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A Genetic Algorithm for corrective control of voltage and reactive power

Kumar.P
Assistant Professor/Department of EEE
P.A. College of Engineering, Pollachi, India

Vignesh Kumar.M
Assistant Professor/Department of EEE
P.A. College of Engineering, Pollachi, India

Abstract-This paper presents an algorithm for the selection of corrective control actions for the bus voltage and generator reactive power in a power system. A genetic algorithm (GA) using linear approximation of the load flow equations and a heuristic selection of participating controls were combined in a search method for minimum number of control actions. The method was successfully applied to IEEE 30-bus model. The GA is compared with inter-programming based solution method and showed a considerably reduced calculation time.

***Keywords- Genetic Algorithm (GA), reactive power control, voltage control*.**

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I. INTRODUCTION

One of the principle tasks of the operator of an electricity supply system is to ensure that the bus voltages and line loads are maintained within predefined limits. A situation in which operational limits are violated is described as an emergency state, and the actions required to correct this state are called emergency control actions. It should be noted that the expression "emergency" does not necessarily indicate an immediate collapse of the system but rather a situation requiring correction. The task of secondary voltage control (SVC) is to eliminate any voltage deviations that remain after the actions of the primary voltage regulators (PVRs).Automatic SVC reduces to minimum the risk of reaching an emergency state. This task cannot be achieved in the same way by manual control. However in systems that lack automatic real-time SVC, this task is performed manually by the supervisor in the dispatch centre. Control actions may be prepared in advance for certain emergencies, so that the supervisor in accordance with the clearly defined defense plans can prevent the system from getting into emergency state. In the absence of such plans, the survival of the electricity system depends on the experience and the skill of the supervisor. Due to the complexity of modern power systems and severe consequences to the economy due to power failures, an ever-increasing reliance has to be placed on computer algorithms.

This paper deals with the selection of control actions for the elimination of violations of constraints on bus voltage and generator reactive power, in a system without automatic real-time SVC.As bus voltages deviate from nominal values, usually the first constraints violated are operational(procedural) constraints, such as a 5% allowable margin around the nominal value. Further deviation of voltage values may pose a threat to system stability. This means that corrective control is usually performed well before the system reaches the stability limits. This paper deals with the more common cases where manual corrective control is required for the alleviation of procedural constraint violations. It is assumed that for more severe voltage deviations, which are out of the scope of this paper, under voltage protection automatically disconnects customer loads. Several methods for the selection of control actions have been developed in the past. A major problem common to many of the proposed analytical techniques is that despite the essentially discrete nature of the equipment such as switched capacitors and transformer tap changers, the calculations treat all variables as continuous.

The common treatment for this issue is to round off the variables to a near discrete value. This inconsistency may cause inadequate solutions [2], [3].An additional difficulty is that solutions may be found that require a large number of actions, which could be unacceptable since we are dealing with manual operator actions.

For both the fore-mentioned problems, a genetic algorithm (GA) seems to bring a solution, considering the ability of this algorithm to deal with continuous as well as discrete variables and a wide range of optimization objectives. The objective of this paper was to determine if a GA can provide an adequate solution for the corrective control problem while acting sufficiently rapid to be relevant for operational service.

II.SYSTEM MODELLING

The theoretical background of the reactive power/voltage control problem will be presented, using the following equations governing the energy balance at every node i of an electricity system:

$$F_{Pi} = P_{Gi} - P_{Li}$$

$$= -\sum_{j=1}^{n} V_i V_j [g_{ij} \cos(\theta_j - \theta_i) - b_{ij} \sin(\theta_j - \theta_i)] \quad (1)$$

$$F_{Qi} = Q_{Gi} - Q_{Li}$$

$$= -\sum_{j=1}^{n} V_i V_j [g_{ij} \sin(\theta_j - \theta_i) + b_{ij} \cos(\theta_j - \theta_i)] \quad (2)$$

Where,

F_{Pi}, F_{Qi}	energy balance of active and reactive powers at bus i ;
P_{Gi}, Q_{Gi}	Active and reactive powers generated at bus i ;
P_{Li}, Q_{Li}	Active and reactive parts of load at bus i ;
V_i, V_j	Voltage amplitudes at bus i and j ;
g_{ij}, b_{ij}	active and reactive parts of admittance of the line between buses i and j
θ_i, θ_j	phase angle of the voltages at buses i and j
n	number of buses.

