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Reactive Power Market Clearing based on Pay-as-Bid Method with System Security

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Abstract

This paper presents a marketing mechanism based on the Pay-As-Bid (PAB) method for reactive power ancillary services in the deregulated electricity market. Security, reliability and the location is major concern for Independent System Operator (ISO). So a modified Optimal Power Flow (OPF) optimization method is proposed in this paper to provide the system security. Firstly, the reactive power solution is obtained by solving a modified OPF model which maximizes system loadability subject to transmission security constraints imposed by thermal limits, voltage limits and stability limits. This modified OPF model is used for ensuring systemsecurity as well as for contingency analysis. Secondly, the Expected Payment Function (EPF) of generators is used to develop a bidding framework while Total Payment Function (TPF) based OPF is used to clear the PAB market. For the simulation and analysis purposes, a 24 bus RTS network is used in normal condition as well as in worst contingency state. The system security is preserved even in the worst contingency state.

Index Terms: Pay-as-bid, reactive power procurement, ancillary services, optimal power flow, OPF, expected payment function, contingency analysis, reliability test system, GAMS, general algebraic modeling system

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1. Introduction

Voltage control is important for proper functioning of electrical power equipment in a power system to prevent damage, to minimize transmission losses and to prevent voltage collapse. A voltage collapse may occur when the system tries to serve much more load than the voltage can support. Some of the major blackouts in power systems which have occurred around the world are, September 23, 2003 in Sweden and Denmark, September 28, 2003 in Italy and also the United State and Canada blackout (August 2003) was reported due to insufficient reactive power of system resulting in the voltage collapse as one of the main reasons[1-4]. The primary source of reactive power in electrical power systems is synchronous generators. Although alternative

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or secondary reactive power sources such as shunt capacitors and Flexible AC Transmission System (FACTS) controllers (e.g. Static VAR Compensators or SVCs and Shunt Static Synchronous Compensators or STATCOMs) are also important. Generators are responsible to maintain the voltage profile of the network up to great extent [5, 6].

Power systems security limits and the stability is closely approximated by voltage stability criteria [7]. The reactive power limits (Q-limits) of one or more synchronous generators is reached in almost all voltage instability incidents [5]; thus the proper modelling of reactive power capabilities is required for voltage stability studies. Various models have been proposed for market analysis and voltage stability on the basis of Q-limits. The method proposed by Ismael El-Samahy[8] used representation of Q-limits of synchronous generators in system security and reactive power procurement market model. In this paper Q-limits is also considered for system security analysis and Zonal Pricing Mechanism is proposed as a better method for marketing mechanism.

Continuation Power Flow(CPF) and Optimal Power Flow(OPF) are widely used methods in voltage stability analysis. The loading level is increased in CPF method until there is no feasible solution to the power flow equations and the system fails to satisfy the ranges of certain variables such as voltages or power transfers [9]. On the other hand OPF method is more of optimization method which maximizes the system loadability while satisfying all operating constrains such as reactive power maximum limits (Qmax), reactive power minimum limits (Qmin), voltage and power transfer limits, power flow equations as discussed in [8, 10, 11]. The reactive power procurement model is inherently non-linear and multi-objective in nature. Various methods like Quantum Particle Swarm Optimization[12], Differential Evolution[13], and Simple Branch and Bound (SBB) algorithm [14] are proposed. In order to dispatch generators and obtain pricing mechanism in power electricity market number of OPF models are used [18, 19, 20, 22]. Many more OPF models have been proposed concerning the voltage stability and market clearance problems [10, 23, and 24]. A number of methods of pricing are being used for reactive power markets namely Pay-at-Market Clearing Price (MCP) and Pay-As-Bid (PAB) method, Nodal pricing, Zonal pricing, auction etc. Looking at the localized nature of reactive power N. Amjady et. Al [21] suggest the PAB market clearing mechanism for the reactive power market.

Reactive power procurement and reactive power dispatch are two classes of problems when analyzing reactive power provisions in the context of deregulated electricity markets. Reactive power procurement is a long term issue while the reactive power dispatch corresponds to the short-term, “real-time” allocation of reactive power on current operating constraints. The independent system operator(ISO) seeks optimal allocation of reactive power which meets all seasonal operating constraints such as minimization of total system losses[8, 22], minimization of reactive power cost [23-24], minimization of deviations from contracted transactions [25], or maximization of system loadability to minimize the risk of voltage collapse [26].

In this paper modified OPF method is used to ensure system security and reliability. Only reactive power supports from generators is considered as one of the ancillary services to be eligible for financial compensation. Expected Payment Function (EPF) of generator is used to develop a bidding framework while the Total Payment Function (TPF) is used to clear the PAB market.

