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Effective Generator Reactive Power Reserve Management Using Fuzzy Constrained Optimization

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Abstract*— Present paper aims to propose an effective procedure to maximize EGRPR by formulated it as a Fuzzy constrained optimization problem where P-δ loop and Q-V loop is updated in every iteration. It is required to define system constraints that are to be maintained within their limits to achieve adequate reactive power margin. Reactive power reserve at generating stations is measure for degree of voltage stability. The power system should be operated with an acceptable voltage stability margin by proper scheduling of reactive power resources and voltage profile. Otherwise it leads to voltage instability and requires proper control. Main control actions against voltage instability are classified into preventive and corrective control. In this paper to enhance the voltage stability a preventive counter measure is proposed by managing generator reactive power reserve properly. The voltage and reactive power management is considered from generator's point of view to maximize the Effective Generator Reactive Power Reserve. A simple fuzzy logic based optimal power flow and Benders' decomposition methods are used to maximize the same and the methodology is tested on 6 -bus system.

***Keywords*— Voltage stability, Benders' Decomposition, Q-V curves, Generator Reactive Power Reserve, Fuzzy logic.**

I. INTRODUCTION

After restructuring the power industry, the system operator is sole responsible for voltage and reactive power management in the network. Also the power system operation is constrained by firm economic constraints. As a result, the system will be under stress and operates close to operating limits leading to wide spread of blackouts. Insufficient voltage and reactive power reserve support is a key factor to major blackouts [1, 2]. Under such electricity markets, the voltage and reactive power control services are the critical ancillary services. These services should be continuously provided by the system operator for reliable operation of power system. Sufficient control actions should be taken for security of bulk power system against the short and long-term instabilities. These actions comprises of Reactive Power Reserves (RPR) and emergency counter measures that can be considered as the preventive and corrective controls. The main preventive actions against power system voltage instability are management of reactive power reserves through load tap changing, capacitor switching and implementation of hierarchical voltage and reactive power control schemes [2]. Both reactive power generation and reserve should be considered for procurement and scheduling of reactive power resources. Such reactive power management will improve the voltage stability margin. It must be noted that RPR can be viewed from loads' and generator's side. Literature paid more attention on load point of view rather than generator point of view. The generator reactive power reserve (GRPR) is classified into Technical generator reactive power reserve (TGRPR) and effective generator reactive power reserve (EGRPR). Many studies utilize TGRPR rather than EGRPR, since it can be easily calculated [27, 28]. In [15] it is shown that effective RPR not only depend on generator capability curve but also depend on the transmission network characteristics. In [15] the author implements the two level benders decomposition, including a base case and stressed cases, based on OPF to improve the voltage stability. The effective RPR for a bus or an area is found in [16] as the weighted sum of the individual RPRs of generators at the minimum of VQ curve. In [16] author uses two level Benders' decomposition method as preventive control action against voltage instability.

Load flow studies play an important role in power system studies. A number of conventional power flow methods [14-19] have been proposed in literature. In stability studies, the solution of load flow problem is obtained when a power system is operated at loadability limit. Maximum loadability margin is the amount of load demand that a power system can support before voltage collapse [20-26]. The loadability margin is a function of reactive power reserve in the network and the relationship between voltages and network loadability is nonlinear. To determine the maximum loadability limit of power system continuous power flow (CPF) technique and optimal power flow methods (OPF) or mathematical optimization techniques are widely used. The fundamental approaches to determine reactive power reserve range from the linear programming techniques to nonlinear programming [7-13]. Due to the power flow derivatives, the conventional methods face jacobian singularity and fail to give solution at those situations. And repetitive solution of these methods requires large amount of memory. To overcome these limitations a number of evolutionary optimization methods like Particle Swarm Optimization (PSO), Genetic Algorithm (GA), and Fuzzy Logic (FL) have been proposed [4-6]. These approaches are not based on the power flow derivatives, hence, do not face problem of singularity at maximum loading conditions. In [4] author proposes fuzzy logic controller to update the power variables.

