Chapter 5

Genetic Algorithm based Reactive Power Dispatch and Voltage Control

Introduction

The purpose of reactive power dispatch is the maintenance of satisfactory voltage profiles at various loading conditions and economic operation of the system by minimizing the real power losses. In this chapter, the development of **genetic algorithm (GA)** technique and its variation in the form of the small population based called micro-GA to solve the reactive power dispatch problem described in chapter two is presented. The optimization process usually results in the movement of all the recommended control variables. This is not desirable from controllers execution time perspective and practical application. Furthermore, for large scale application a considerable bit length will be required to code the available controllers with the consequences on the processing time and convergence problem. Motivated by these observations, a reactive power controller pre-selection mechanism was developed as a module in order to select *a priori* the electrically most closest controller(s) with respect to node(s) experiencing voltage limits violation. These are then passed on to the GA reactive power dispatch module to determine their optimum setting. After the optimization, a further reduction in the number of control actions can be achieved by neglecting any small movement after a post-effect analysis of the approximation has been carried out. The **varying fitness function** technique of handling constraints proposed by [8] was adopted in this work to take care of voltage limits constraint violation. The results of the GA based reactive power dispatch with / without incorporating reactive power controller pre-selection mechanism for both micro - and conventional - GA types implemented on an operator training simulator are compared and conclusions drawn.

5.1 Reactive Power Controller Pre-Selection Mechanism

Because of the reasons stated in the introductory section above, it is essential to develop a procedure to find the closest controllers with respect to nodes experiencing a voltage problem. This procedure reproduces the way an experienced power system operator actuates when voltage limits violations appear. For reactive power / voltage support in a high voltage transmission network, the number of tap changing transformers and generating units is usually higher than the number of reactive elements (coils and capacitors). Due to this reason, an *a priori* selection of only tap changing transformers and generating units is considered in this work. Under this condition, the electrically closest controllers are selected based on the elements of the impedance matrix, and only these selected ones together with the available reactive shunt elements will be involved in the optimization process. The general processes applied in the realization of this mechanism are described in the next section.

5.1.1 Approach

At the initialization stage, all the necessary power system data need to be actualized from the process database, and information about the voltage profile and node(s) experiencing voltage violation(s) are correspondingly determined. Since branches (lines and transformers) reactances (x) are much greater than the corresponding resistances (r) (i.e. $|x : r| \approx$ 5-20 in most high voltage transmission systems) [26], the bus admittance matrix of the present network topology is then established using only branches (lines and transformers) reactances and the impedance matrix obtained by taking the inverse of this pure reactive bus admittance matrix.

To search for tap changing transformers and/or generators closest to voltage problem nodes, all the topological paths between the regarded node experiencing voltage violation and generator nodes are determined for generating units, while for transformers the existence of on-load tap changing transformers in the branches connecting this node and adjacent node(s) is (are) determined. The corresponding elements of the impedance matrix are extracted, and by comparison a controller with highest value of impedance is said to have highest voltage sensitivity and adjudged being electrically closest to the node experiencing the voltage problem. This process is repeated until generating units and/or on-load tap changing transformers have been found for all the node(s) experiencing voltage problems. At the end of the selection process, some controllers may be selected more than once; these redundant controllers are filtered out to give the control variables which are required to be optimized. Finally, lists of selected control variables types as well as availability of controllers for optimization are created.

5.1.2 Realization

For the operator training simulator used in this work as substitute for real power system control, all the necessary power system data required for simulation studies are actualized from the database by the **topology evaluation**, **generation observer** and **load observer** routines as enumerated in chapter 3 (see section 3.6 and table 3.3). Furthermore, the information about the available shunt elements (capacitors and reactors) and allowable voltage limits are retrieved from the process database by the **database (DB) access** routine, and default values are assumed in case that they are not specifically defined in the process database. Also, information about all the available on-load tap changing transformers is obtained by mapping the transformer list of the topology evaluation program.

With the snapshot of the power system under consideration obtained, a Newton-Raphson load flow program is then fed to furnish information about the voltage profile, and by comparison with the pre-defined allowable voltage limits retrieved from the process database and/or default values, node(s) experiencing voltage limits violation(s) are accordingly determined. The above described procedure is then applied to determine the total number of selected tap changing transformers, the branch numbers and their identification in GDL format; correspondingly the total number of involved generating units, their topological node connections and identifications. The total number of selected controllers is then computed by summing all the selected controllers and available shunt elements to further determine the operational availability of the controllers.

Lists of selected tap changing transformers' and generating units' as well as controllers' availability are created by mapping the information into system object files until they are accessed by the GA reactive power dispatch module which in turn determines their optimal adjustment. The flow chart of figure 5.1 depicts the above described processes.