For the solution of the load flow problem, the above used variables and constants are traditionally classified in the following vectors:

$\underline{x}$	State variables (generator reactive power and voltage phase angle, load voltage amplitude)
$\underline{u}$	Control variables (generator active power and voltage amplitude)
$\underline{d}$	Disturbance variables (load active and reactive power)
$\underline{z}$	Constants (line admittance and the relevant transformer ratio).

In generalized form, the energy balance for all the buses is presented by vector f .A solution of the load flow equations is obtained when $\underline{f}(\underline{x}, \underline{u}, \underline{d}, \underline{z}) = \underline{0}$,where d, z are considered constant.

The elimination of the voltage constraint violations is achieved by adjusting generator voltages, transformer ratio, and switching shunt devices. This means that what distinguishes the voltage control problem from the load flow problem is that transformer ratio and the load reactive power are no longer considered as constants but are controlled quantities as well. The goal of emergency control is therefore to find the proper combination u, d, z such that,

$$\underline{f}(\underline{x}, \underline{u}, \underline{d}, \underline{z}) = \underline{0} \qquad (3)$$

while enforcing constraints $\underline{\hat{g}}$ to variables such as bus voltages, generator loads, line currents, as well as controlled quantities, together represented by g .

$$\underline{g}(\underline{x}, \underline{u}, \underline{d}, \underline{z}) \underline{<} \underline{\hat{g}} \qquad (4)$$

Given the wide range of combinations $\underline{u}, \underline{d}, \underline{z},$ the number of possible solutions is generally large, and it is possible to make an optimal choice of control actions. If the control problem is defined as an optimization problem, the equations become,

Optimize $\underline{h}(\underline{x}, \underline{u}, \underline{d}, \underline{z})$ subject to

$$\underline{f}(\underline{x}, \underline{u}, \underline{d}, \underline{z}) = \underline{0}$$

$$\underline{g}(\underline{x}, \underline{u}, \underline{d}, \underline{z}) \underline{<} \underline{\hat{g}} \qquad (5)$$

III.SOLUTION METHODS

The first published analytical methods were based on classic optimization method such as linear programming [4], [5].In the majority of the studies, the load flow problem is presented by linear approximation of system equations around an initial solution such as

$$\Delta x = S.(\Delta u, \Delta d, \Delta z) \qquad (6)$$

In this incremental network model, matrix S, the so called sensitivity matrix, represents the sensitivity of state variables (bus voltages and generator reactive powers) to changes of controls(generator voltages ,transformer taps and var devices).For a system of n buses , m generators ,r var devices and q tap changing transformers , the model can be written as

$$\begin{bmatrix} \Delta Q_1 \\ . \\ . \\ \Delta Q_{Gm} \\ \Delta V_{m+1} \\ . \\ . \\ \Delta V_n \end{bmatrix} = \begin{bmatrix} S_1 & S_3 & S_5 \\ S_2 & S_4 & S_6 \end{bmatrix} \begin{bmatrix} \Delta V_1 \\ . \\ \Delta V_m \\ \Delta Tap_1 \\ . \\ \Delta Tap_q \\ \Delta Q_{L1} \\ . \\ \Delta Q_{Lr} \end{bmatrix} \qquad (7)$$

Where

$\Delta V_1, \ldots, \Delta V_m$	changes in generator voltage amplitude;
$\Delta Q_{G1}, \ldots, \Delta Q_{Gm}$	changes in generator reactive power;

$\Delta V_{m+1,...,}\Delta V_n$	changes in load bus voltage amplitude;
$\Delta Q_{L1},...,\Delta Q_{Lr}$	changes in reactive load;
$\Delta Tap_1,...,\Delta Tap_q$	changes in transformer taps;
$S_1,...,S_6$	sub matrices of S.

Applying linear programming to solve (5) has some restrictions.

1. All variables are continuous, so essentially, discrete variables such as representing transformer taps and switched var devices are treated as continuous, after which they must be rounded off to their closest discrete values.

2. The objective function is linear and continuous. This, for example, does not allow minimization of the number of controls used or the time needed to execute the actions.

