI indicates greater market power in that particular area.

As discussed above, there are times when an equipment close to a location is in a much better position to supply reactive power than a cheaper supplier elsewhere owing to the locational nature of reactive power. Thus using the HHI index as an identifier of market power, an attempt is made to identify generators that are likely to exhibit market power in a standard test system. The test system chosen for this study is a modified IEEE 300 bus system with specifications as in Table I.

TABLE I. SPECIFICATIONS OF THE IEEE MODIFIED TEST SYSTEM

Number of Generators	34
Number of transmission lines	304
Number of loads	195

An estimate of the individual generator's market concentration can be obtained from the product of the sensitivity matrix ($\partial V_a/\partial Q_b$) and the reactive power producing capacity of the generator.

Degree of market concentration =

$$((\partial V_a/\partial Q_b) \times \text{reactive producing capacity})$$

The sensitivity matrix gives an estimate of the voltage change at a particular bus that results due to unit change in reactive power production. The matrix required for the study is obtained by calculating the Jacobian matrix (J) and inverting the sub-matrix ($\partial Q/\partial V$) to obtain the sensitivity matrix ($\partial V_a/\partial Q_b$).

The modified IEEE 300 bus system is divided into four zones based on geographical locations and the issue of market power is investigated for each of the zones by selecting a particular bus in that zone. The sensitivity matrix ($\partial V_a/\partial Q_b$) was analyzed by observing the voltage deviation at a selected bus due to incremental change in reactive power at each generator bus in that zone. The simulation for this study has been done in PowerWorld Simulator and the results obtained are tabulated in Table II.

IV. TABLE II. MARKET SHARE AND MARKET POWER IDENTIFICATION

Zone 1, bus selected for study is Bus 52		Zone 2, bus selected for study is Bus 115	
Gen. bus #	Market concentration	Gen. bus #	Market concentration
7055	0.5525	177	0.4585
7023	0.8436	146	0.0658
7062	5.76	185	0.975
84	15.696	176	0.03915
7002	16.32	143	1.04
7049	System slack	171	5.18
7024	9.1392	124	1.8
7012	4.704	170	1.185
98	1.7802	171	5.18
7057	2.538	HHI index = 0.238	
7003	63		
HHI index = 0.3198			
Zone 3, bus selected for study is Bus 217		Zone 4, bus selected for study is Bus 9121	
Gen. bus #	Market concentration	Gen. bus #	Market concentration
198	0.6864	9055	0.0256
191	4.52	9054	0.7232
190	1.38	9053	0.109
243	0.002	9051	0.1509
242	0.1452	9002	0.039
241	0.0882	HHI index = 0.51	
239	0.002		
236	0.0128		
233	0.1734		
220	0.1588		
213	0.0217		
HHI index = 0.4436			

The market concentration in Table II is calculated by taking the product of the sensitivity factor of a generator and the reactive power producing capacity for the generator. For example, the sensitivity factor of the generator connected to bus 7055 as seen from bus 52 is 0.0221 while the reactive power producing capacity of the generator is 25MVAr. Thus the market concentration turns out to be 0.5525. The sum of all the generators' market concentration divided by each generator's market concentration gives the market share of the generator. These market shares are squared and added for each zone to obtain the HHI for each of the four zones. It can be seen that zone 4 has the highest HHI whereas zone 2 has the lowest HHI. This gives an approximate estimate that zone 4 has the highest market power in all of the zones under study. Also it can be seen that generator at bus 7003 in zone 1 has high market concentration and dominates the market in that zone. Thus for proper operation of a uniform price reactive power market, generators that have formidable market power, need to be identified and market power mitigation strategies must be implemented through energy market policies.

It may be noted that in the following study, the zones are classified based on their geographical location. Subsequently, a better approach to classify the zones in a reactive power market is to segregate them based on the concept of voltage control areas. The characteristic of a voltage control area is that the voltage profile of all buses in the area depends on the reactive power sources in that area and are very less influenced by reactive power sources in other control areas.

V. PRICE VOLATILITY IN REACTIVE POWER PRICING

Reactive power support, as was described in the earlier sections of the paper, has two sources – static and dynamic. While static support is cheaper to obtain and dynamic sources are expensive, a contingency situation might demand dynamic reactive power support. This situation results in a sudden spike in the price of reactive power, which leads to price volatility. Price volatility is one of the major challenges behind having reactive power markets. Some argue that price volatility is not necessarily a bad thing, since it reflects the true cost of the commodity. This may be true, however, the uncertainty and the difference in prices in reactive power markets is a whole level different. For a loss of 1 MVAr static reactive power support, 1 MVAr of dynamic reactive power had to be injected into the system, due to which there was a price spike of over 3000 %. To hedge risk against this price volatility, spot markets with forward contracts have been proposed in the later sections of this paper.