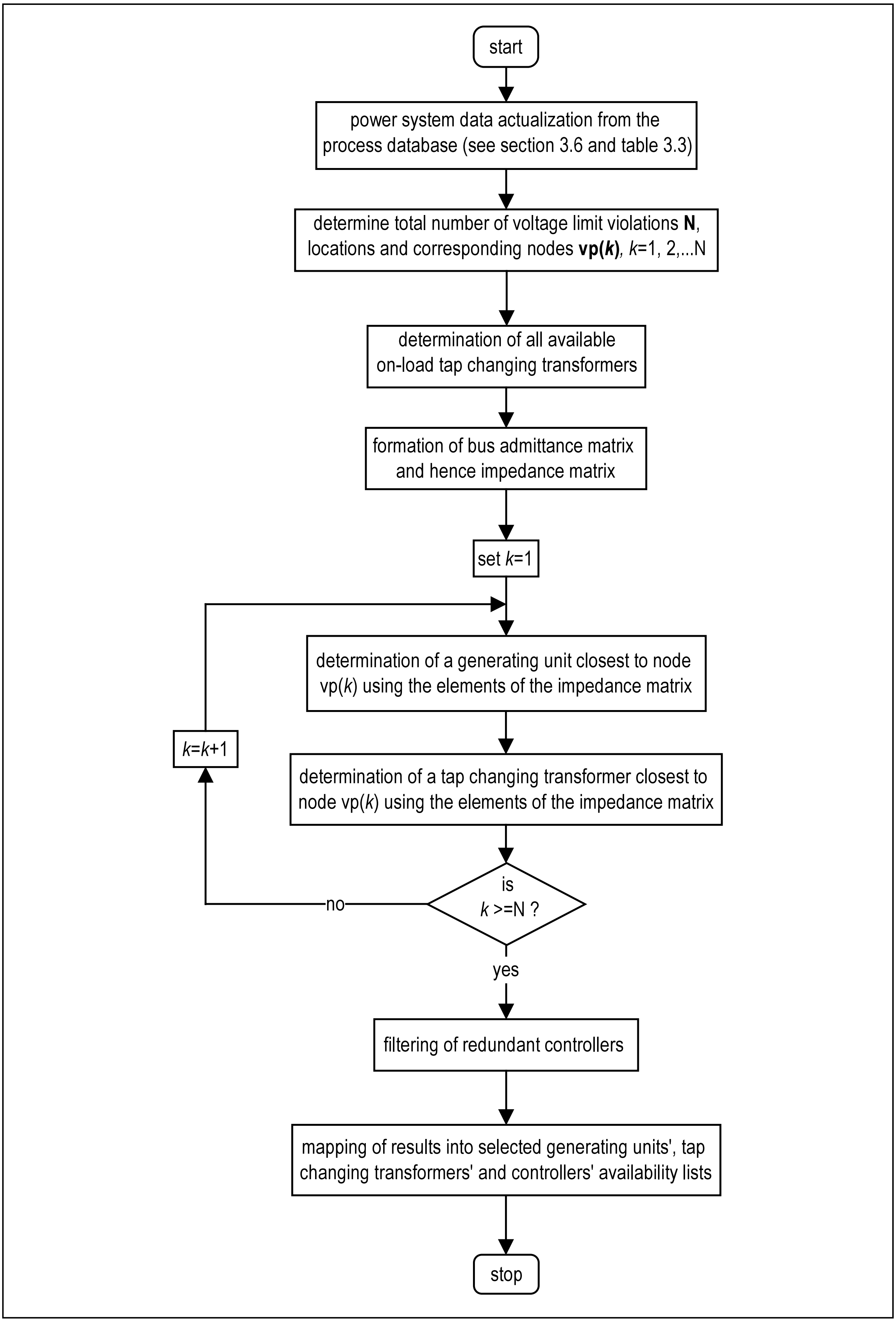

Figure 5.1 Reactive power controller pre-selection mechanism

5.2 Reactive Power Dispatch and Voltage Control using Genetic Algorithm

The control variables usually considered in the reactive power dispatch problem are generating unit terminal voltage, position of tap in transformers equipped with on-load-tap changing facility and shunt reactances which are adjusted within a restricted feasible area in the parameter space. Besides these options, [5,70] considered the occasional possibility of switching off long lines during minimum load periods. By executing the GA based reactive power dispatch, the optimal operating condition of the network is obtained. The system then moves to the optimal operating status by executing the recommended settings. Two approaches based on GA technique were applied to this problem as presented in chapter 2, and these include:

- Conventional GA and
- Micro GA.

The general concepts of each of these methods as applied to the problem of reactive power dispatch are described in the following sections:

5.2.1 Concept of Conventional GA based Reactive Power Dispatch

The processes involved in the development of **conventional** GA based reactive power dispatch are discussed below:

5.2.1.1 Initialization Process

At the initialization stage, all the necessary power system data required for the computational process have to be made available to the GA reactive power dispatch which will be explained in the following sections. Genetic algorithm parameters such as population size, number of children per pair of parents and genetic operations probabilities such as crossover rate per pair of parent, mutation rate per bit and creep mutation rate per parameter must be defined as well as parameter resolutions for some of the pre-selected control variables as described in the following sections. The pre-selected control variables suggested by the reactive power controller pre-selection module are retrieved by the GA reactive power dispatch module by accessing the corresponding data file, see section 5.1.

5.2.1.2 Encoding and Decoding of Control Variables

Binary string representation was used to code the control variables. A string consists of sub-strings; the number of sub-strings is equal to the number of decision or control variables. The encoding parameters are the control variables mentioned above. A 3 bits parameter resolution is enough to code each of generating unit's terminal voltage in the range 92% to 110% with a changing step of 0.025. In the encoding process of tap changing transformers it is necessary to consider the tap ratio voltage change of the transformer and thus optimize the bits representation. Since this value may not be the same for all the constituent tap changing transformers, the encoding bits are adapted using the nearest approximate integer value of the required string length computed from

$$b_{T_j} = \log_2\left(1.0 + \frac{\left[T_j^{\max} - T_j^{\min}\right]}{T_j^{\text{step}}}\right) \qquad ; \qquad (5.1)$$

otherwise there will be a control parameter limit violation thus leading to convergence problems in the load flow program. In case of shunt capacitors, the total number of available shunt capacitor banks (N_C^k) at a particular node k determine the number of bits required in the string representation of chromosomes. The same principle applies to reactors of number N_X. The switching "on" and "off" states of the shunt elements' breakers are represented in the genetic simulation process as 1 and 0 respectively.