Previous publications on corrective control show a wide range of objective functions for the optimization problem, such as minimization of cost of control actions [5],[6],deviation of controls from initial operating point [6],[7], and number of controls used and time for completing the control actions [6].

The nature of power system operation under various stress and strain conditions has been discussed in [1].

A complete methodology for the solution of real and reactive sub problems of the general optimization problem that appears as part of the corrective strategies function of power system control centers is presented and analysed [8].

The set of control actions (via generator bus voltage, transformer tap-setting and var source instalments) are required for eliminating constraint violations i.e. voltage and reactive power.

Mixed-integer programming is able to deal with discrete as well as continuous variables and has been applied to the voltage control problem [9]; however, this method is known for its long calculation time.

In recent years, expert systems have been developed based on operator’s experience [10]-[12].

These methods do not aim to optimize any objective function but rather to provide a fast, feasible solution. A disadvantage is that no solution may be found in cases where no applicable rules exist. Some publications [6] propose using expert systems for less severe emergencies while relying on traditional algorithms such as linear programming for severe emergency cases, which expert systems might not able to solve.

A genetic algorithm (GA) using linear approximation of load flow equations and a heuristic selection of participating controls were combined in a search method for the minimum number of control actions [20].

GAs may be an alternative way of solving such problem [13].GAs does not require linearity, continuity or differentiability of the objective function, nor do they need continuous variables. These two features make GAs particularly effective in dealing with discrete control devices such as tap changing transformers and with objectives such as minimal number of control actions.

Several GA applications on the voltage-reactive power problem are known. Applications exist for planning and optimal allocation of reactive power sources [14], [15], as well as for voltage security enhancement by preventive control [16].The optimal power flow (OPF) problem has also been addressed in several publications [17-[19].Although the OPF solution also includes the elimination of constraint violations, the control actions are primarily directed towards loss or cost optimization. In this paper, however, the primary goal is the elimination of the constraint violations. The topic of minimizing the number of operator actions is included in [19] through the preselection of control devices participating in GA and afterward by neglecting control commands of less than prescribed thresholds.

Genetic Algorithm for solving multi-objective reactive power dispatch problem is discussed in [21].

A genetic algorithm based approach for short–term scheduling of reactive power controllers is presented in [22].It involves proper settings of the control devices i.e. capacitor banks and transformer taps.

Solution of mixed-integer nonlinear programming problem associated with reactive power and voltage control in distribution system based on nonlinear interior-point method and discretization penalties is addressed in [23].

An optimal reactive power flow (ORPF) incorporating static voltage stability based on multi-objective adaptive immune algorithm (MOAIA) is proposed in [24].

The status of security analyses in vertically integrated utilities and the impact of system security on the operation and planning of restructured power systems are reviewed in [25].

A genetic algorithm for voltage stability enhancement optimal load shedding is discussed in [26].

A genetic algorithm based approach for solving security constrained optimal power flow problem (SCOPF) with FACTS devices is proposed in [27].

The novel approach in the algorithm presented in this paper is that the number of control actions is to be an explicit part of the search objective.

IV.ALGORITHM

For the emergency control problem, calculation time of GA may be improved by not including all the control devices in the search process but rather making a proper selection of participating candidates. Control devices may count, many hundreds in a power supply system, while many of them have only a marginal influence on the distributed bus voltages and generator reactive loads. The algorithm proposed here combines the benefits of both the linearized system model and the GA, in the following steps.

1. Calculate the sensitivity coefficients for all available control devices

2. According to the estimated ability of the control devices to decrease the constraint violations, select a first set of candidates of controls that will take part in the next calculation stage.

3. Use the GA to find the proper set of control actions .The fitness of a solution is determined by remaining constraint violations and the number of controls used.