The paper is organized as follows: In section 2 generator reactive power capability limits and curves are discussed. The discussion about reactive power ancillary service limits and price offers has been made in section 3. Section 4 describes about the Q-limits and it’s relation with capability limits. Proposed reactive power procurement model is presented in Section 5 which contains the discussion about reactive power support, security and reliability. The last unit of Section 5 presents the PAB marketing model. In Section 6, where the implementation of 24 bus Reliability Test System (RTS) is discussed and results are presented for normal condition as well as for worst contingency state. Section 7 contains the conclusion.

2. Generator Reactive Power Capability

The power output of a generator, is limited by the prime mover/turbine’s capability, limited to a value close to its MVA rating. When the real power and terminal voltage is fixed, its armature and field winding heating limits restrict the reactive power generation from the generator[27, 28]. The armature heating limit is a circle centred at origin Ca and radius is Ra= $(\sqrt{V_t I_a})$ is given by the equation (1)

$$PG^2 + QG^2 \leq \left(\sqrt{V_t I_a}\right)^2 \tag{1}$$

The field limit is also a circle, cantered at Cf and radius is Rf=$(\frac{V_t E_{af}}{X_s})$ is given as follows:

$$PG^2 + \left(QG + \frac{{V_t}^2}{X_S}\right)^2 \leq \left(\frac{V_t E_{af}}{X_s}\right)^2 \tag{2}$$

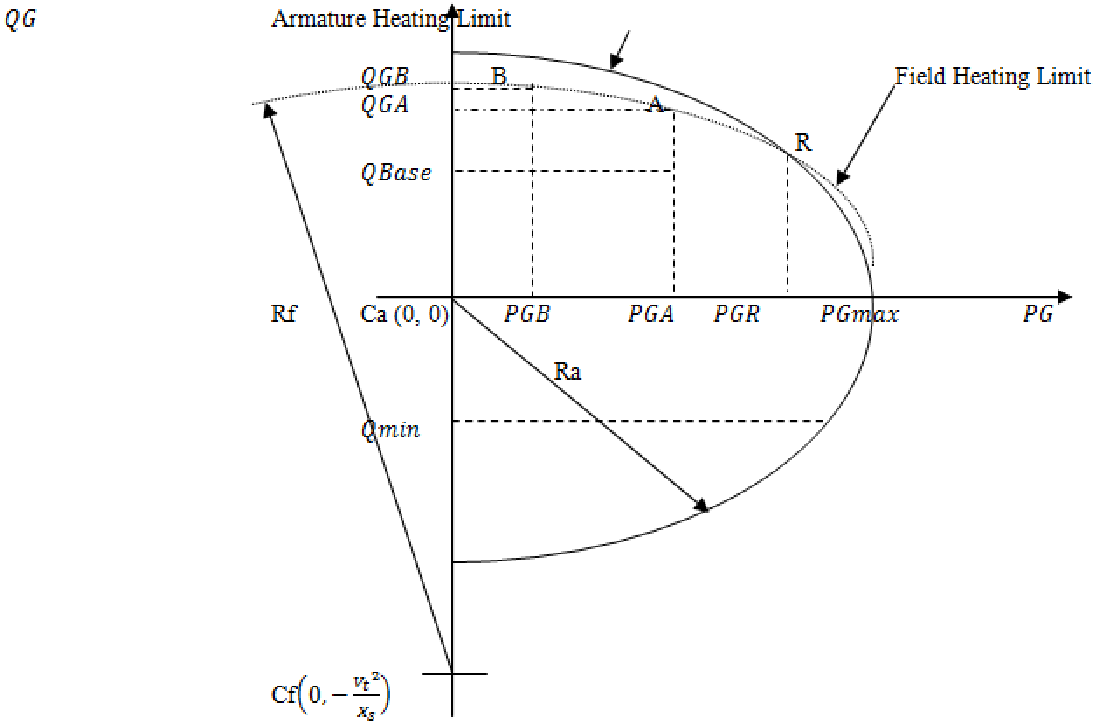

Fig.1. Generator Capability Curve

Where V_t is the voltage at generator terminal bus, I_a is the armature current, E_{af} is the excitation voltage, X_s is the synchronous reactance, and PG and QG are the real and reactive power outputs of the generator, respectively. The MVA rating of generator's is the point of intersection of two curves as shown in the Fig. 1 and given as PGR. The limit on QG is imposed by the generator's field winding heating limit equation (2) when $PGA<PGR$ while the limit on QG is imposed by generator's armature winding heating limit equation (1) when $PGA>PGR$.

Consider the operating point A (PGA, QGA) on the field limit curve given by the equation (2). The operating point moves to QGB i.e. on B (PGB, QGB) when there is more reactive power requirement, i.e.$PGB<PGA$. This means that active power generation must be reduced in order to maintain the field heating limits when more reactive power is demanded. There is also an under excitation limit, $Qmin$ usually applicable that restricts the unit operation in under excited mode due to localize heating in the end region of the armature.