The initial population chromosomes are randomly generated from the set of pre-selected control variables ranging over $[V_G^{\min}, V_G^{\max}]$, $[T^{\min}, T^{\max}]$, $[0, N_C^k]$ and $[0, N_X]$, and are formed into a series of fixed length binary strings which are then concatenated to form a complete chromosome given by

$$C = \left[s_{Vi'}^{im},\quad s_{Tj'}^{jm},\quad s_{Cl'}^{lm},\quad s_{Xw'}^{wm}\right] \quad , \qquad m = 1,2,\ldots.n_p \qquad (5.2)$$

i=1,2, ... $b_{Vi'}$, i'=1,2, ... $n_{G'}$, j=1,2, ... $b_{Tj'}$,j'=1,2, ... n_T
l=1,2, ... $b_{Cl'}$, l'=1,2, ... N_C^k , w=1,2, ... $b_{Xw'}$, w'=1,2, ...N_X

where
n_p is the population size,
$b_{Vi'}$, $b_{Tj'}$, $b_{Cl'}$ and $b_{Xw'}$ are respectively the number of bits required to code a particular generating unit terminal voltage, transformer taps, shunt capacitor banks and reactors;

$s^{im}_{Vi'}$, $s^{jm}_{Tj'}$, $s^{lm}_{Cl'}$, and $s^{wm}_{Xw'}$ are the particular bits $\in \{0,1\}$ for generating units, transformer taps, shunt capacitor banks and reactors respectively;
$n_{G'}$, n_T, N^{k}_{C} and N_X are the total number of required generating units for voltage control, on load tap changing transformers, shunt capacitor banks and reactors respectively.

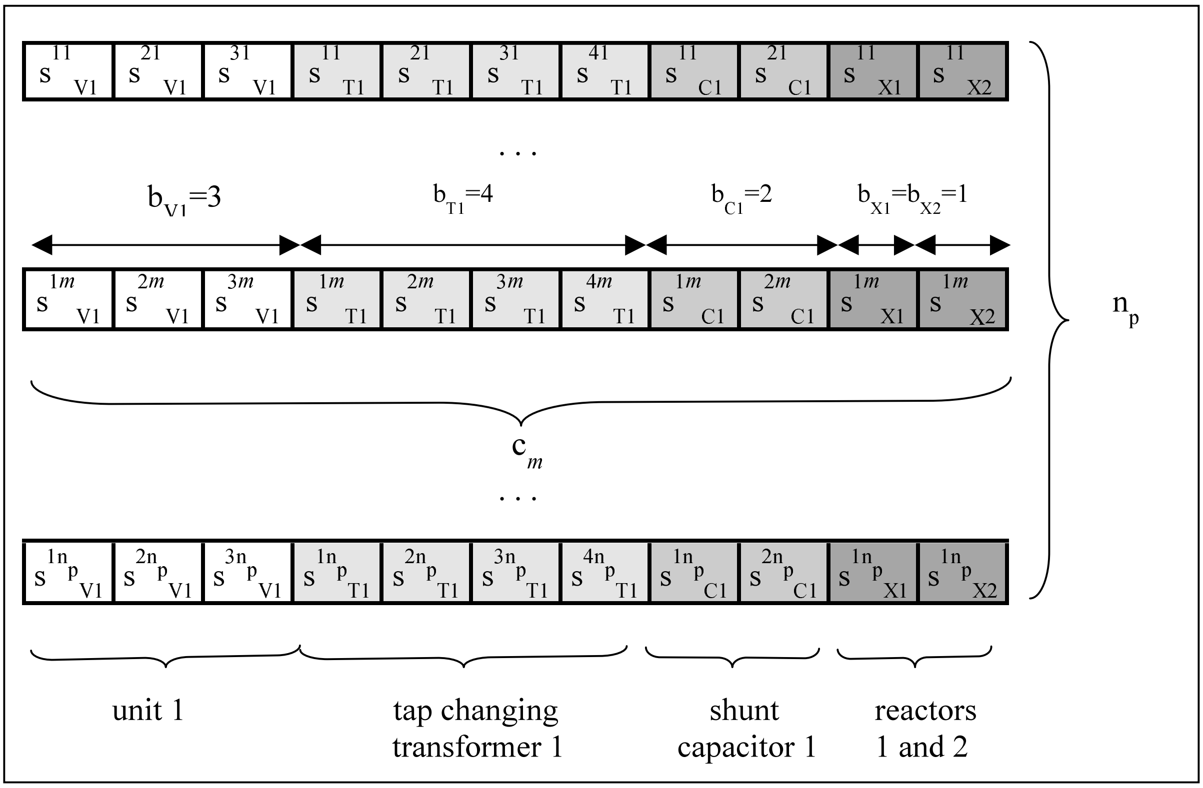

Figure 5.2 Encoding of reactive power control variables

An example of this representation for a system consisting of one generating unit, a tap changing transformer, a shunt capacitor with two banks and two reactors coded with $b_{V1}=3$, $b_{T1}=4$, $b_{C1}=2$ and $b_{X1}=b_{X2}=1$ bits respectively is as shown in figure 5.2.

Sub-strings of each selected generating unit terminal voltage and transformer taps of specified bits length are extracted from the concatenated strings (see figure 5.2) and are then decoded into their decimal equivalent and mapped into the value in the corresponding search space using the equation (D.4), appendix D. Decoding of shunt capacitor banks is done by taking the number of ones as the number of banks to be switched on (see chapter 2, figure 2.1). Similarly, for reactors, the chromosome bits position with 1 means that the reactor is to be switched on as shown in figure 2.2, chapter 2.