To achieve adequate reactive power margin, system constraints that are to be maintained within their limits must be defined, hence constituting a better approach is required.

The present work aims to propose an effective procedure to maximize EGRPR by formulated it as a Fuzzy constrained optimization problem where P-δ loop and Q-V loop are updated in every iteration.

II. REACTIVE POWER RESERVE MANAGEMENT

The RPR is spare reactive power available in the system to assist the voltage control, to respond to unforeseen events that lead to a sudden change of reactive power requirement. Thus, the generators are the main sources of reactive power reserve. The RPR can be viewed from load's and generator's side. A two bus system shown in the Fig. 1a shows various view points of RPR. A generator and load is connected to bus 1 and bus 2, the QV-curve method for which details are in [14], is used to get the reactive power margin to voltage collapse point. For this purpose a fictitious reactive power supports Q_f's are connected to particular voltage sensitivity nodes (pilot nodes). The QV-curve in Fig.1-b shows the relationship between reactive power support (Q_f) at a given bus and the amount voltage at that bus (V) [1-3]. The minimum of QV-curve shows the reactive power margin to lose the operating point this point is called collapse point and it is shown by white circle. The operating point at which ($Q_f=0$) is shown by black circle. Present work uses optimal power flow (OPF) method to compute the reactive power margin to the voltage collapse point [15, 16].

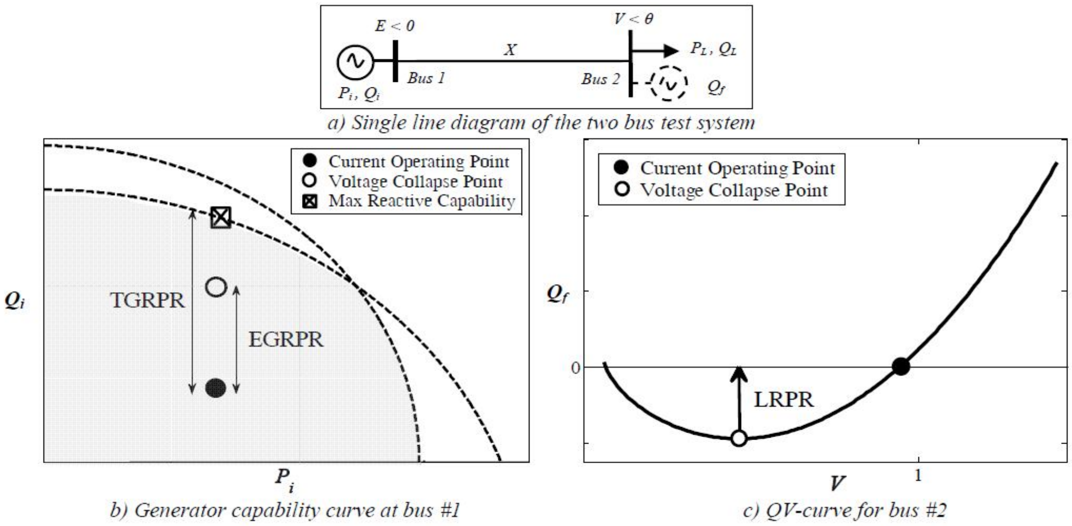

Fig. 1 LRPR, TGRPR, and EGRPR for the two bus system [3, 16]

The Load RPR (LRPR), given in Fig. 1-c, stated as the minimal amount of the reactive load increase for which the system losses its operability [1-3, 16]. The GRPR focuses on the value of RPR provided by each generator. TGRPR is the difference between the maximum reactive power capability of the generator and its reactive power generation at the current operating point. However, this quantity may not represent the useful quantity of the RPR since at the collapse point all the amount of the TGRPR cannot be utilized. EGRPR, as a more accurate representative of the GRPR, is the difference between the generator's reactive power output at the voltage collapse point and the generator's reactive power output at the current operating point. The TGRPR is an upper bound for the EGRPR. LRPR, TGRPR, and EGRPR for the two bus test system are shown in Fig. 1-c and 1-b [3, 16].