3. Reactive Power Ancillary Service Limits and Price Offers

A brief discussion has been presented on generation of reactive power and its impact on active power in the previous section. Further, Fig 1 leads us to some important conclusions. $QBase$ in the Fig 2 is the reactive power required to fulfil the requirements of reactive power by the generator's auxiliaries (such as boiler feedpump motor, circulating water system pump motors, ID fan and FD fan motors, step up transformers etc.). If the operating point lies inside the limiting curves $(PGA, QBase)$ then the generator unit can increase its reactive power generation from $QBase$ to QGA without adjusting the PGA. Since increase in reactive power generation increases losses in the coil, hence it increases the cost. The cost function graph of synchronous generator is shown in Fig 2.

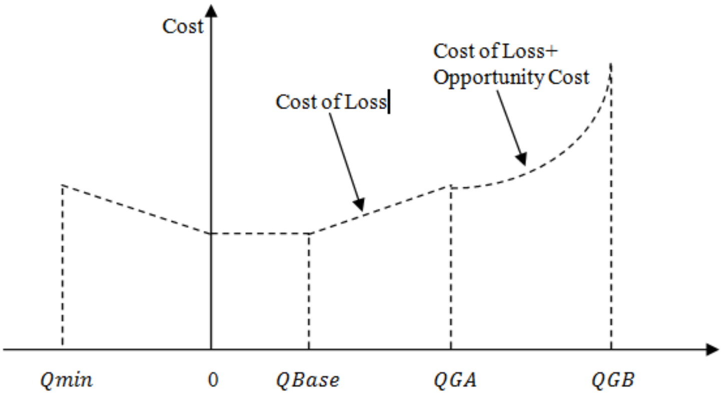

Fig.2. Reactive Power Production Cost of Synchronous Generator

We define three operating region of a synchronous generators on the reactive power coordinates to formulate the generator's EPF. The expected payment function is critically important in PAB marketing mechanism as shown in Fig 3. It is expected payment function who can either encourage or discourage the ISO from bidding. From knowledge of generator's expectation of payment, the ISO can call for reactive power bid [28]. The EPF for the ith generator can be expressed as:

$$\mathrm{EPF_i} = a_i + \int_{Qmin}^{0} m_{1i}\, dQ_i + \int_{QBase}^{Q_A} m_{2i}\, dQ_i + \int_{Q_A}^{Q_B} (m_{3i}Q_i)\, dQ_i$$

Here the coefficients used in the above equation are the reactive power price offers to be submitted by the generators. Explanations of these coefficients are:

- Availability price offer (a): This is the availability price offer by the generator in $.
- Cost of loss offer (m_1, m_2): This is the linearly varying component as shown in Figure y which is cost of loss payment accounted for the increased in winding losses as reactive power output increases. Loss of cost payment is consider in under excitation and over excitation ranges in $/MVAR unit.
- Opportunity Cost offer (m_3): This is quadratic varying component as shown in Figure y which is Opportunity Cost accounted when supplier is constrained from producing scheduled active power. Opportunity Cost is measured in $/MVAR/MVAR.

Four regions can be identified from the Fig 3 for reactive power generation.

Region I: $Qmin \leq QG \leq 0$. The reactive power produced in this region is eligible for under-excitation payment for reactive power absorption.

Region II: $0 \leq QG \leq QBase$. This region is mandatory region and the reactive power produced in this region is used to meet generator's own requirements. Thus Region II is not eligible for any kind of payment.

Region III: $QBase \leq QG \leq QGA$. The reactive power produced in this region is recognized as an ancillary service and eligible for payment. A payment offer in this region is for the increased in winding losses and referred as cost of loss payment.

Region IV: $QGA \leq QG \leq QGB$. This region is also recognized as ancillary service and thus eligible for payment. A payment offer in this region is due to supplier constrained from producing scheduled active power and referred as opportunity cost payment.

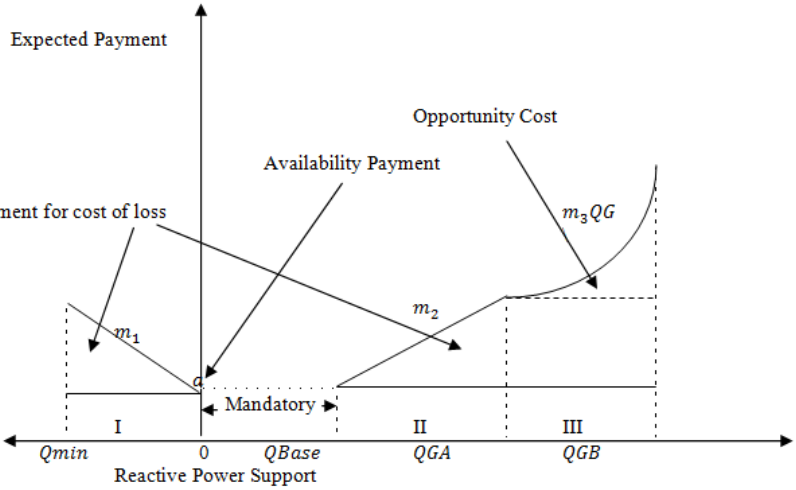

Fig.3. Generator's Expectation Payment Function Graph And Three Operating Regions

4. Representation of Q-limits

Due to scarcity of resource and increasing demand, economical usage of power system capability is required. Hence for better generator's capabilities generator reactive power maximum limit is model as a function of active power output [27, 28].

