A Load Flow based Approach for Reactive Power Evaluation in Deregulated Power Systems

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ABSTRACT
With the advancement of technology and open access of transmission services, the power flows over the transmission lines has become unprecedented and increased many fold, which causes the power system to work under the stressed operating conditions. So for the reliable, safe and required degree of quality of power supply, the ancillary services have come into being under deregulated environment. These services provide the support to transmission of power in interconnected grids. Out of seven major ancillary services, (black start, frequency regulation, system protection, scheduling and dispatch, reactive power and voltage regulation and load balancing), this paper deals with the reactive power and voltage regulation. The reactive power regulation is used to keep the voltage within its limits and improves the voltage profile, which has become a major concern in present day power system operation. It becomes very important to ensure the presence of sufficient amount of reactive power source in the network for secure and reliable operation of electrical power system. In this paper, the reactive power procurement from various generating sources has been evaluated under specified transactions with the aid of load flow analysis program. The proposed methodology has been tested on two sample power systems. The results obtained show that the proposed method is able to maintain voltage profile at load buses by procuring reactive power from available generation resources.

Keywords
Ancillary services, deregulation, load flow study, reactive power regulation

1. INTRODUCTION
The restructuring of electric power systems has been materialized in many countries of the world such as Chile, USA, UK, Sweden, Finland, Norway and some countries of South America. Deregulation is the process in which government restructured the rules and regulations to control and drive the electric power industry. But after that there are many issues in the restructured power systems such as transmission pricing, optimal bidding, network congestion, market power, market architecture design, ancillary service management etc.[1]. Ancillary services are the services which are used for the transmission in the interconnected grids with the safe, reliable and required level of quality operation. The ancillary service management further has different services such as reactive power regulation, frequency regulation, black start, reserves, backup supply, system control, dynamic scheduling, real power transmission losses [1],[2]. One of the major concern for un-interrupted power supply is to maintain bus voltage profile within the safe limits, which is the major objective of this paper.

In general, there are two classes of problems when analyzing reactive power regulation in deregulated electricity markets, namely, reactive power procurement and reactive power dispatch. The first level consists the procurement which is a long-term process and done on the seasonal basis. In the second level, the reactive power dispatch is a short-term process which is done on real time basis i.e 30 min to 1 h ahead of real time [3]. The function of reactive power procurement is to maintain the voltage stability. The reactive power regulation is also known as voltage regulation [2]. The reactive power can be procured generally from synchronous generators[4] but the other sources of reactive power are synchronous condensers, reactors, capacitor banks, FACTS controllers, reactive compensators [3],[5]. The biggest part of reactive power consumption goes to induction motors and elements of transmission system (transformers, lines). The reactive power sources are placed near the bus with the reactive power consumption are much better position to provide necessary voltage control service than one that is located far from this bus[4]. The reactive power flow should be decreased as much as possible and in doing this, the quantity of active power increased and the losses in the system are decreased. This is the reason why voltage should be controlled on the local level [2]. Methods for reactive power evaluation should have some features such as it should be simple to compute, It should take location-based nature of reactive power into account, It should adapt to changing operating conditions [4]. Different methods are used for the reactive power evaluation and they may be Voltage Sensitivity (VS) based Method, PV curves Method, Equivalent Reactive Compensation (ERC) Method, Back-up generation Method [6]. A brief literature review on reactive power and voltage regulation is presented in Table 1.

Table 1. Brief literature review on reactive power and voltage regulation

S. No.	Author(s)	Name of Journal/ conference/ others resources	Main contribution
1	Abhyankar and Khaparde [1]	National Programme On Technology Enhanced Learning (nptel)	National and international scenarios of deregulation
2	Svigir *et al.* [2]	World Scientific And Engineering Academy And Society	Ancillary services under deregulation.
3	El-Samahy *et*	IEEE Transactions On Power Systems	Maximization of loadability under

	al. [3]	(Feb. 2008)	system security
4	Kuzle *et al.* [4]	IEEE Melecon (2004)	Reactive power evaluation and market power measuring
5	Singh *et al.* [5]	African Journals Online	Reactive power procurement model and management
6	Staniulis [6]	*www.iea.lth.se*	Voltage sensitivity PV curves, equivalent reactive compensation and back-up generation methods
7	Fattahi *et al.* [7]	IEEE Electrical Power & Energy Conference (2008)	AHP method to classify and valuation Reactive power sources
8	Singh *et al.* [8]	Electric Power Components and System (2010)	Reactive power and congestion management

This paper aims to the procurement of the reactive power from specified generators for voltage profile improvement at load buses. The voltage stability depends on the reactive power which is procured from different sources. The problem is formulated to improve the reactive power profile and/or voltage stability. This problem is formulated by using load flow study (Newton-Raphson method).