Changes to the selected control variables are mapped into the data of their respective controllers and topological changes caused by introducing reactors and capacitors into the network are processed, and a load flow is performed for each individual chromosome constituting the population in order to supply information about total real power losses, unit reactive power outputs and nodal voltage profile. The total voltage deviation is then computed and the fitness functions determined using the process described below in section 5.2.1.3.

5.2.1.3 Fitness Evaluation and Treatment of Constraints

In order to minimize the objective function of real power losses in the system while fulfilling the task of keeping the voltage within the feasible range, the varying fitness function technique of handling the constraints using penalty function proposed by [8] was adopted in this work. The added penalty term is a function of the degree of voltage limits violations, so as to create a gradient toward a valid solution in order to guide the search. The penalty factors are kept low at the beginning of the GA evolution thus allowing a certain degree of voltage violations in order to simplify the search and give the GA the opportunity to explore the search space more efficiently. As the evolution proceeds, the penalty factors increase linearly with the generation index, so that at the end of the run they reach appropriately large values, which results in the separation of the valid solutions from the invalid ones. A linear varying penalty term η_v for any solution that violates the constraints is taken care of, depending on the defined degree of violation $d(S')$ by the expression [8]

$$\eta_v\left(d(S'),gen^{act}\right) = \frac{gen^{act}}{gen^{max}} \cdot \Omega \cdot d(S') + \frac{gen^{act}}{gen^{max}} \cdot \eta_{GA} \tag{5.3}$$

where gen^{max} is the maximum value of generations and gen^{act} is the actual generation number. The parameter η_{GA} is the penalty threshold factor and should be chosen for the minimization problem for minimum value $F_{obj}(S')^{min}$ and maximum value $F_{obj}(S')^{max}$ of the objective function in an actual population in the following way:

$$\eta_{GA} > \left(F_{obj}(S')^{max} - F_{obj}(S')^{min}\right) \tag{5.4}$$

so that no invalid solution is ranked better than the worst valid one. The parameter Ω represents the slope of the penalty function and the value was determined empirically, see table 5.1. The penalty term is added to the objective function to be optimized to form the fitness objective function

$$\mathrm{F_{fit}} = \mathrm{F_{obj}}(\mathrm{S}') + \eta_{\mathrm{v}}(\mathrm{d}(\mathrm{S}'),\mathrm{gen}^{\mathrm{act}}) \cdot \mathrm{w} \tag{5.5}$$

where

$$\mathrm{w} = \begin{cases} 0.0\,, & \text{for a valid solution} \\ 1.0\,, & \text{otherwise} \end{cases}$$

The corresponding non-varying penalty term is formed by setting the value $\mathrm{gen}^{\mathrm{act}}/\mathrm{gen}^{\mathrm{max}}$ in equation (5.5) equal to 1.0. With regard to the reactive power dispatch problem, the objective function which is minimization of system real power losses $\mathrm{P_T}$, which in their turn are determined from the load flow program. In order to form the penalty function for the violation of voltage constraints, a measure of the degree of voltage limits violation for the $\mathrm{n_B}$ nodes is calculated by using the expression

$$\mathrm{d}_{\mathrm{V}}^{m} = \sum_{i=1}^{\mathrm{n_B}} \left| \left(|\mathrm{V}_i|^{m} - \mathrm{V}_i^{\lim} \right) \right| \tag{5.6}$$

for d (S′) in equation (5.3), where $\mathrm{n_B}$ is the number of nodes of the considered network, m=1,2,.....$\mathrm{n_p}$ and

$$\mathrm{V}_i^{\lim} = \begin{cases} \mathrm{V}_i^{\max} & \text{if} \quad |\mathrm{V}_i|^{m} > \mathrm{V}_i^{\max} \\ |\mathrm{V}_i|^{m} & \text{if} \quad \mathrm{V}_i^{\min} \le |\mathrm{V}_i|^{m} \le \mathrm{V}_i^{\max} \\ \mathrm{V}_i^{\min} & \text{if} \quad |\mathrm{V}_i|^{m} < \mathrm{V}_i^{\min} \end{cases}$$

The fitness objective function of the m^{th} individual is obtained by summing the individual objective function of total system real losses p^{m}_{T} in (p.u.) and the penalty terms

$$\mathrm{F}_{\mathrm{fit}}^{m} = p_{\mathrm{T}}^{m} + \left(\Omega \cdot \frac{\mathrm{gen}^{\mathrm{act}}}{\mathrm{gen}^{\max}} \cdot \mathrm{d}_{\mathrm{v}}^{m} + (p_{\mathrm{T}}^{\max} - p_{\mathrm{T}}^{\min}) \cdot \Psi \cdot \frac{\mathrm{gen}^{\mathrm{act}}}{\mathrm{gen}^{\max}} \right) . \mathrm{u}^{m} \tag{5.7}$$

where

$$\mathrm{u}^{m} = \begin{cases} 0.0\ , & \text{if the total voltage deviation } \mathrm{d}_{\mathrm{V}}^{m} \text{ is less than a certain tolerance } \varepsilon_{\mathrm{V}} \\ 1.0\ , & \text{otherwise} \end{cases}$$

and $p_T^{\min}$ and $p_T^{\max}$ are respectively the minimum and maximum values of the objective function in a population. The parameter Ψ is a factor that enables η_{GA} to satisfy equation (5.4) and its value must be empirically determined, see table 5.1.