Mathematically the maximum reactive power limit is defined as:

$$Q_{Gen1}^{max} = \sqrt{\left(\frac{V_{tn}E_{fn}}{X_{sn}}\right)^2 - (P_{Genn})^2} - \frac{{V_{tn}}^2}{X_{sn}} \tag{3}$$

$$Q_{Gen2}^{max} = \sqrt{(V_{tn}I_{an})^2 - (P_{Genn})^2} \tag{4}$$

$$Q_{Genn}^{max} = \begin{cases} Q_{Gen1}^{max} \; if \; P_{Genn} < P_{GenR} \\ Q_{Gen2}^{max} \; if \; P_{Genn} > P_{GenR} \end{cases} \tag{5}$$

Where,

P_{Genn} Generator active power output at bus n
P_{GenR} Generator rated active power which is generally close to the maximum active power output P_{Genn}^{max}
V_{tn} Terminal voltage of generator n at which its capability curves are calculated (1.05 in p.u)
Q_{Gen1}^{max} Reactive power limits due to maximum field currents
Q_{Gen2}^{max} Reactive power limits due to maximum stator currents

OPF model proposed by the authors [27, 28] used this reactive power limit as one of many constraints.

5. Reactive Power Procurement Model

Once the prices are offered, the ISO needs a proper mechanism to determine the best offers and formulate its reactive power procurement model. The major concern of ISO is to find a reactive power solution that doesn't violate transmission security constraints, which are voltage, thermal and stability limits [29]. Also the ISO checks the technical feasibility before energy market settlement; only those transactions that are within the transfer capabilities of the network are allowed [27]. Unlike active power the reactive power market depends on location also. For example, a low priced reactive bid at a bus remotely located is not a better option for ISO [28].

5.1. Reactive power support, security and reliability

As discussed in the introduction section that voltage control is an important parameter for secure operation of power system even in the worst contingency state. Hence, it is required to maintain the voltage security margin to prevent the system from voltage collapse. The voltage security margin as shown in Fig 4 is the distance between current operating point (λ_{LFa}) and maximum operating point (λ_{LFm}).The maximum operating point (λ_{LFm}) is the maximum allowable load increments which satisfy all operating constraints, equations (8)-(23). The modified OPF method proposed in this paper maximises the loadabilityand the total payment function (TPF). In regards of system losses the ISO determines maximum loading on the system while meeting all operating constraints (8)-(23). Many of the models proposed earlier fails to provide necessary security to the system due to either violation of constraints or infeasible solution.

The OPF model proposed here provides the necessary security to the system without violating any of the operating constraints (8)-(23). Even in the worst contingency state the system maintains its reliability. The reactive power requirement at different buses is calculated after maximizing the loading factor (λ_{LF}) and the optimum price is obtained after minimizing the TPF. The objectives of the OPF model are:

$$\left.\begin{matrix} max. & \lambda_{LF} \\ min. & TPF \end{matrix}\right\} \tag{6}$$

Where,

$$TPF = \sum_{i\epsilon gen}(a_i.W_{0,i} - m_{1,i}.W_{1,i}.Q_{G1,i} + m_{2,i}.W_{2,i}.\left(Q_{G2,i} - Q_{Base,i}\right) + m_{2,i}.W_{3,i}.\left(Q_{G3,i} - Q_{Base,i}\right) + 0.5m_{3,i}.W_{3i}\left({Q_{G3,i}}^2 - {Q_{GA,i}}^2\right) \tag{7}$$

In the above equation gen denotes the generators in the system, $Q_{G1,i}$, $Q_{G2,i}$, and $Q_{G3,i}$ are the reactive power values in the under-excited, over-excited and opportunity regions i.e. in the region I, region II and region III as shown in Fig 3. The variables $W_{1,i}, W_{2,i}, and\ W_{3,i}$ are the binary variables associated with the region I, region II, and region III while the binary variable $W_{0,i}$ is operating region security criteria.