This paper deals with maximization of GRPR especially on EGRPR as main preventive action to improve the voltage stability margin. An optimization problem is decomposed into two level optimization using Bender's decomposition method based on the participated optimized variables and is further solved with optimal fuzzy- interior point algorithm. Optimization is performed for given active power operating point whose performance is compared with conventional method [16].

III. PROPOSED METHODOLOGY

To ensure the voltage stability of a system, management of reactive power generation and its reserve is a correlated task which strongly depends on the generator and transmission system capabilities. Power supplied by a generator is constrained by capability curve. For a given real power output, the reactive power generation is limited by both field and armature current limitation. The maximum produced reactive powers regarding these two limitations are given by (1) and (2). The smaller of the two values is chosen as maximum reactive power output (Q_k^{max}).

$$Q_{rk} = -\frac{V_k^2}{X_{sk}} + \sqrt{\frac{V_k^2 I_{kf}^2}{X_k^2} - P_k^2} \quad (1)$$

$$Q_{ak} = \sqrt{V_k^2 I_{ak}^2 - P_k^2} \quad (2)$$

Where k is index of generators, V_k is generator terminal voltage, P_k is generator active power output, I_{kf} is maximum field current, I_{ak} is the maximum armature current, and X_{sk} is the synchronous reactance.

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For the k^{th}- generator, *TGRPR* and *EGRPR* are defined by the following equations [23].

$$TGRPR = Q_k^{\max} - Q_k \qquad (3)$$

$$EGRPR = QC_k - Q_k \qquad (4)$$

Where Q_k is the generator reactive power output at current operating point, Q_{Ck} is the generator reactive power output at voltage collapse point and Q_k^{max} is maximum reactive power output obtained from (1) and (2). To maximize EGRPR and as consequence to improve voltage stability margin, the objective function can be formulated as

$$\max EGRPR = \max \sum_{i \in NG} QC_k - Q_k \equiv \min \sum_{i \in NG} Q_k - QC_k \qquad (5)$$

The hierarchical relationship between operating and collapse point in (5) is achieved by decomposing the objective function. Therefore, the problem is decomposed into two parts, a master-problem, and a sub-problem. It is solved by the Bender's decomposition method in an iterative way [15, 16].

By using Benders' decomposition method the problem is decomposed into master-problem and sub-problem according optimization variables. To correlate master- problem and sub-problem a Benders' cut is added to master problem which relates the master-problem and sub-problem. The proposed two level Benders' decomposition is shown in the Fig. 2.

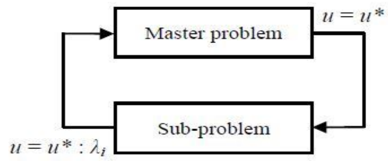

Fig. 2. Two level optimization

A. Master Problem

The main objective function in (5) is formulated as the master-problem

$$\min_{u,\alpha} f(x,u) + \alpha \qquad (6)$$

$$\text{subject to: } h(x,u) = 0 \qquad (7)$$

$$g(x,u) \le 0 \qquad (8)$$

$$\alpha_{down} \le \alpha \qquad (9)$$

$$BC_k^{(i)} \le \alpha_k \qquad i = 1....v, \ \ to\ NG \qquad (10)$$

Where $f(x,y)$ is reactive power output optimization minimization of generators $(\sum Q_k)$. u is the vector of control variables including voltage of *PV* generators and reactive power output of *PQ* generators. x indicates the vector of the state variables. α is optimal objective function vector of sub-problem for master problem. *h(x,u)* are equality constraints like load flow equations is given by (11-12). *g(x,u)* represents inequality constraints like transmission power flow limit given by (13). Limits on reactive power and voltage magnitude are given by (14, 15). The constraint given in equation (10) represents Benders' cut added to the master problem. Here, i denote the number of iterations and v represents number of cuts added to master problem.