Since the GA has to find the optimum dispatch of the controllers that minimizes the fitness function of equation (5.7), it is translated into a minimization problem (see equation (4.16), chapter 4) using the relation

$$\mathrm{f}_m^{\mathrm{ind}} = \frac{1.0}{\left(1.0 + \mathrm{F}_{\mathrm{fit}}^m\right)} \tag{5.8}$$

After the computation of each individual fitness in the population, the individuals then undergo the genetic operations of tournament selection, uniform crossover, binary mutation, creep mutation and generation replacement. An elitist strategy was also used: the best individual of the population is guaranteed to be present in the next generation by the replacement of a randomly chosen individual of the next generation with the best individual of the previous one. Subsequently the fitness of the individuals of the new generation are evaluated, and this procedure continues until the convergence criteria are satisfied. The algorithm was defined to converge when these two conditions are fulfilled:

- There is no node experiencing voltage limits violation (i.e. $d_V^{\mathrm{best}} \le \varepsilon_V = 0$) **AND**
- there is no improvement in the incumbent solution after a specified number of generations (a value of 30 generations was used in this work).

In case the above mentioned convergence criteria are not satisfied, the algorithm stops when the maximum number of generations $\mathrm{gen}^{\max}$ is reached. The control variables of the most fit individual of this generation are chosen as optimum settings. Inserting these optimal settings of control variables back into the load flow program delivers:

- the voltage profile; and
- total system real power losses.

5.2.2 Concept of Micro-Genetic Algorithm based Reactive Power Dispatch

Besides the conventional GA described above, the micro GA approach (µGA) was also applied to the reactive power dispatch problem using the above described procedure (sections 5.2.1.1 to 5.2.1.3) except that a population size of five individuals was used in the test. The adoption of some suitable strategy to prevent the loss of population diversity is crucial to the success of µGA. Infusion of new genetic information and the retention of the previous best individual are guaranteed by a restart procedure in which new individuals are randomly generated while keeping a copy of the best individual of the previous converged generation.

The **genotype convergence** was defined to occur when less than 5% of the bits of other individuals differ from the best individual. This was obtained by counting the total number of bits which are unlike those possessed by the best individual. The algorithm was finally defined to converge when the convergence criteria (specified in section 5.2.1.3) are satisfied. Mutation, however, is not needed in the µGA since enough genetic diversity is introduced after every genotype convergence when 4 new individuals are randomly created.

5.2.3 Realization

The general implementation procedure of both conventional GA and µGA reactive power dispatch described above was realized in this work by coupling with the operator training simulator. Appropriate GA parameters such as population size (n_p), encoded parameter resolution, number of children per pair of parents, elite preserving strategy and genetic operation probabilities such as crossover rate (σ_c) per pair of parents, mutation rate (σ_m) per bit and creep mutation rate (σ_{cr}) per parameter, GA type (conventional or micro), slope of the penalty function (Ω), penalty threshold factor constraint satisfaction parameter (Ψ), and total voltage deviation tolerance (ε_v) were defined as in table 5.1.

For each of these methods, all the necessary power system data required for the computational process are retrieved from the process database by the data actualization programs of **topology evaluation**, **generation observer** and **load observer,** and made available to the GA reactive power dispatch program. These required data are as enumerated in chapter 3 (see section 3.6 and table 3.1). In addition to the data outlined in table 3.1, information about the available shunt switching elements (capacitors and reactors) banks are retrieved from the process database by the **database (DB) access** routine.

Regarding on-load tap changing transformers, the following data: maximum (TS_i^{max}), minimum (TS_i^{min}), and nominal (TS_i^{nom}) steps and the tap ratio step change (T_i^{step}) and the phase angle (Φ_i), are obtained by mapping the transformer list of the topology evaluation program (see table 3.2); the corresponding minimum (T_i^{min}) and maximum (T_i^{max}) tap ratios respectively are then evaluated using the expressions

$$T_i^{min} = 1.0 + T_i^{step} \cdot \cos(\Phi_i \cdot \pi/180.0) \cdot \left(TS_i^{min} - TS_i^{nom}\right) \tag{5.9a}$$

$$T_i^{max} = 1.0 + T_i^{step} \cdot \cos(\Phi_i \cdot \pi/180.0) \cdot \left(TS_i^{max} - TS_i^{nom}\right) \tag{5.9b}$$

Table 5.1 Comparison of applied parameters for conventional - and micro - GA reactive power dispatch

Parameter	**Conventional GA**	**Micro GA**
Population size (n_p) individuals	25	5
Mutation rate (σ_m) per bit	σ_m=1.75/l_c.n_p *	0.0
Creep mutation rate (σ_{cr}) per parameter	0.04	0.0
Uniform crossover rate (σ_c) per pair of parents	0.5	0.5
Number of offspring per pair of parents	1	1
Elite preserving strategy?	yes	yes
Reactive power control parameter resolutions ($b_{Vi'}$, $b_{Tj'}$, $b_{Cl'}$, and $b_{Xw'}$)	3 bits for all the generating units; for tap changing transformers, capacitors and reactors see section 5.2.1.2	same as for conventional method
Maximum number of generations (gen^{max})	200	200
Total voltage deviation tolerance (ε_V)	0.0	0.0
Slope of the penalty function (Ω)	7.5	7.5
Penalty threshold factor constraint satisfaction parameter (Ψ)	1.005	1.005

* l_c is the chromosome length ; n_p is the population size

A range of permissible voltages exists not only for load buses but also for generation buses. In most studies the voltage feasibility range is considered to be 95% to 105% of nominal voltage for load buses and 90% to 110% of generating unit's terminal voltage for generation buses irrespective of the voltage level, but in real systems these limits may vary from bus to bus and are usually defined according to load period and amount of exchange power, besides physical limitations of reactive generation. The voltage level is a determining factor as dictated by the insulation breakdown. Regarding some other aspects, as for example, if there is a consumer or another energy company connected to a bus, the range of admissible voltage magnitude is much stricter, following the values stipulated in the contractual agreements. In view of this, the nodes voltage feasibility range was arranged to be defined in the process database and retrieved by the **database (DB) access** routine during the solution process. Should these values not be specified in the process database, the standard values given above are taken as the default values.