Subject to the following operating constraints

Load Flow Equations:

$$P_{Geni}\,(1+\lambda_{LF}+kg)-\ P_{Di}(1+\lambda)=\sum_j V_iV_jY_{ij}cos\left(\theta_{ij}+\delta_j-\delta_i\right),\forall i \tag{8}$$

$$Q_{Geni}-Q_{Di}(1+\lambda_{LF})=-\sum_j V_iV_jY_{ij}sin\left(\theta_{ij}+\delta_j-\delta_i\right)\,,\forall i \tag{9}$$

Reactive power capability limits:

$$Q_{Gen1}^{max}\leq\sqrt{\left(\frac{V_{tn}E_{fn}}{X_{sn}}\right)^2-(P_{Gn})^2}-\frac{{V_{tn}}^2}{X_{sn}} \tag{10}$$

$$Q_{Gen2}^{max}\leq\sqrt{(V_{tn}I_{an})^2-(P_{Gn})^2} \tag{11}$$

Reactive power limits:

$$Q_{Genn}\leq Q_{Genn}^{max},\forall n \tag{12}$$

$$Q_{Genn}^{max}=\begin{cases}Q_{Gen1}^{max}\ if\ P_{Genn}<P_{GenR}\\ \\ Q_{Gen2}^{max}\ if\ P_{Genn}>P_{GenR}\end{cases} \tag{13}$$

$$Q_{Genn}\geq Q_{Genn}^{min},\forall n \tag{14}$$

$$(Q_{Genn}-Q_{Genn}^{min}).\,v_{n1}\leq 0,\forall n \tag{15}$$

$$(Q_{Genn}^{max}-Q_{Genn}).\,v_{n2}\leq 0,\forall n \tag{16}$$

$$\left.\begin{array}{c}W_{1,i}Q_{Gen,i}^{min}\ \leq\ Q_{G1,i}\ \leq\ 0\\ W_{2,i}Q_{Gen,i}^{Base}\leq Q_{G2,i}\leq W_{2,i}Q_{Gen,i}^{A}\\ W_{3,i}Q_{Gen,i}^{A}\leq Q_{G3,i}\leq W_{3,i}Q_{Gen,i}^{B}\\ Q_{G,i}=Q_{G1,i}+Q_{G2,i}+Q_{G3,i}\\ Q_{G1,i}Q_{G2,i}=0\\ Q_{G2,i}Q_{G3,i}=0\\ Q_{G1,i}Q_{G3,i}=0\end{array}\right\},\forall i \tag{17}$$

Voltage limits:

$$V_i^{min}\leq V_i\leq V_i^{max},\forall i \tag{18}$$

Binary variables limit:

$$\left.\begin{array}{c} W_{0,i}, W_{1,i}, W_{2,i}, W_{3,i} \in (0,1) \\ W_{1,i} + W_{2,i} + W_{3,i} \leq W_{0,i} \end{array}\right\}, \forall i \tag{19}$$

Active power limits:

$$\left|P_{ij}(V,\delta)\right| \leq P_{ij}^{max}, \forall ij \tag{20}$$

$$P_{Geni}(1 + \lambda_{LF} + kg) \leq P_{Geni}^{max}, \forall i \tag{21}$$

Terminal voltage limits:

$$V_{tn} = V_{na} + v_{n1} - v_{n2}, \forall n \tag{22}$$

$$v_{n1}, v_{n2} \geq 0, \forall n \tag{23}$$

$n$represents the generator bus and all the variables are taken in per unit (p.u).

Where,

λ_{LF} Loading Factor
kg Variable to model a distributed slack bus
Q_{Geni} Generation of reactive power at bus i
Q_{Di} Demand of reactive power at bus i
Q_{Genn}^{max} Maximum reactive power of generator n
Q_{Genn}^{min} Minimum reactive power of generator n
P_{Geni} Generation of active power at bus i
P_{Di} Demand of active power at bus i
P_{ij} Power flow between bus i and bus j
V_i Voltage magnitude at bus i
δ_i Voltage angle at bus i in radians
P_{ij}^{max} Maximum power flow between bus i and bus j
V_i^{max} Maximum voltage magnitude at bus i
V_i^{min} Minimum voltage magnitude at bus i
Y_{ij} Admittance matrix elements
θ_{ij} Angle of admittance matrix elements
V_{na} Terminal voltage of generator n w.r.t operating point a, as shown in Figure 4
v_{n1}, v_{n2} Changes in generator n bus voltage is represented by these auxiliary variables

While the variables $Q_{Gen,i}^{Base}$, $Q_{Gen,i}^{A}$, $Q_{Gen,i}^{B}$ are the nothing but the same as $QBase$, QGA and QGB for ith generator as shown in Fig 2.

OPF model is described by the equation (6)-(23).