$$P_{kn} - P_{dn} - \sum_{m \in NB} V_n V_m (G_{nm} \cos\theta_{nm} + B_{nm} \sin\theta_{nm}) = 0 \qquad n \in NB \qquad (11)$$

$$Q_{kn} - Q_{dn} - \sum_{m \in NB} V_n V_m (G_{nm} \sin\theta_{nm} - B_{nm} \cos\theta_{nm}) = 0 \qquad n \in NB \qquad (12)$$

$$(G_{nm}^2 + B_{nm}^2).(V_n^2 + V_m^2 - 2V_n V_m \cos\theta_{nm}) \le (T_l^{\max})^2 \qquad \{n,m\} \in l, l \in NL \qquad (13)$$

$$Q_k^{\min} \le Q_k \le Q_k^{\max} \qquad k \in NG \qquad (14)$$

$$V_k^{\min} \le V_k \le V_k^{\max} \qquad k \in NB \qquad (15)$$

$$-QC_k^{(i)} + \lambda_{k-pv}^{(i)}.(V_k - V_k^{(i)}) \le \alpha_k \qquad i = 1.........v, (k \in NG : PVnodes) \qquad (16)$$

$$-QC_k^{(i)} + \lambda_{k-pq}^{(i)}.(Q_k - Q_k^{(i)}) \le \alpha_k \qquad i = 1.........v, (k \in NG : PQnodes) \qquad (17)$$

The control variables obtained from the master- problem u* are used as input to the sub-problem (Fig. 2) and determines the generator's reactive power output at voltage collapse point. Obviously the results of master-problem and sub-problem are dependent to each other. The reactive power output of generators at voltage collapse point is evaluated by following optimization.

B. Sub Problem

The objective function of sub-problem is formulated as follows.

$$\max_p e(x, u^*, p) \qquad (18)$$

Subject to

$$h(x, u^*, p) = 0 \qquad (19)$$

$$g(x,u^*) \le 0 \tag{20}$$

$$u_k = u_k^* : \lambda;\ k = 1...NG \tag{21}$$

e(x,u,p)* summation of reactive power output of generators at voltage collapse point $\sum_{k\in NG} QC_k$.

It should be noted that maximization of reactive power output at voltage collapse point is the same as maximization of fictitious reactive power injection at pilot nodes $\sum_{k\in NP} Q_{fp}$, where the index *p* represents pilot nodes and *NP* is number of pilot nodes. Q_{fp} is fictitious reactive power injection at pilot nodes at bus *p*. Positive and negative values of Q_{fp} , are devoted for reactive power consumption and generation. Where *h(x,u*,p)* and *g(x,u*)* are the equality and inequality constraints as like master-problem given by (23, 24).All the constraints are similar to master problem, except reactive power balance equation (24) is different with (12). In (24) the term Q_{fp} is added which indicates reactive power injection at pilot nodes. *p* is the fictitious injected reactive power at the voltage collapse points for each voltage sensitivity nodes (pilot nodes). λ_k is the lagrangian multipliers obtained by solving the sub-problem [29-31]. These multipliers are calculated for all PV nodes (λ_{k-pv}) PQ nodes (λ_{k-pq}) . By using the dual variables obtained from sub-problem Bender's cut is added to master-problem as like (10) shown in (16-17).

$$BC_k^{(i)} = -e(x, u_k^{(i)}, p) + \lambda_k^{(i)}.(u_k - u_k^{(i)}) \tag{22}$$

Constraints of sub-problem:

$$P_{kn} - P_{dn} - \sum_{m\in NB} V_n V_m (G_{nm}\cos\theta_{nm} + B_{nm}\sin\theta_{nm}) = 0 \qquad n \in NB \tag{23}$$

$$Q_{kn} - Q_{dn} - Q_{fp} - \sum_{m\in NB} V_n V_m (G_{nm}\sin\theta_{nm} - B_{nm}\cos\theta_{nm}) = 0 \qquad n \in NB \tag{24}$$

$$(G_{nm}^2 + B_{nm}^2).(V_n^2 + V_m^2 - 2V_n V_m \cos\theta_{nm}) \le (T_l^{\max})^2 \qquad \{n,m\} \in l, l \in NL \tag{25}$$

$$Q_k^{\min} \le Q_k \le Q_k^{\max} \qquad k \in NG \tag{26}$$

$$V_k^{\min} \le V_k \le V_k^{\max} \qquad k \in NB \tag{27}$$

C. Optimal Fuzzy Load Flow

In the conventional load flow problems like, Fast Decoupled Load Flow method (FDLF) the repetitive solution is obtained by considering equation (28) and (29).