The tap changing transformer(s) and/or generating unit(s) required to be optimized already mapped into tap changing transformer and generating unit control variable system object files by the reactive power controller pre-selection module, as well as available shunt switching elements are accessed by the GA reactive power dispatch module. Initial population chromosomes are randomly generated from each of the pre-selected controllers together with available shunt switching elements within their feasible range, and decoded as described in section 5.2.1.2. The fitness of all individuals in the population are computed as described in section 5.2.1.3. The generating units' reactive power output limits are taken care of in the Newton-Raphson load flow in which the corresponding reactive power output set at either the minimum or the maximum value; in this case the voltage controlled (PV) bus is changed to a load (PQ) bus and a new load flow iteration is performed.

After each individual fitness in the population has been computed, the genetic operations of tournament selection, uniform crossover, binary mutation, creep mutation, generation replacement and elitism are applied in order to generate a new population of the same size if the convergence criteria described in section 5.2.1.3 above are not yet met; otherwise the algorithm stops when the pre-defined maximum generation is reached.

Curtailment of Controller Actions

In addition to the reactive power controller pre-selection mechanism to curtail the number of control actions, a further possibility to reduce the number of control variables is the omission of all transformer taps and generating unit terminal voltage settings in which only a small magnitude change would result after the optimization. All generating unit control commands which would induce a correction of $\Delta v_{Gi}=|v_{Gi}^{\text{init}} - v_{Gi}^{\text{opt}}|\leq 1\%$ of generator rated terminal voltage and transformer tap changes of less than half a tap position (i.e. $\Delta T_i \leq 0.5$) are neglected. By executing an additional load flow program, the final decision to carry out the approximations can be justified by noting the effect on the system performance. If this curtailment of control actions does not lead to any voltage limits violation, the suggestion is accepted, otherwise the optimized pre-selected control variables are retained. The final recommended optimal control variables are then mapped into four lists of:

1. tap changing transformer optimal setting list which contains information such as total number of tap changing transformers, their identifiers in GDL format, initial and final taps,
2. generating unit optimal setting list in the form of total number of generating units, their identifications, initial and optimal terminal voltage settings,
3. shunt capacitor optimal setting list with the information such as the number of banks, their identifications and aspired switching statuses, and
4. shunt reactor optimal setting list with the information such as the number, their identifications and aspired switching statuses.

These system object files of recommended control variables can then be retrieved by the super-ordinate expert system for further execution either autonomously or manually by the operator as will be discussed in chapter 6.

The results of the genetic algorithm evolution process in the form of convergence behavior and voltage profile improvement obtained by comparing the node voltage violations of the actual operating state with those of the optimal state can be graphically displayed on the training simulator's measured data window as shown in section 5.3. The combination of pre-selection of electrically closest controller(s) to the node(s) experiencing voltage problem(s) and elimination of small controller's change after the optimization process lead to a considerable reduction in the number of moveable controllers and unnecessary load flow convergence problems normally encountered as a result of interaction of the movement of too many controllers. In this sense can the execution of control variables change within a reasonable time and real world application perspectives be achieved.

The flow chart of figure 5.3 depicts the processes of micro - and conventional - GA based reactive power dispatch described above. They can be practically applied alternatively by pre-selection. Both are displayed in one and the same diagram to enable one to comparatively recognize the difference between both approaches.