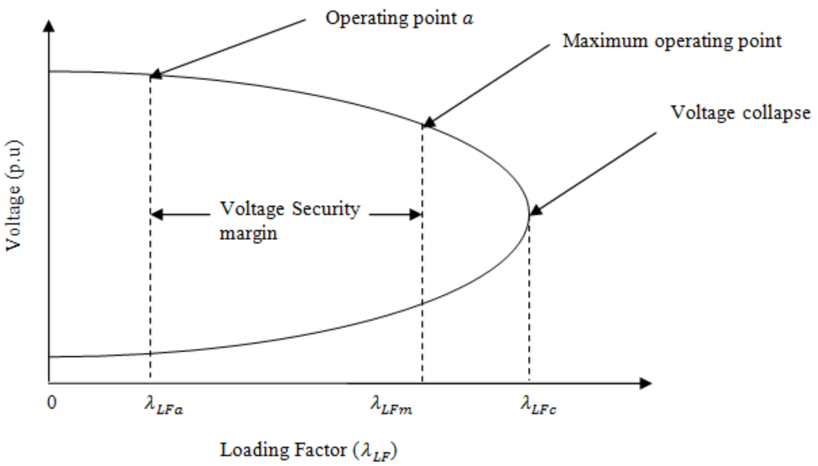

Fig.4. PV Curve

6. Results and Discussion

The reactive power procurement model is tested on a 24 bus RTS network as given in the Fig 5. The test has been performed on 24 bus RTS network in normal condition as well as stressed condition. Prices offered by generators are given in the Table 1 and generators are eligible for financial compensation in all of the three regions. Since the region I and region II are eligible for cost of loss payment hence offered prices will be same in these regions i.e$m1 = m2$. In the deregulated power market, participants are asked to send their $Qmin$, $QBase$ and $Qmax$ values. Normally it is assumed that $QBase = 0.1 * Qmax$ while the QGA and QGB as shown in Fig 3 is 0.8*QGB and $Qmax$.The lower and upper bound of voltage are taken as 0.95 and 1.05 in p.u. Terminal voltage is very crucial element for the maximization of loading factor (λ_{LF}) , hence (V_t) is also taken as 1.05 (in p.u). Operating point terminal voltage must be maximum to ensure minimum deviation in voltage and betterλ_{LF}. Operating point graph is shown in the Fig 4.

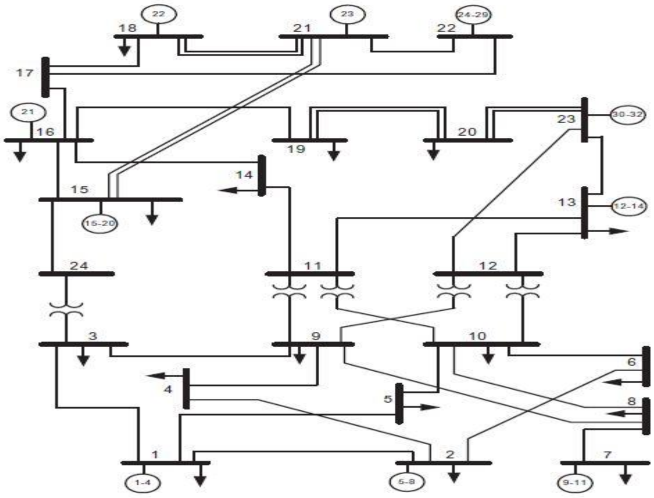

Fig.5. RTS 24 Bus Network

In the RTS 24 bus network, both the bus no. 15 & 22 have 6 generating units, 1 & 2 have 4 generating units, 7, 13 & 23 have 3 generating units, and each 14, 16, 18 & 21 having 1 generating unit. In this paper all generating units at a bus are combined to make a single unit with associated maximum bidding price. The $Qmax$, $Qmin$, $Pmax$, and $Pmin$ are taken as the summation of all generating units. The bidding price, active power limits and reactive power limits are shown in Table 2.

Case I: Implementation on 24 bus RTS network in normal condition

Active and reactive power minimum, maximum, generation and demand values are taken from the IEEE reliability test system [30]. The optimum generation of reactive power by i^{th} generator and its price is obtained by solving OPF model as given in section 5.

Since the OPF optimization model is a non-linear problem, so the high level programming language General Algebraic Modeling System (GAMS) is used for modeling and the problem is solved using CONOPT solver [31]. The reactive power is obtained at different buses and the total payment to be made by the ISO after simulation is shown in the Table 2. In the normal condition only two generating units 15 and 18 are eligible for opportunity cost payment while the other two units are operating in the under-excited mode.