$$\left[\frac{\Delta P}{V}\right] = [B'][\Delta\delta] \tag{28}$$

$$\left[\frac{\Delta Q}{V}\right] = [B''][\Delta V] \tag{29}$$

The above equation (28) & (29) can be expressed as

$$\Delta Y = J.\Delta X \tag{30}$$

Where, ΔY , real and reactive power mismatch vector.

ΔX , correction vector (voltage magnitude or voltage angles)

The above equation states that the correction of state vector, ΔX at each node of the network is directly proportional to vector, ΔY . The fuzzy load flow algorithm is based on previous fast decoupled load flow equations (28) & (29) but the repeated update of correction vector of the power system will performed via fuzzy logic controller [4,5].

$$\Delta X = fuz(\Delta Y) \tag{31}$$

where *fuz* represent a fuzzy logic function.

In fuzzy load flow algorithm, both power mismatch and summation of power mismatch are taken as two crisp input signals for fuzzy logic controller at each node of the system. Considering the magnitude of power mismatch and sign of power mismatch, 25 fuzzy rules are considered from two set of input signals. Two separate loops are used to update the power flow variables [4-6].

D. Selection of Maximum Range for Fuzzy Input and Output Variables

The maximum ranges for input and output variables can be evaluated by using following formulae [5].

1) $P-\delta$ loop:

$$\Delta\delta_{\max} = [B']^{-1}\left[\frac{\Delta P_{\max}}{V_m}\right] \tag{32}$$

$$\max(\sum \Delta P) = |\Delta P_{\max}|;\ if\ |\Delta P_{\max}| > \left|\sum_{i\in(n-1)} \Delta P_i\right| = \left|\sum_{i\in(n-1)} \Delta P_i\right|;\ otherwise \tag{33}$$

2) $Q-V$ loop:

$$\Delta V_{\max} = [B'']^{-1}\left[\frac{\Delta Q_{\max}}{V_m}\right] \tag{34}$$

$$\max(\sum \Delta Q) = \left|\Delta Q_{\max}\right|;\ if\ \left|\Delta Q_{\max}\right| > \left|\sum_{i \in m} \Delta Q_i\right| = \left|\sum_{i \in m} \Delta Q_i\right|;\ otherwise \qquad (35)$$

Where,

$\Delta P_{\max}$ is maximum real power mismatch at mth bus & $\Delta Q_{\max}$ is maximum reactive power mismatch at mth bus.

B' & B'' are admittance matrices, n is number of buses & m is PQ buses.

E. Membership Function for Input and Output Variables

The two crisp input signals are fuzzified with five linguistic variables; negative Large (NL), negative (N), zero (Z), positive (P), positive Large (PL). The triangular membership functions for *Q-V loop* are shown in Fig. 3-5. The fuzzy crisp input signals are sent to process logic, which generates a fuzzy output signal. The fuzzy output signal then sent defuzzification interface having five linguistic variables similar as input linguistic variables shown in Fig.5.The centroid of area (COA) strategy is employed for defuzzification of fuzzy output signal.