VI. SPOT MARKETS FOR REACTIVE POWER

The present reactive power compensation rules do not provide the right signals and do not incentivize the operators to dispatch the system in a cost efficient manner. Thus leading to unwarranted high prices for acquiring reactive power to maintain system security. To balance real-time supply and demand of reactive power in the system and to account for unexpected changes in the demand a spot market is necessary [7].

Presently, all generators are paid an administratively determined price for reactive power capability on an annual basis and these units are then dispatched by the regulator in real-time based on the demand for reactive power. Spot prices for reactive power are highly volatile as they are close to zero most times and are very high during contingencies. These prices represent the true operating cost of the system but also result in increased investment risks in reactive power markets. To hedge themselves against this price volatility, some consumers and suppliers chose to enter into forward contracts. However, having only a forward market may create reliability concerns as a situation may arise where the contracted generator is unable to provide reactive power support in real-time. The supplier could then use the spot market to trade its supply at the marginal cost thus satisfying the demand and ensuring reliability [8].

Spot markets facilitate transparency in pricing by allowing non-discriminatory access to all sources of reactive power (generators, loads, controllable transmission devices) to participate in the market. Thus the operator has incentives to choose from the cheaper source of reactive power. Additionally, it provides transparent system planning standards and ensures consistent policies associated with reactive power.

The voltage levels needed to maintain reliability are specified by the system operator rather than the reactive power limits. Generators are supposed to oblige by these limits until they are operating in their specified power factor range. Thus, a combination of forward contracts; where the generators receive an advance payment for the capacity they are contracted to provide or consume in real-time within the power factor range and spot markets where generators might receive spot prices for consuming or producing above the power factor range is feasible [9].

VII. Localized Spot Markets

Total reactive power losses are much higher than the reactive power loads and about ten times the active power losses owing to the inductive nature of the lines. Thus it can be inferred that reactive power does not travel well and should be provided locally. Localized reactive power markets with different prices for reactive power in different areas are proposed and justified. Location based Reactive Power markets reduce the burden and increase the efficiency with which reactive power service is managed. In addition, by having varied prices of reactive power based on reactive power requirement in distinct zones provides the right signals for efficiently dispatching and using generators and existing sources. This leads to economic efficiency in localized reactive power markets [10].

The zones are divided based on electrical distance into non-overlapping areas. Each of these areas independently control their voltages and changes in the control of voltage in one area does not affect the voltage in other areas significantly [11]. Reactive power bids are submitted by all participants of each zone to the ISO in the form of four components, the system operator then runs auctions to determine optimal reactive and real power at a location and the market is cleared based on uniform locational-based prices [12].

VIII. Spot Markets with Forward Contracts

Spot markets for reactive power markets have potential challenges associated with them such as market power and price uncertainties, which involves risk. Therefore, to hedge these risks, spot markets with forward contracts have been proposed [13]. Like the name suggests, these markets are essentially a combination of spot markets and forward contracts. Forward contracts allows markets participants to hedge risk since it gives them an opportunity to trade in advance; spot markets can be used for real-time trading of reactive power depending on the requirement, as was mentioned in the earlier section.

IX. Reactive Power Bid Structure

Generators and other sources of reactive power submit their offers as “bids” to the ISO in a market environment. Hence, designing a reactive power bid structure becomes important. The following section deals with the possible bid structure design. Many papers in the literature have dealt with bid structure for synchronous generators [14]. Using these papers as a reference, the following bid structure has been developed. The “bid” has three major components associated with it: availability component, cost of loss component and lost opportunity cost component. Availability component is the readiness of the reactive power providers to supply reactive power support; it represents the capital costs associated with proving reactive power. Cost of loss component is the amount of real power lost in the field windings of a generator or a synchronous condenser for absorbing reactive power. Lost opportunity cost is the loss in revenue of a generator due to reduced production of real power to generate additional reactive power. Note that not all components are applicable to all the reactive power sources. Reactive power providers are expected to submit their bids from the components which are applicable to them. For e.g., capacitors will only have availability component; therefore their bids would only reflect the availability component.

To further illustrate these components more effectively, consider Fig. 1 showing the capability curve of a synchronous generator. Horizontal axis represents real power (P) and vertical axis represents reactive power (Q). P_{max} and Q_c respectively are the maximum real and reactive powers that the generator can produce.