Table 1. Price Offers From Generators

Bus No.	Unit No.	Prices offered from each generator			
		a	$m1$	$m2$	$m3$
1	1	0.96	0.86	0.86	0.46
	2	0.94	0.82	0.82	0.45
	3	0.85	0.79	0.79	0.39
	4	0.83	0.82	0.82	0.40
2	1	0.50	0.54	0.54	0.28
	2	0.42	0.42	0.42	0.35
	3	0.69	0.68	0.68	0.39
	4	0.65	0.62	0.62	0.37
7	1	0.75	0.61	0.61	0.43
	2	0.80	0.75	0.75	0.36
	3	0.70	0.65	0.65	0.32
13	1	0.68	0.50	0.50	0.31
	2	0.70	0.54	0.54	0.39
	3	0.75	0.60	0.60	0.50
14	1	0.94	0.81	0.81	0.00
15	1	0.65	0.60	0.60	0.30
	2	0.50	0.58	0.58	0.25
	3	0.60	0.73	0.73	0.38
	4	0.55	0.61	0.61	0.27
	5	0.52	0.50	0.50	0.26
	6	0.51	0.51	0.51	0.27
16	1	0.50	0.50	0.50	0.30
18	1	0.90	0.85	0.85	0.48
21	1	0.80	0.75	0.75	0.41
22	1	0.42	0.42	0.42	0.17
	2	0.50	0.48	0.48	0.20
	3	0.45	0.42	0.42	0.38
	4	0.48	0.44	0.44	0.35
	5	0.49	0.45	0.45	0.33
	6	0.55	0.46	0.46	0.32
23	1	0.90	0.85	0.85	0.48
	2	0.95	0.89	0.89	0.55
	3	0.86	0.80	0.80	0.45

Case II: Implementation on 24 bus RTS network in worst contingency state

As can be seen from the Table 2 that unit 15,16 and 18 are the major contributors of reactive power, hence demand high financial compensation. Outage of a generator is one of the many way for creating a contingency. In this case contingency is created by the outage of unit 18, which gives sudden increment of load or high demand conditions on the system. The 400MW of decrement in active power, can be observed in the system with this contingency while 333MW of active power load is still demanded. Along with the active power there is no reactive power generation left at unit 18 which was among the major participant in normal condition, while 68MVAR reactive power is still demanded. Reactive power obtained and the total payment after simulation is shown in Table 3.

In worst contingency state with the outage of unit 18, the total reactive power is decreased by 205.6 MVAR while the payment is also decreased by $150.23. To maintain the security even in the worst contingency state the generating unit 21, nearest to the outage unit 18 increased its generating limit by 56.7MVAR to support the outage. This clearly signifies the optimality of proposed algorithm and also verifies the fact that reactive power is best provided locally.

Table 2. Total Payment for a Reactive Power Market Based on Pay As Bid Method (Normal Condition)

Bus no.	a	$m1$	$m2$	$m3$	$Pmin$ (in MW)	$Pmax$ (in MW)	$Qmin$ (in MVAR)	$Qmax$ (in MVAR)	$Q_{G,i}$ (in MVAR)	Total Payment (in $)
1	0.96	0.86	0.86	0.46	62	192	-50	80	6.2	0
2	0.69	0.68	0.68	0.39	62	192	-50	80	-49.1	34.078
7	0.80	0.75	0.75	0.43	75	300	0	180	62.0	33.80
13	0.75	0.60	0.60	0.50	207	591	0	240	79.6	34.11
14	0.94	0.81	0.81	0	-	-	-50	200	82.4	51.484
15	**0.65**	**0.73**	**0.73**	**0.38**	**64**	**215**	**-50**	**110**	**110.0**	**900.56**
16	0.50	0.50	0.50	0.30	54	155	-50	80	80.0	382.1
18	**0.90**	**0.85**	**0.85**	**0.48**	**100**	**400**	**-50**	**200**	**110.4**	**77.74**
21	0.80	0.75	0.75	0.41	100	400	-50	200	24.9	4.475
22	0.55	0.48	0.48	0.38	0	300	-60	96	-35.4	17.542
23	0.95	0.89	0.89	0.55	248	660	-125	310	72.9	38.241
								Total reactive power Generation (in MVAR) = 543.9 Total Payment = $1574.13		

Table 3. Total payment for a reactive power market based on pay as bid method (stressed condition) (Outage of unit 18)

Bus no.	a	$m1$	$m2$	$m3$	$Pmin$ (in MW)	$Pmax$ (in MW)	$Qmin$ (in MVAR)	$Qmax$ (in MVAR)	$Q_{G,i}$ (in MVAR)	Total Payment (in $)
1	0.96	0.86	0.86	0.46	62	192	-50	80	-14.1	13.086
2	0.69	0.68	0.68	0.39	62	192	-50	80	-50.0	34.69
7	0.80	0.75	0.75	0.43	75	300	0	180	55.6	29.0
13	0.75	0.60	0.60	0.50	207	591	0	240	29.6	4.11
14	0.94	0.81	0.81	0	-	-	-50	200	7.9	0
15	**0.65**	**0.73**	**0.73**	**0.38**	**64**	**215**	**-50**	**110**	**110.0**	**900.56**
16	0.50	0.50	0.50	0.30	54	155	-50	80	80.0	382.1
18	0.90	0.85	0.85	0.48	100	400	-50	200	0	0
21	**0.80**	**0.75**	**0.75**	**0.41**	**100**	**400**	**-50**	**200**	**81.6**	**47.0**
22	0.55	0.48	0.48	0.38	0	300	-60	96	-4.3	2.614
23	0.95	0.89	0.89	0.55	248	660	-125	310	42.0	10.74
								Total reactive power Generation (in MVAR) = 338.3 Total Payment = $1423.9		