1) Crisp Input-1& Input-2:

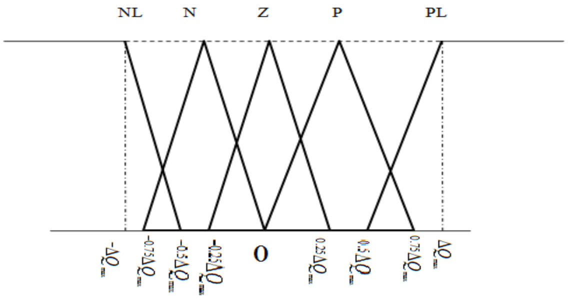

Fig. 3 Membership function for crisp input-1 ΔQ

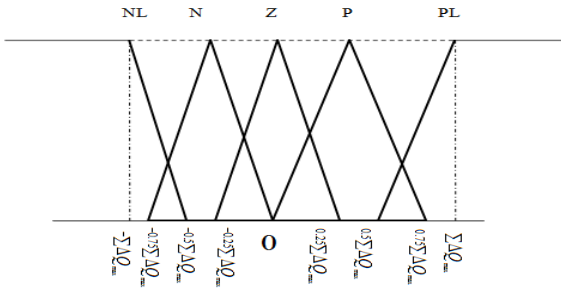

Fig. 4 Membership function for crisp input-2 summation of ΔQ

2) Crisp output-1

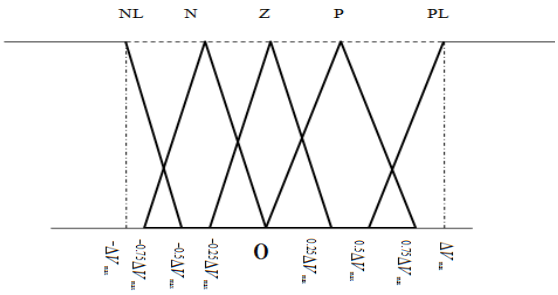

Fig. 5 Membership function for crisp output: Voltage correction vector

For two inputs similar type of membership functions are considered to generate the rule base with 25 rules is as shown in Table 1.

TABLE 1
FUZZY RULES FOR *Q-V* LOOP

ΣΔQ \ ΔQ	NL	N	Z	P	PL
NL	NL	NL	N	Z	P
N	NL	N	N	Z	P
Z	N	N	Z	P	P
P	Z	Z	P	P	PL
PL	P	P	P	PL	PL

The correction vectors calculated from two fuzzy control loops and the power variables are updated in every iteration for each node of the system.

IV. CASE STUDY

The proposed method of optimization i.e. maximization of *EGRPR* is a non-linear OPF model and it is tested on 6-bus system shown in Fig. 6. The 6-bus system has 3 generators, 3 loads, and 11 transmission lines. Here, bus-5 is chosen as voltage sensitivity node (pilot node) since it is directly connected to all generators. The simulation is carried out with 3 PV generators. The data for 6-bus system, active and reactive power loads, transmission system data is given in [32].The same capability curves are considered for all 3 PV generators and the parameters of (1) and (2) are equal to $I_f=2pu$, $I_a=1.5pu$, $X_s=1pu$. The voltage deviation of all the buses is acceptable within ±5% of nominal voltage value. The optimization stops at the k^{th} iteration where $EGRPR^k$ becomes lower than $EGRPR^{(k-1)}$.

$$EGRPR^{k} - EGRPR^{(k-1)} < 0 \quad (36)$$

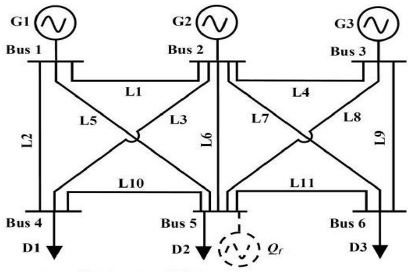

Fig. 6 One line diagram of 6-bus system

V. RESULTS AND DISCUSSIONS

On the test system it takes 8 iterations to satisfy the defined optimization criteria in (36). The obtained voltage values from optimal fuzzy load flow analysis at satisfied maximum real and reactive power mismatches are V_1=1.0514, V_2=1.025-j0.0564, V_3=1.038-j0.0667, V_4=0.971-j0.067, V_5=0.9607-j0.0836 and V_6=0.9721-j0.0935. The voltage at all buses is within acceptable voltage deviation $\pm 5\%$. Fig.7 shows the generators reactive power output at the current operating point (Q_k) and at collapse operating point (Q_{Ck}). Fig.8 shows increase in *EGPRP versus* number of iterations. The obtained set point voltages of 3 PV generators are V_1=1.0514pu, V_2=1.0467pu and V_3=1.0604 pu. The reactive power output ($\sum Q_k$) before and after optimization is 179.939 and 182.3554 respectively. The generators reactive power output at voltage collapse point ($\sum Q_{Ck}$) before and after optimization are 198.622 MVAR and 219.9465 MVAR respectively. The reactive power reserve improved from 18.683 MVAR to 37.5911 MVAR.