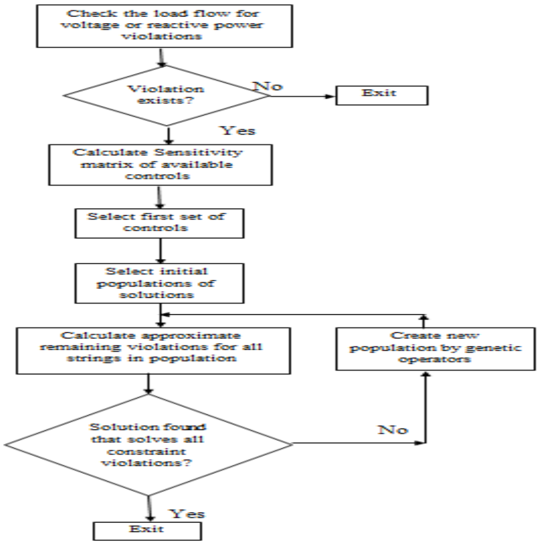

Figure 1Flow chart of the algorithm

This algorithm combines the fast and approximate sensitivity analysis with the ability of GA to deal with discrete variables and a non-continuous objective function. Figure. 1 presents the calculation scheme. In the following, the three steps are discussed in detail.

Step1.Sensitivity coefficients are determined that present the approximate influence of every available control device on every load bus voltage and generator reactive power. The coefficients are calculated for the operating range around initial values of controlling devices, such as transformer ratio and generator voltages.

Step2.The following heuristic method of preselecting participating controls avoids including all possiblecontrol actions C in the genetic search algorithm. The sensitivity coefficients, together with the operation range of controls, enable a fast estimation of the possible improvement of system bus voltages and generator reactive powers.

For every out of bound variable g_i (bus voltage or generator reactive power), it is calculated how much the constraint violation $\hat{g}_i - g_i$ can be reduced, control $c(c = 1,...,C)$.

This enables to rank the controls according to decreasing value of their effectiveness and make a selection of a set of candidates y ,whose cumulative effect is enough to eliminate the violation of constraint i .Because of the ranking the most effective controls for constraint violation, $\hat{g}_i - g_i$ are selected first.

This rule is applied in order to find the sets of controller candidates for every individual out of bound variable. However, in case there are multiple constraint violations, it is theoretically possible that a control is highly effective in decreasing constraint violation a while increasing the constraint violation $b(a \neq b)$ .In addition to this, it is possible that some control actions cause new constraint violations .In view of this, the set of candidate controls for each violated constraint $\hat{g}_i > g_i$ is enlarged such that their cumulative effect enables elimination of twice the value of the constraint violation $\hat{g}_i - g_i$.

Step3.This stage, the GA, involves the determination of which of the control devices included in $\underline{y}$ are actually to be activated, that is, which controls are used and to what extent. The algorithm creates in every generation a large number of sets of possible control actions $\Delta\underline{y}$ and checks their fitness.

Control actions are represented as binary values, concatenated into a string or chromosome of bits. The coding is selected to fit the type of type of control devices. For example, four digits can represent 16 transformer taps; one digit is enough to represent switched shunt. Also, continuous variables are represented by discrete values. The fitness of a set of controls is first of all a function of the changes in the load flow, in particular the remaining constraint violations. For every string representing a set of control actions $\Delta\underline{y}$, the resulting system state is $\underline{x}^1$ approximated by,

$$\underline{x}^1 = \underline{x}^0 + S.\Delta\underline{y} \qquad (8)$$

And new constraint violations are given by,

$$\underline{g}(\underline{x}^0 + S.\Delta\underline{y}, \underline{y}^0 + \Delta\,\underline{y}) > \hat{\underline{g}} \qquad (9)$$

where $\underline{x}^0$ and $\underline{y}^0$ are previous values of state variables and controls .As the fitness f of a solution, the following expression is used:

$$f = K - m_1 \sum_{i=1}^{n} | g_i - \hat{g}_i | - m_2 \sum_{j=1}^{k} Y_j \qquad (10)$$

where $i = 1,...,n$ represent the number of violated constraints and $j = 1,...,k$ the set of controls included in $\underline{y}$ .Also, $Y_j = 0 \; for \; \Delta y_j = 0$ and Y_j =1 $for \; \Delta y_{ij} \neq 0$

The constant K is chosen sufficiently large so as to ensure a positive value for the fitness function. The second term in (10) expresses a penalty for the constraint violation, while the third term is a penalty added to minimize the number of controls used. The constants m_1 and m_2 represent weight factors. Since the goal of the search process is first of all to find a set of control actions that eliminates all the constraint violations, the weight factor must be chosen sufficiently large in comparison with m_2 .In order to ensure that a single 0.01 p.u. voltage constraint violation will cause a heavier penalty than k control actions do, $m_1 > 10000xkxm_2$ should be chosen.