The rest of the paper is organized as follows. Section 2 presents the mathematical formulation for reactive power procurement. Section 3 defines the solution of the problem. Section 4 presents the algorithm procedure. Section 5 presents the results of two different systems. Section 6 presents the conclusion of the paper. At the end of the paper, appendix is there, in which the data of two different systems are given.

2. MATHEMATICAL FORMULATION OF REACTIVE POWER PROCUREMENT PROBLEM

The reactive power procurement is solved by load flow equations. The load flow can be solved with the help of solution of Jacobian equation, which may be written as:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta|V| \end{bmatrix} \quad (1)$$

$$\Delta P_i = P_{i(specified)} - P_{i(calculated)} \quad (2)$$

$$\Delta Q_i = Q_{i(specified)} - Q_{i(calculated)} \quad (3)$$

The mathematical real and reactive power equations which are used in load flow studies are as

$$P_i = \sum_{k=1}^{n} |V_i||V_k||Y_{ik}| \cos(\theta_{ik} + \delta_k - \delta_i); i = 1,2..n \quad (4)$$

$$Q_i = -\sum_{k=1}^{n} |V_i||V_k||Y_{ik}| \sin(\theta_{ik} + \delta_k - \delta_i); i = 1,2..n \quad (5)$$

where Pi is the real power at ith bus and Qi is the reactive power at the ith bus

The solution of the newton raphson (NR) method are obtained from the Jacobian and the elements of Jacobian matrix J_1, J_2, J_3, J_4 can be calculated from the equations written as

Real power equations

When $i \neq k$

$$\frac{\partial P_i(x)}{\partial \delta_k} = |V_i||V_k||Y_{ik}| \sin(\delta_i - \delta_k - \theta_{ik}) \quad (6)$$

$$\frac{\partial P_i(x)}{\partial V_k} = |V_i||Y_{ik}| \cos(\delta_i - \delta_k - \theta_{ik}) \quad (7)$$

When $i = k$

$$\frac{\partial P_i(x)}{\partial \delta_k} = -\sum_{\substack{k=1 \\ k\neq i}}^{n} |V_i||V_k||Y_{ik}| \sin(\delta_i - \delta_k - \theta_{ik}) \quad (8)$$

$$\frac{\partial P_i(x)}{\partial V_k} = 2|V_i||Y_{ii}| \cos(\theta_{ii}) + \sum_{\substack{k=1 \\ k\neq i}}^{n} |V_k||Y_{ik}| \cos(\delta_i - \delta_k - \theta_{ik}) \quad (9)$$

Reactive power equations

When $i \neq k$

$$\frac{\partial Q_i(x)}{\partial \delta_k} = -|V_i||V_k||Y_{ik}| \cos(\delta_i - \delta_k - \theta_{ik}) \quad (10)$$

$$\frac{\partial Q_i(x)}{\partial V_k} = |V_i||Y_{ik}| \sin(\delta_i - \delta_k - \theta_{ik}) \quad (11)$$

When $i = k$

$$\frac{\partial Q_i(x)}{\partial \delta_k} = \sum_{\substack{k=1 \\ k\neq i}}^{n} |V_i||V_k||Y_{ik}| \cos(\delta_i - \delta_k - \theta_{ik}) \quad (12)$$

$$\frac{\partial Q_i(x)}{\partial V_k} = -2|V_i||Y_{ii}| \sin(\theta_{ii}) + \sum_{\substack{k=1 \\ k\neq i}}^{n} |V_k||Y_{ik}| \sin(\delta_i - \delta_k - \theta_{ik}) \quad (13)$$

These equations can be used for any number of bus systems. The dimensions of Jacobian matrix is

$$(n + n_p - 1) \times (n + n_p - 1)$$

Where n is the total number of buses and n_p is total number of P-Q buses.