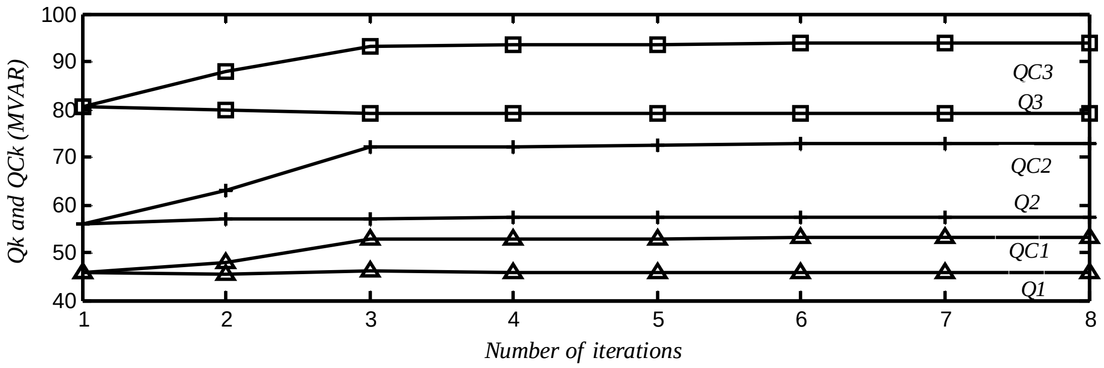

Fig. 7 Q_k and QC_k Vs Number of iterations

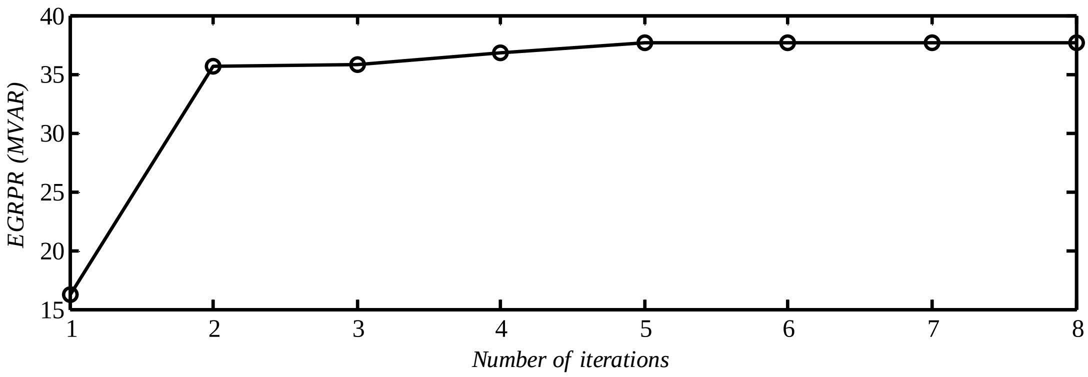

Fig. 8 Increase in EGRPR Vs Number of iterations

VI. CONCLUSION

This paper discusses the management of generators reactive power generation and reserves for improving the voltage stability margin. The proposed methodology is based on optimal fuzzy load flow method. The proposed optimal fuzzy load flow method takes more number of iteration than the conventional load flow methods. But the proposed method do not require any factorization and computation of Jacobian matrix at every iteration. In the proposed method the optimal power flow problem is decomposed into a master-problem and a sub-problem through bender decomposition method, optimal fuzzy load flow method is used to solve master and sub problems. The obtained results show that EGRPR is increased at end of optimization. The method ensures the maximum attainable preventive voltage margin from the available voltage and reactive power control resources.

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