In the first generations created by GA, the constraint violations will be minimized and eventually become zero when and if a solution for a control problem is found. At this stage, the algorithm may be stopped, since the primary goal of the search process is reached. However it is possible to continue with the search process and population of solutions will develop according to the last term of fitness, which the term is expressing the number of controls used .Unacceptable large changes of control variables are avoided by constraints in the GA.

In addition to the constraints used in GA basic constraints like voltage, reactive power constraints should be included. The nominal voltage and reactive power shouldn't violate the minimum and maximum limits.

$$V_i^{\min} < V_i < V_i^{\max} \qquad (11)$$

$$Q_i^{\min} < Q_i < Q_i^{\max} \qquad (12)$$

Selection of initial population of solutions:

Theinitial population of solutions may be chosen at random, as is traditionally done. However, a careful choice of the initial population can improve its efficiency in a substantial way. In view of the fact that a solution consisting of a small number of control actions is preferred, a part of the initial population is selected to present "one control action" solutions. For a case of k participating controls, the first $i = 1,...,k$ strings represent a single step increase in control i, while all controls remain unchanged. Step size is the smallest possible, according to the coding of the variable. A similar procedure is followed for the next k strings, representing a decrease in each of the control values .In total, $2k$ strings are selected and the others are randomly chosen.

V. APPLICATION OF THE ALGORITHM

In this work, IEEE 30-bus system has been used to show the effectiveness of the algorithm. The network consists of 6 generator-buses, 21 load-buses and 41 branches, of which four branches (6,9),(6,10),(4,12) and (28,27) are under load-tap setting transformer branches. The parameters and the variable limits are listed. The possible var source instalment buses are buses 26 and 30.All power and voltage quantities are per-unit values.

The IEEE 30 bus system is represented in the figure 2.Three set of controls are employed in the corrective control strategy. The first set of control involves generator bus voltage at the buses 1,2,5,8,11,13 .The generator buses are tuned as per table 1. .The first set of controls are represented with red colour in the figure 2. The second set of control involves transformer tap-settings between buses (6,9),(6,10),(4,12),(27,28).The transformer tap-settings are tuned as per table 2.The second set of controls are represented by golden yellow colour in figure 2. The third set of control involves var source instalments at the buses 26 and 30.The tuning of the var sources is done as per table 6.The third set of controls are represented by violet colour in the figure 2.

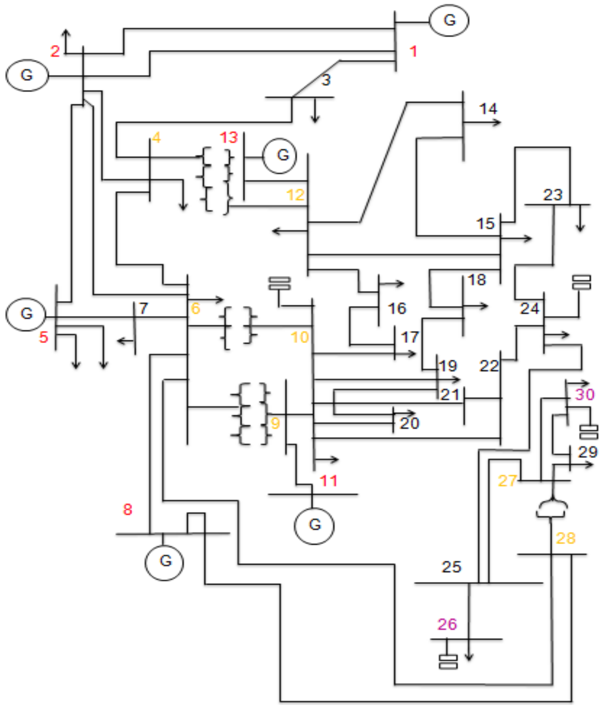

Figure 2. IEEE 30 bus system

VI PARAMETERS AND LIMITS

Table 1. Reactive Power generation limits

Bus no	$Q_g^{\min}$	$Q_g^{\max}$
26	*0*	*36*
30	*0*	*36*

Table 1. gives the reactive power limits of the capacitors that are being installed at the buses 26 and 30 respectively.