3. SOLUTION OF THE PROBLEM

The management of reactive power in deregulated environment has become the responsibility of Independent System Operator (ISO). ISO takes the reactive power bids from the reactive power providers and develops a reactive power procurement schedule. In this paper, reactive power procurement problem has been solved by Newton Raphson method. The Newton Raphson method is a power full method which is used to solve the non-linear algebraic equations. It is a practical method of load flow solution which is used for large power networks. This method has faster convergence characteristics.

4. ALGORITHM FOR REACTIVE POWER PROCUREMENT

In general, the algorithmic steps in the proposed solution methodology are discussed below:

Step1. Solve the load flow studies (LFS) using the NR method under base case conditions.

Step2. Specify the amount of transaction between the seller and buyer at designated generator for reactive power procurement.

Step3. Perform load flow studies including the specified transactions.

Step4. Check the voltage limits. If all bus voltages are within limits then stop. Else if minimum voltage limit has been violated go to step 5 else if maximum bus voltage limit violated then go at step 7.

Step5. Consider the bus which is violating minimum bus voltage limit, specify the generation company (Genco) from which capacitive reactive power can be procured.

Step6. Increase the capacitive reactive power in steps of the generator specified in step 3 and perform load flow studies, go to step 4.

Step7. Consider the bus which is violating maximum bus voltage limit, specified Genco from which inductive reactive power can be procure.

Step8. Increase the inductive reactive power in steps of the generator specified in step 3 and perform load flow studies, go to step 4.

Flow chart for the algorithm is shown in Fig.1

5. RESULTS AND DISCUSSION

The methodology described above, have been applied to a 4-bus test system [9] and IEEE 9-bus system [10].

5.1 4-bus test system

The load data and single line diagram of 4-bus system are given in table 2 and Fig. 2 respectively and table 3 show the results. The series impedance of each line is 0.1+j0.7 Ω/km and shunt admittance is j0.35*10^-5 Ω/km. Lines are rated at 220 kV and 100MVA.