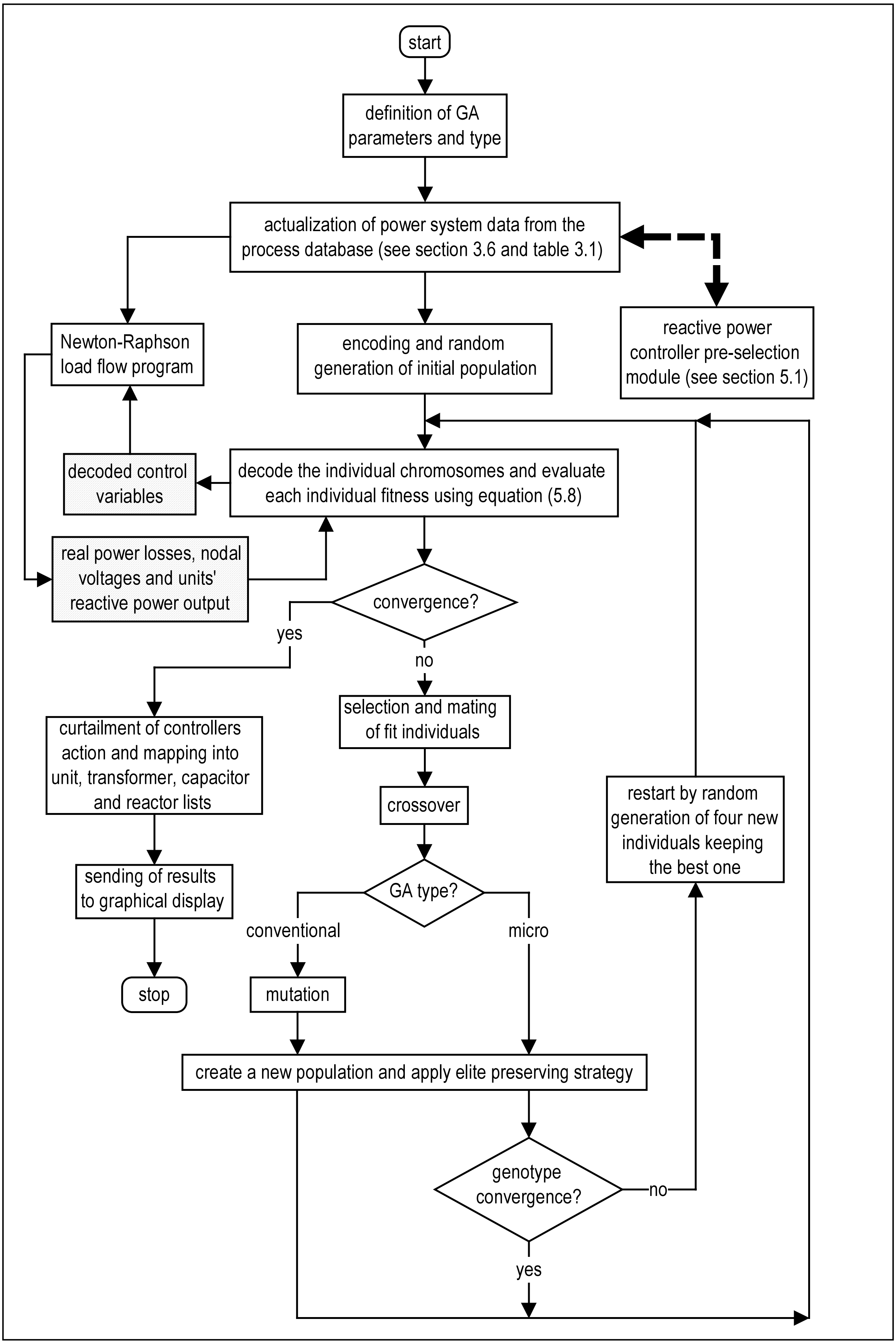

Figure 5.3 Flow chart of alternative processes of conventional - and micro - GA based reactive power dispatch

5.3 Simulation Results

To demonstrate the capabilities of the GA-based reactive power dispatch, both of the above described GA approaches were tested on two real power systems of:

1. Duisburg municipal 110/25/10 kV power system. Regarding voltage / reactive power control, there are 5 power units as continuos voltage regulators, 44 transformers equipped with tap changing facilities, and 5 compensation reactors (pure cable network).
2. Part of the German high voltage 400/230/110 kV transmission system. Similarly, for voltage / reactive power control support, there are 24 generating units and 85 on load tap changing transformers.

Both power systems are replicated on the operator training simulator in full operational detail as described in chapter 7. A multitude of test cases was performed on both systems, and samples of typical simulation results obtained for both GA approaches with / without controllers pre-selection mechanism are presented below:

5.3.1 Illustrative Example with Duisburg Power System

As an illustrative example on the above named power system, an initial scenario was preset on the simulator by wrong tap settings of three tap changing transformers (two 110/25/10 kV and one 110/10 kV) at substation MEIDE (see figure 7.1); the terminal voltage set-points of all four operative thermal generating units were set at 100%. These actions led to voltage limit violations in 13 nodes and corresponding increase in total system losses from 3.6 MW to 4.61 MW. Both developed GA approaches were applied to solve this problem with the incorporation of and without controllers pre-selection mechanism resulting in two cases.

Case 1:

Both conventional - and micro - GA were alternatively applied to this scenario, considering all the 4 generating units actually synchronized and 35 tap changing transformers. Figures 5.4 and 5.5 show the results of the application of both GA approaches to this sample scenario.

The diagrams essentially depict the nodal voltage expressed in percentage of the nominal voltage level. The operating voltage limits (low and high voltage) are represented by the cylinders of the first and the last row respectively. The initial voltage (third row) is the operating voltage before execution of the GA reactive power dispatch while the final voltage (second row) shows the nodal voltage correction as a result of the application of GA reactive power dispatch. It should be further emphasized that serial numbers were used for node identification on the abscissa, but the actual designation on the training simulator is, of course, done by the original operators' notions for bus-bars or bus-bar sections in GDL format (see chapter 3), thus also reflecting all physical detail of the regarded power system.

It can be seen from figure 5.4 that the conventional GA approach fulfils the criterion of keeping the voltage at all nodes within limits, connected with a 26.3% reduction of losses. Rather, the improvement in incumbent maximum fitness after 30 generations was not satisfied; thus the algorithm was stopped at the maximum number of 200 generations, see figure 5.6. A processing time of 1034 seconds was required by the conventional GA to achieve the voltage improvements and reduction of losses as shown in figure 5.4; however, antiquated Apollo workstations were used for the tests carried out here, see comments in section 5.4.