Table 2. Generator bus voltage limits

Bus No	*1*	*2*	*5*	*8*	*11*	*13*
$V_g^{\min}$	*0.9*	*0.9*	*0.9*	*0.9*	*0.9*	*0.9*
$V_g^{\max}$	*1.1*	*1.1*	*1.1*	*1.1*	*1.1*	*1.1*

Table 2. gives the permissible voltage limits at the generator buses .The permissible voltage limits are taken as 10 percent

above or below the nominal value ,which is usually taken to be 0.9 and 1.1.

LOAD FLOW SOLUTION WITHOUT CORRECTIVE CONTROL			
BUS NO	***VOLTAGE MAG***	***ANGLE DEGREE***	***QG MVAR***
1	*1.060*	*0*	***180.654***
2	*0.993*	*-13.472*	***93.144***
3	*0.994*	*-18.853*	*0*
4	*0.928*	*-23.096*	*0*
5	*0.960*	*-34.875*	***94.330***
6	*0.935*	*-27.493*	*0*
7	*0.926*	*-31.743*	*0*
8	*0.960*	*-29.662*	***63.215***
9	*0.975*	*-34.824*	*0*
10	*0.934*	*-38.788*	*0*
11	*1.082*	*-34.824*	***55.918***
12	*0.961*	*-36.963*	*0*
13	*1.021*	*-36.963*	***65.610***
14	*0.926*	*-39.171*	*0*
15	*0.915*	*-39.383*	*0*
16	*0.933*	*-38.404*	*0*
17	*0.921*	*-39.197*	*0*
18	***0.893***	***-40.975***	*0*
19	***0.888***	***-41.430***	*0*
20	***0.897***	***-40.906***	*0*
21	*0.904*	*-39.912*	*0*
22	*0.905*	*-39.871*	*0*
23	***0.889***	***-40.358***	*0*
24	***0.874***	***-40.768***	*0*
25	***0.871***	***-40.035***	*0*
26	***0.829***	***-41.217***	*0*
27	***0.891***	***-38.877***	*0*
28	***0.829***	***-29.0***	*0*
29	***0.841***	***-42.246***	*0*
30	***0.812***	***-44.817***	*0*

Table 3. Transformer tappings limits

Branch No	*(6,9)*	*(6,10)*	*(4,12)*	*(27,28)*
$T_{\min}$	*0.95*	*0.95*	*0.95*	*0.95*
$T_{\max}$	*1.05*	*1.05*	*1.05*	*1.05*

Table 3. gives the minimum and the maximum limits for the tap-changing transformers. The tuning of the control parameters is usually done by means of genetic algorithm and optimal tuned parameters of the generator bus voltages, transformer tap-settings and var source installments are given in the tables 4,5and 6 respectively.

Table 4. Generator bus voltages

Bus	***1***	***2***	***5***	***8***	***11***	***13***
X	*1.1000*	*1.0806*	*1.0935*	*1.0742*	*1.1000*	*1.0290*

Table 5. Transformers tap-settings

Branch No	***(6,9)***	***(6,10)***	***(4,12)***	***(28,27)***
Y	*1.0113*	*1.0468*	*0.9887*	*0.9532*

Table 6. Var source installments

Bus	***26***	***30***
Z	*9.2903*	*1.1613*

Where

X represents BGA (Binary Genetic Algorithm) values for generator bus voltages.

Y represents BGA (Binary Genetic Algorithm) values for transformer tap settings.

Z represents BGA (Binary Genetic Algorithm) values for var source instalments

After applying the control actions like generator bus voltage, transformer tap settings and var source installments. The bus voltages and reactive power violations can be limited within the constraint limits. Thus the corrective control strategy serves for both the voltage control and reactive power control

VII. RESULTS

Table 7. Load Flow solution without corrective control

IEEE 30-bus model is taken as test system .For analysis in order to check the effectiveness of the genetic algorithm, at first the demand is doubled from the normal case and the load flow solution is obtained. The load flow solution is given in the table 7.It is to be noted that no set of corrective control is employed for the above case.

As per IEEE standards the optimum voltage profile at the sending and the receiving end should be maintained within the limits. i.e. 0.9 p.u. and 1.1 p.u. respectively. From table we observe that buses 18,19,20,23,24,25,26,27,28,29,30 are violating constraint limits as voltage magnitudes goes below 0.9 p.u.