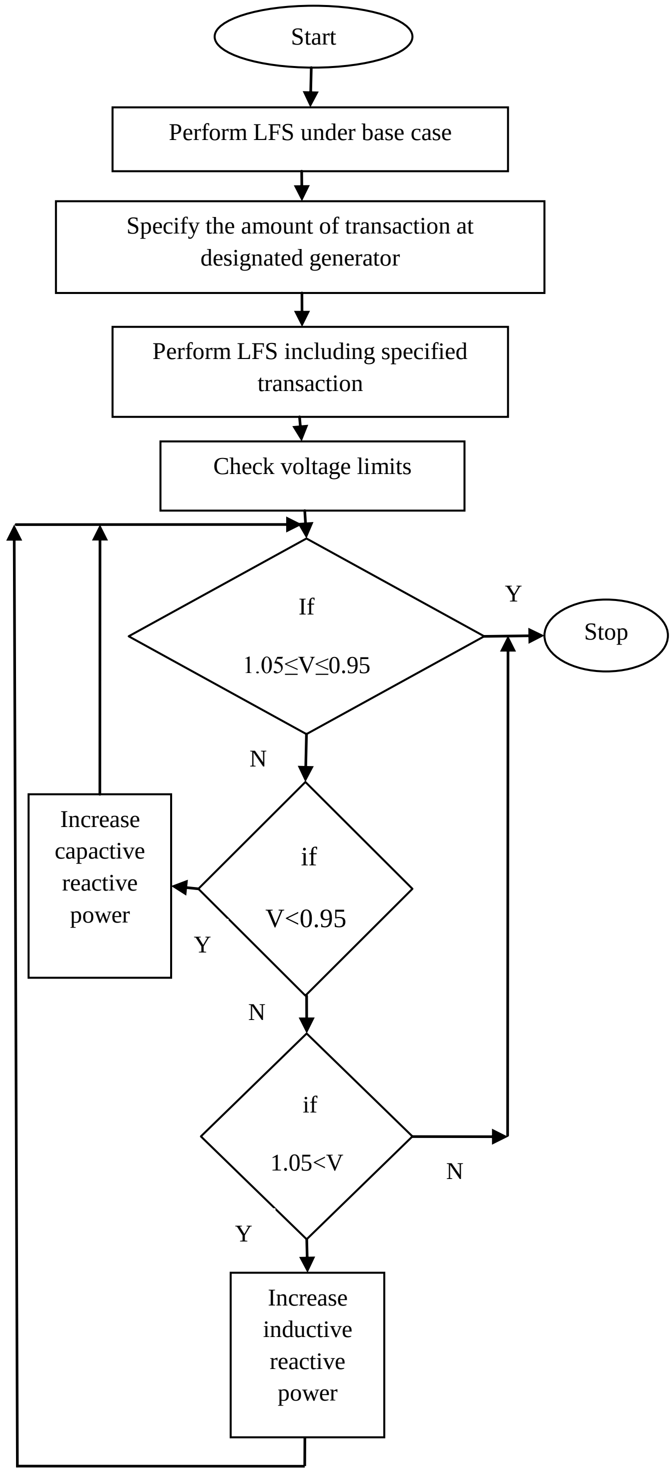

Fig 1: Flow Chart for Reactive Power Evaluation

In this system, four cases have been considered as follows:

Base case: Bus 1 is slack bus, bus 2 is PV bus and bus 3 and 4 are PQ buses. The load flow by NR method is performed and the unspecified variables are calculated as shown in table 3.

Table 2. Load data of 4-bus test system

Bus	Bus Power		Voltage (pu)	Bus Type
	Real (MW)	Reactive (MVAr)		
1	Unspecified	Unspecified	1.02	Slack
2	95	Unspecified	1.01	PV
3	-200	-100	Unspecified	PQ
4	-100	-20	Unspecified	PQ

Table 3. Reactive power and voltage of 4 bus system

Cases	Bus no.	Reactive Power (in MVAr)	Voltage (in p.u.)
Base case/ Case 1	1	172	1.02
	2	48	1.01
	3	-100	0.79
	4	-20	0.91
Case 2	1	200	1.04
	2	15	1.01
	3	-100	0.82
	4	-20	0.93
Case 3	1	250	1.09
	2	-38	1.01
	3	-100	0.87
	4	-20	0.95

Case 1: Bus 2 is the slack bus and rest are the PQ buses. Bus 1 is designated generator bus from which reactive power is procured, so when case 1, slack bus has been changed to bus 2. If bus 1 will be used as slack bus then it is not possible to fetch the reactive power from it. Hence, bus 2, which contains a generating source, is specified as slack bus. After that the load flow is performed. In this the voltage at PQ bus is not in limits. So increase the reactive power.

Case 2: In case 2 the reactive power is increased up to 200MVAr instead of 172MVAr at generation bus. In case 2 again voltage is not in limits.

Case 3: In case3, there is further increase in the reactive power up to 250 instead of 200. In case3 the voltage may become in limits, so no need to increase the reactive power any more. It is shown in table 3.

After all the cases it is concluded that if the reactive power is increased after 250MVAr, the upper voltage limit will be violated at bus 1. In order to remove this short coming, shunt capacitor banks/ shunt FACTS device should be installed at the load bus 3, which would provide the local reactive power.

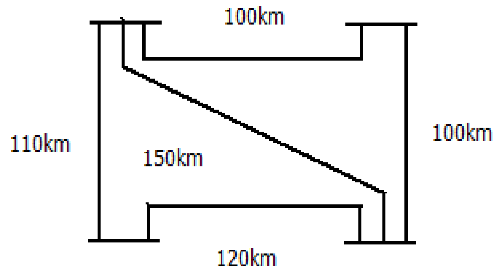

Fig 2: One line diagram of 4-bus test system

Table 4. Load data of IEEE 9-bus test system

Bus	Type of bus	Voltage		Load		Generation P(MW)
		|v|(pu)	δ ($\boldsymbol{\theta}$)	P (MW)	Q (MVAr)	
1	slack	1.0300	0	0	0	
2	PQ	1.0000	0	10	5	
3	PQ	1.0000	0	25	15	
4	PQ	1.0000	0	60	40	
5	PV	1.0600	0	10	5	80
6	PQ	1.0000	0	100	80	
7	PQ	1.0000	0	80	60	
8	PV	1.0100	0	40	20	120
9	PQ	1.0000	0	20	10	