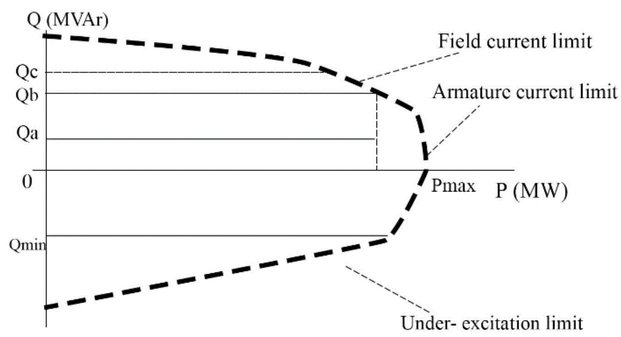

Fig 1. Generator capability curve

The explanation regarding the above-mentioned bid components using this curve can be made simpler by dividing the capability curve into four regions [15]. The first region is 0 to Q_a. In this region, the amount of reactive power produced Q_a is consumed by the generator itself for its own functioning. Hence, the generator would not be compensated in this region. The second region is Q_a to Q_b. Here, the generator would be paid a “cost of loss” component since the increase in the reactive power supply results in losses in the field windings. The third region is 0 to Q_{min}. Similar to the second region, absorbing reactive power would cause losses in the generator field windings; hence it would be compensated with “cost of loss” component. The fourth region is Q_b to Q_c. For generating reactive power, the generator would actually have to reduce its real power production in this region to stay within the MVA limits. Therefore, the generator would be compensated with a “lost opportunity cost”, which accounts for the real power production it had to reduce for generating reactive power. A figurative representation of “cost of loss” component and “lost opportunity cost” component is given in Fig 2.

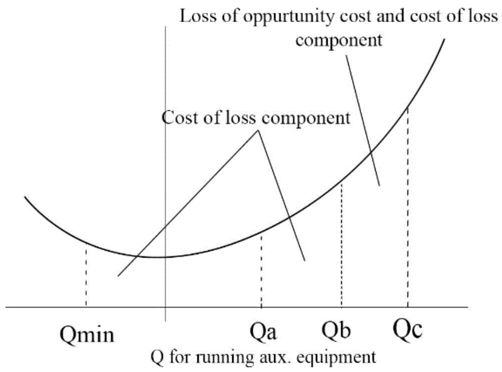

Fig. 2. “Bid” components of synchronous generator.

A mathematical representation of these components, called an Expected Payment Function (EPF) had been derived in the paper [16]. EPF is the sum of all the three bid components and is calculated as given below.

$$EPF_i = a_{o,i} + \int_{Q_{\min}}^{0} m_{1i}\, dQ_i + \int_{Q_a}^{Q_b} m_{2i}\, dQ_i + \int_{Q_b}^{Q_c} (m_{3i} Q_i)\, dQ_i$$

The coefficients in the above given equation no. represent the bid components for each of the regions described earlier.
‘i’ represents any generator ‘i’
‘a_o’ represents availability component of the bid.
‘m_{1i}’ represents cost of loss component for third region
‘m_{2i}’ represents cost of loss component for second region
‘m_{3i}’ represents lost opportunity cost component for fourth region
EPF would be used by reactive power providers to submit their bids in the market. Like mentioned earlier, their bid would reflect the appropriate component or components of EPF.

X. Computational Complexity of the AC Optimal Power Flow

The DC optimal power flow (DCOPF) is a linearized version of the AC optimal power flow (ACOPF) problem in which a flat voltage profile is assumed. Unit commitment decisions using DCOPF is a mixed integer linear programming problem and is used by the independent system operators in US to run electric markets. However, to model the reactive power market it is required to solve an actual ACOPF which is a non-convex non-linear program and is a computational burden. For a proper functioning reactive power market, computationally robust algorithms need to be developed for handling large scale ACOPF problems.

XI. Conclusion

This paper identifies the necessity of reactive power to maintain voltage stability and reliability in an electric grid. The advantages of having a reactive power market has been looked into and it may be identified that a market environment will provide better price discovery and value discovery of the commodity and help to efficiently procure the resource. Additional advantages of having a market environment are improved efficiency in operations and cost. In view of various stakeholders-a market environment provides better incentives for investment and provides incentives for the grid operators to dispatch the system in the most efficient way. On the other hand, issues with a reactive power market environment such as price volatility, computational complexity in solving an ACOPF and market power have been looked at. The paper also presents a discussion on the spot market structure that could be implemented along with a spot market structure with forward contract. Finally, the bid structure and its components for different reactive power providers have been identified and discussed. It may be concluded that future research is required to come up with strong market power mitigation policies and robust computational algorithms to solve large scale ACOPF problems.

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