Table 8. Load Flow solution with corrective control

LOAD FLOW SOLUTION WITH CORRECTIVE CONTROL			
BUS NO	***VOLTAGE MAG***	***ANGLE DEGREE***	***QG MVAR***
1	*1.100*	*0*	***194.991***
2	*1.031*	*-12.188*	***84.812***
3	*1.003*	*-17.222*	*0*
4	*0.989*	*-21.017*	*0*
5	*1.043*	*-31.740*	***75.010***
6	*0.999*	*-25.051*	*0*
7	*1.000*	*-28.861*	*0*
8	*1.024*	*-27.009*	***57.093***
9	*0.998*	*-32.006*	*0*
10	*0.954*	*-35.808*	*0*
11	*1.100*	*-32.006*	***44.166***
12	*0.965*	*-34.048*	*0*
13	*1.009*	*-34.048*	***46.895***
14	*0.934*	*-36.184*	*0*
15	*0.927*	*-36.442*	*0*
16	*0.944*	*-35.465*	*0*
17	*0.940*	*-36.214*	*0*
18	***0.909***	***-37.959***	***0***
19	***0.905***	***-38.381***	*0*
20	***0.916***	***-37.869***	*0*
21	*0.929*	*-36.873*	*0*
22	*0.931*	*-36.834*	*0*
23	***0.914***	***-37.384***	*0*
24	***0.915***	***-37.768***	*0*
25	***0.958***	***-37.314***	*0*
26	***0.957***	***-39.723***	*0*
27	***0.985***	***-35.788***	*0*
28	***0.994***	***-26.520***	*0*
29	***0.941***	***-38.579***	*0*
30	***0.918***	***-40.685***	*0*

The corrective controls parameters i.e. generator bus voltage, transformer tap-setting and var source installments are tuned by genetic algorithm. The optimal values of the tuned parameters and their location are traced using genetic algorithm. The tuned parameters and their locations are given in the tables 4, 5 and 6 respectively.

The tuned parameters i.e. generator bus voltage in table 4 are replaced with initial values in the bus data, transformer tap-settings in table 5 are replaced with the initial values in the line data and var source installments in table 6 are replaced with initial values in bus data. The load flow solution obtained through corrective control is given in table 8.

Table 9. Comparative result for voltage control

LOAD FLOW SOLUTION WITHOUT CORRECTIVE CONTROL			***LOAD FLOW SOLUTION WITH CORRECTIVE CONTROL***	
BUS NO	***VOLTAGE MAG***	***ANGLE DEGREE***	***VOLTAGE MAG***	***ANGLE DEGREE***
18	***0.893***	***-40.975***	*0.909*	*-37.959*
19	***0.888***	***-41.430***	*0.905*	*-38.381*
20	***0.897***	***-40.906***	*0.916*	*-37.869*
23	***0.889***	***-40.358***	*0.914*	*-37.384*
24	***0.874***	***-40.768***	*0.915*	*-37.768*
25	***0.871***	***-40.035***	*0.958*	*-37.314*
26	***0.829***	***-41.217***	*0.957*	*-39.723*
27	***0.891***	***-38.877***	*0.985*	*-35.788*
28	***0.829***	***-29.0***	*0.994*	*-26.520*
29	***0.841***	***-42.246***	*0.941*	*-38.579*
30	***0.812***	***-44.817***	*0.918*	*-40.685*

Table 9. gives the comparative load flow solution without corrective control and with the corrective control. From the table we observe that without corrective control the voltage limits at the buses 18,19,20,23,24,25,26,27,28,29,30 gets violated i.e. goes below 0.9 p.u..This voltage limit violation arises due to increase in load. By employing the corrective control strategy by proper tuning of the control parameters i.e. generator bus voltage, transformer tap-setting and capacitor bank switching the bus voltages at the buses 18,19,20,23,24,25,26,27,28,29,30 are brought within the limits i.e. between 0.9 p.u. and 1.1 p.u.

Table 10.Reactive power limits for generator buses

Bus	$Q_g^{\min}$	$Q_g^{\max}$
1	*-20*	*200*
2	*-20*	*100*
5	*-15*	*80*
8	*-15*	*60*
11	*-10*	*50*
13	*-15*	*60*

The reactive power limits for various generator buses is given in the table above. The limits given in table corresponds to the minimum and maximum limits at the generator buses.