5.2 IEEE 9-bus test system

The system data of IEEE 9-bus system is given in tables 4 and 5 and single line diagram is shown in Fig. 3. The results with different transactions are shown in Tables 6, 7, 8, 9.

Table 6 shows the base case results. This is the result when bus 1 is slack bus, bus 5 and 8 are the PV buses and rest are the PQ buses. Load flow is performed. The unspecified variables are obtained from these results. These base case results are taken as reference for all the specified transactions as discussed in different cases below.

5.2.1 Case 1: Transaction of 200MW from bus 8 (generator bus) to bus 3 (load bus)

Base case is taken as reference which is shown in Table 6. It is the case, in which the bus 1 is slack bus and all the other buses are PQ buses. The transaction of 200MW is considered from generation bus to load bus. The voltage at load bus i.e. at bus 3 is within its limits. So there is no need to increase the reactive power at generation bus. It is shown in Table 7.

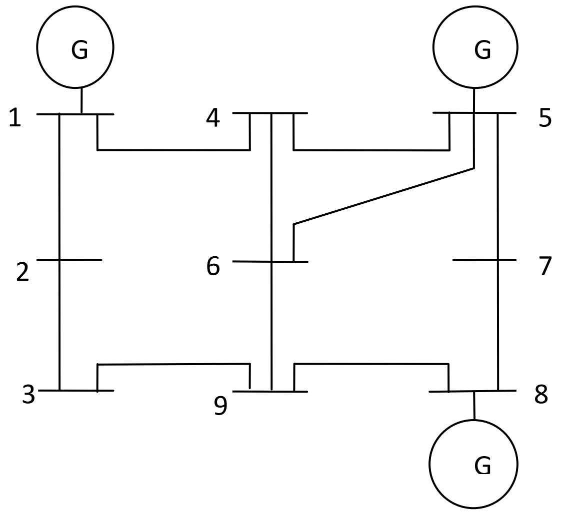

Fig 3: One line diagram of 9-bus test system

Table 5. Data of IEEE 9-bus test system

Bus no.	Bus no.	R (pu)	X (pu)	½ B (pu)	Transformer tap
1	2	0.018	0.054	0.0045	1
1	4	0.015	0.054	0.0045	1
2	3	0.018	0.056	0	1
3	9	0.02	0.06	0	1
4	5	0.013	0.036	0.003	1
4	6	0.02	0.066	0	1
5	6	0.06	0.03	0.0028	1
5	7	0.014	0.036	0.003	1
6	9	0.01	0.05	0	1
7	8	0.032	0.076	0	1
8	9	0.022	0.065	0	1

5.2.2 Case 2: Transaction of 200MW from bus 5 (generator bus) to bus 3 (load bus)

Base case is taken as reference which is shown in table 6. It is the case, in which the bus 1 is slack bus and rest are PQ buses.

Sub case 2A: It is the case in which the transaction of 200MW is considered from bus 5 to bus 3. In sub case 2A the voltage at demand bus is not in the limits. So it is needed to increase the reactive power at generation bus. Sub case 2B: In sub case 2B the reactive power at bus 5 is increased up to 300MVAr instead of 272.3MVAr. By increasing the reactive power at bus 5 in sub case 2B, the voltage becomes in its limits at bus 3 in sub case 2B. It is shown in table 8.

5.2.3 Case 3: Transaction of 300MW from bus 5 (generator bus) to bus 3 (load bus)

Base case is taken as reference which is shown in table 6. It is the case, in which the bus 1 is slack bus and all the other buses are PQ buses.