Table 4. Total payment for a reactive power market based on pay as bid method (stressed condition) (Outage of unit 15)

Bus no.	a	$m1$	$m2$	$m3$	$Pmin$ (in MW)	$Pmax$ (in MW)	$Qmin$ (in MVAR)	$Qmax$ (in MVAR)	$Q_{G,i}$ (in MVAR)	Total Payment (in $)
1	0.96	0.86	0.86	0.46	62	192	-50	80	-4.1	4.486
2	0.69	0.68	0.68	0.39	62	192	-50	80	-50.0	34.69
7	0.80	0.75	0.75	0.43	75	300	0	180	58.0	30.8
13	0.75	0.60	0.60	0.50	207	591	0	240	51.9	17.49
14	0.94	0.81	0.81	0	-	-	-50	200	56.9	30.829
15	0.65	0.73	0.73	0.38	64	215	-50	110	0	0
16	0.50	0.50	0.50	0.30	54	155	-50	80	80.0	382.1
18	**0.90**	**0.85**	**0.85**	**0.48**	**100**	**400**	**-50**	**200**	**114.6**	**81.31**
21	**0.80**	**0.75**	**0.75**	**0.41**	**100**	**400**	**-50**	**200**	**108.0**	**66.8**
22	0.55	0.48	0.48	0.38	0	300	-60	96	-31.8	15.814
23	0.95	0.89	0.89	0.55	248	660	-125	310	68.3	34.147

Total reactive power
Generation (in MVAR) = 451.8
Total Payment = \$698.466

Table 5. Total payment for a reactive power market based on pay as bid method (stressed condition) (Outage of unit 15 and 18)

Bus no.	a	$m1$	$m2$	$m3$	$Pmin$ (in MW)	$Pmax$ (in MW)	$Qmin$ (in MVAR)	$Qmax$ (in MVAR)	$Q_{G,i}$ (in MVAR)	Total Payment (in $)
1	0.96	0.86	0.86	0.46	62	192	-50	80	-23.0	20.74
2	0.69	0.68	0.68	0.39	62	192	-50	80	-50.0	34.69
7	0.80	0.75	0.75	0.43	75	300	0	180	52.8	26.9
13	0.75	0.60	0.60	0.50	207	591	0	240	8.5	0
14	0.94	0.81	0.81	0	-	-	-50	200	1.6	0
15	0.65	0.73	0.73	0.38	64	215	-50	110	0	0
16	0.50	0.50	0.50	0.30	54	155	-50	80	80.0	382.1
18	0.90	0.85	0.85	0.48	100	400	-50	200	0	0
21	**0.80**	**0.75**	**0.75**	**0.41**	**100**	**400**	**-50**	**200**	**142.2**	**92.45**
22	0.55	0.48	0.48	0.38	0	300	-60	96	13.7	2.518
23	0.95	0.89	0.89	0.55	248	660	-125	310	51.5	19.195

Total reactive power
Generation (in MVAR) = 277.3
Total Payment = \$578.593

In order to test the optimality of the proposed algorithm the test has been performed for the outage of unit 15 and both the units 15, 18. In this case also when unit 15 goes out then its nearest generating unit 21 increases its generation limits to support the outage unit as well as secure the system. The generating unit 21 increasees its reactive power generation by 83.1MVAR. In normal condition when both the major participants, unit15 and unit 18 go out then its nearest unit 21 increases its generation limit by 117.3 from normal condition. Obtained results also signify its optimality. The results are shown in the Table 4 and Table 5.

The algorithm is also very useful from the marketing mechanism point of view because it reduces the risk of making any generating unit excercise market power and preserves the system security. Thus, it will reduce the total payment,as less generating units will run in opportunity region. Even in the worst contingency, the contributed effort from each generator can be seen from Table 2, 3 and 4.

7. Conclusions

System security has become a major concern in deregulated electricity markets for the ISO. Hence in this paper, the security aspect is considered and a modified OPF model is proposed in the context of ISO for better security, trust, reliability and easy market settlement. The modified OPF provides the flexibility to add more generators and can easily be applied on real time systems. PAB marketing mechanism is proposed which reduces the risk of generating units exercising market power. Thus PAB is good for the competitive power electricity market as well as monopoly electricity market. The proposed security as well as marketing model is applied on 24 bus RTS system and the obtained result is a clear indication of effectiveness of the algorithm. The comprehensive reactive power framework developed in this paper has also been tested on CIGRE 32 bus system [21], which also confirms the effectiveness of the proposed approach.

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