Table 11.Comparative result for reactive power control

Bus	***LOAD FLOW SOLUTION WITHOUT CORRECTIVE CONTROL***	***LOAD FLOW SOLUTION WITH CORRECTIVE CONTROL***
	QG	***QG***

	MVAR	***MVAR***
1	*180.654*	*194.991*
2	*93.144*	*84.812*
5	***94.330***	*75.010*
8	***63.215***	*57.093*
11	***55.918***	*44.166*
13	***65.610***	*46.895*

Algorithm Type	*Number of Controls in Solution*	*Calculation time (seconds)*
Genetic Algorithm	*3*	*1.928*
Integer Programming	*3*	*192*

Comparative variations in the reactive power injections at the generator buses arise after employing corrective control strategy. The variations in the reactive power injections before and after employing the corrective control are presented in the table 11.

From the table we infer that the reactive power limits at the buses 5,8,11,13 getting violated without corrective control and the reactive power violations are brought within limits after employing corrective control.

Because of the stochastic nature of the GA, results may differ slightly for different calculation runs. Fitness values shown here were normalized, and a value of 1 presents the theoretical case that no constraints are violated and the number of control actions is zero. The fitness of the best solution in the population increased considerably faster.

The control actions found by the algorithm were checked with a full Newton-Raphson load flow calculation. These results show that no significant violations of constraints (0.95 and 1.05 p.u.) remained after the application of control actions. Also, reactive power of all generators was brought within boundaries. Since no control device exist at the extreme ends of the network(close to the initial low voltages),the effect of control actions on buses with correct voltage in the center of the system is unavoidable but causes no new constraint violations.

VII. COMPARISON WITH INTEGER PROGRAMMING

In order to compare the performance of the developed algorithm with other calculation methods, the same problem was solved by means of integer linear programming (IP).The reason why the IP method in particular was chosen for comparison is that IP is the only other method capable of dealing with an objective of a minimum number of control actions. As expected, IP finds the absolute minimum of control actions (3) that solve the constraint violations.

Table 8 summarizes the performance of the GA and IP methods. The IP algorithm guarantees to find the optimal solution, but it is unsuited here because of its computation time. The GA method produces a near optimal solution at affordable computation time. It should be recalled that the comparison deals with one particular load flow case only but nevertheless indicates the strength of the GA method.

Table 11. Comparison of computation times GA and IP

VIII. CONCLUSION

The results show that the heuristic method of pre-selecting a set of control devices, together with the GA for finding the ultimate set of required control actions, produce a sufficient solution to the voltage/reactive power problem.

The fact that a solution was found based on an integer number of transformer tap changes is a significant improvement compared to other methods that require rounding off to the nearest whole value. Furthermore, the GA was capable of decreasing the number of control actions. Although reaching the absolute minimum of control actions may require considerable computation time, keeping in mind that minimization of the number of control actions is a secondary goal, there is no need to reach this absolute minimum.

The overall calculation time of the algorithm compares favourably with IP and is considered small enough to enable real time application. While comparing methods for the selection of corrective control actions, one should not only consider calculation time but also the time needed to execute the control actions, including the time to verify the completion of the commands. Thus, a decreased number of control actions may compensate for the extra calculation time involved.

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Authors Profile

P.Kumarreceived the **B.E.** degree in Electrical and Electronics Engineering from the PSNA College of Engineering and Technnology, dindigul, Anna University, Chennai, India, in 2010.He received the**M.E.** degreein PowerSystems EngineeringfromCollege of Engineering, Guindy, AnnaUniversity, Chennai, India, in 2012.He is currently working as Assistant Professor at P.A. College of Engineering and Technology. His research interest includes Power Systems Stability, Power System Operation and Control, PowerSystem Deregulation, Power System Protection.

M.Vignesh kumarreceived the **B.E.** degree in Electrical and Electronics Engineering from the Sri Subramanya College of Engineering and Technnology, Palani, Anna University, Chennai, India, in 2007.He received the M.E**.** degreein Power Electronics and Drives from Karpagam University, Coimbatore, India.He is currently working as Assistant Professor at P.A. College of Engineering and Technology. His research interest includes Power System Protection, Electric drives and control.

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