Table 6. Reactive power and voltage of IEEE 9 bus system base case results

Bus no.	Reactive Power (in MVAr)	Voltage (in p.u.)
1	-10	1.03
2	-5	1.01
3	-15	0.99
4	-40	1.02
5	272.3	1.05
6	-79	1.00
7	-59	1.01
8	-30.45	1.00
9	-09	1.00

Table 7. Reactive power and voltage of IEEE 9 bus system

Bus no.	Reactive Power (in MVAr)	Voltage (in p.u.)
1	34	1.03
2	-5	0.98
3	-15	0.95
4	-40	1.02
5	272.3	1.05
6	-80	0.99
7	-60	1.02
8	-30.45	1.01
9	-10	0.98

Table 8. Reactive power and voltage of IEEE 9 bus system

Cases	Bus no.	Reactive Power (in MVAr)	Voltage (in p.u.)
Sub case 2A	1	20	1.03
	2	-5	0.98
	3	-15	0.94
	4	-40	1.03
	5	272.3	1.07
	6	-80	0.99

	7	-60	1.03
	8	-30.45	1.00
	9	-10	0.97
Sub case 2B	1	-6	1.03
	2	-5	0.99
	3	-15	0.95
	4	-40	1.04
	5	300	1.09
	6	-80	1.00
	7	-60	1.04
	8	-30.45	1.01
	9	-10	0.98

Sub case 3A: It is the case in which transaction of 300MW from bus 5 to bus 3 is considered. In sub case 3A the voltage at load bus (bus 3) is not in limits. So it is required to increase the reactive power at generation bus. Sub case 3B: In this, the reactive power is increased from 272.3 to 300MVAr but the voltage does not become in limits.

Sub case 3C: Increase the reactive power 350 instead of 300MVAr, still the voltage does not become in limits.

Sub case 3D: In this case, further increase the reactive power up to 400 instead of 350MVAr, the voltage becomes approximately in limits at bus 3. It is shown in table 9.

After the entire sub cases of case 3, it is concluded that if the reactive power is increased after 400MVAr, the voltage limit will be violated at all the other buses. In order to remove this short coming, shunt capacitor banks should be installed at the load bus 3, which would provide the local power.

Table 9. Reactive power and voltage of IEEE 9 bus system

Cases	**Bus no.**	**Reactive Power (in MVAr)**	**Voltage (in p.u.)**
Sub case 3A	1	65	1.03
	2	-5	0.96
	3	-15	0.90
	4	-40	1.02
	5	272.3	1.07
	6	-80	0.97
	7	-60	1.02
	8	-30.45	0.98
	9	-10	0.95
Sub case 3B	1	36	1.03
	2	-5	0.96
	3	-15	0.91
	4	-40	1.03
	5	300	1.09
	6	-80	0.98
	7	-60	1.04
	8	-30.45	0.99
	9	-10	0.96
Sub case 3C	1	-12	1.03
	2	-5	0.97
	3	-15	0.92
	4	-40	1.05
	5	350	1.11
	6	-80	1.00
	7	-60	1.06
	8	-30.45	1.02
	9	-10	0.98
Sub case 3D	1	-59	1.03
	2	-5	0.98
	3	-15	0.93
	4	-40	1.06
	5	400	1.14
	6	-80	1.02
	7	-60	1.08
	8	-30.45	1.04
	9	-10	1.00

6. CONCLUSIONS

This paper has presented an off-line approach for reactive power procurement to satisfy the total system reactive power demand while targeting safe voltage profile of the power system. The presented methodology is performed by repeated load flows while taking the reactive power from designated generators. The proposed methodology provides flexibility to the system operator to procure the reactive power from available sources as per the needs of the demand based on their base case voltage profile. In 4-bus system, it has been observed that the shunt capacitor banks at load bus 3 are additionally required to maintain voltage profile. In IEEE 9-bus system, under transaction of 200MW from bus 5 to bus 3, an additional reactive power of 27.7 MVAr is required to be procured from generator at bus 5 to maintain system voltage profile. Similarly, in case 3, the reactive power is increased up to 400MVar from 272 MVar to set the safe voltage profile.

In future, the present problem is being extended to be formulated as an optimization problem incorporating the cost of reactive power and system losses. The effect of other ancillary services may be included. The procurement of reactive power from other sources such as FACTS devices rather than synchronous generators may be included.

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