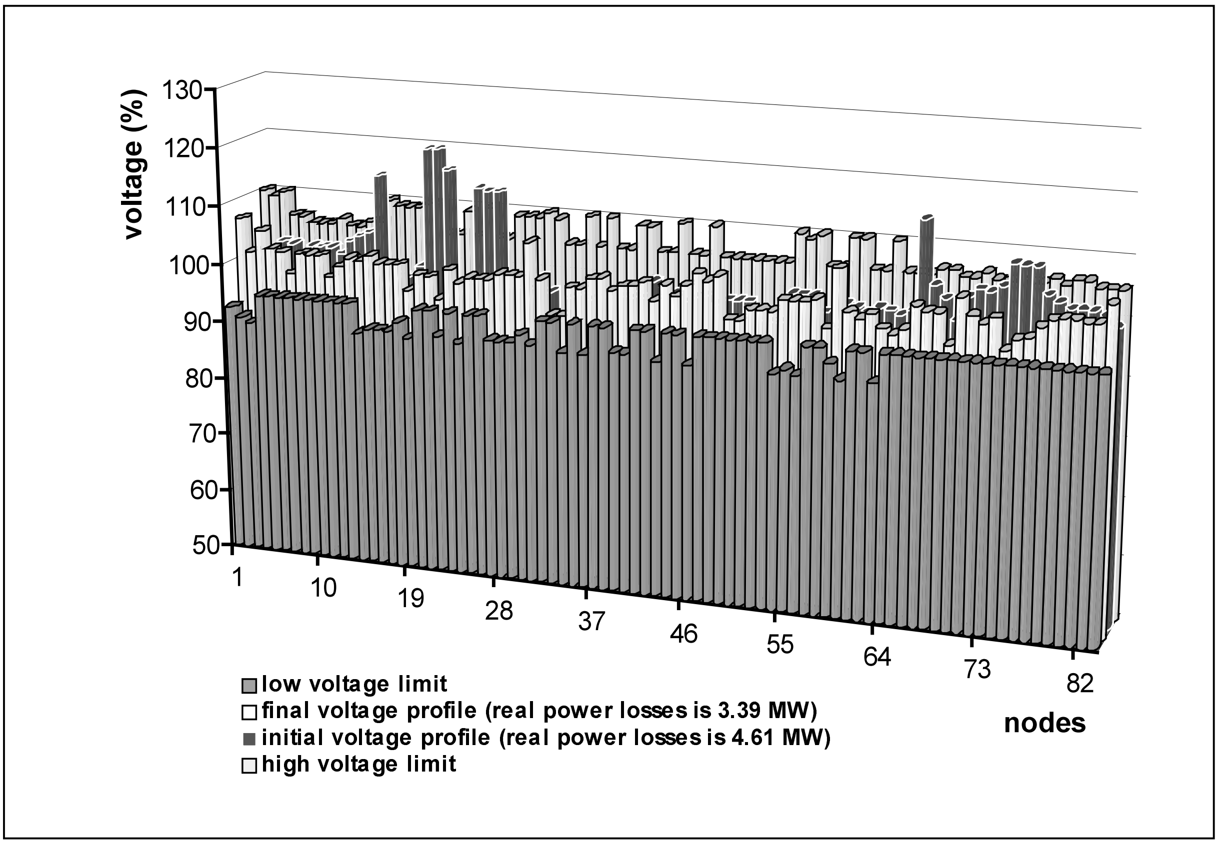

Figure 5.4 Voltage profile correction and reduction of losses as a result of conventional GA considering all the controllers (Duisburg power system)

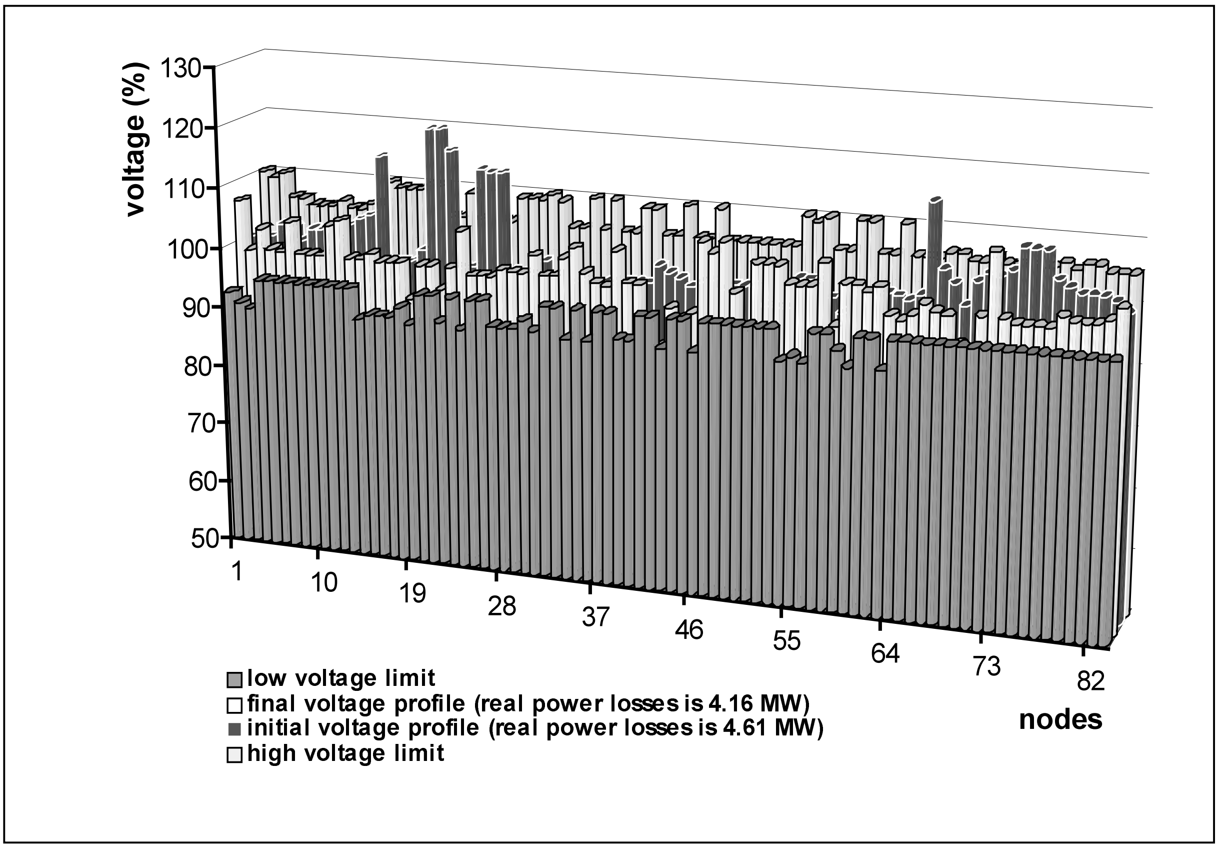

Figure 5.5 Voltage profile correction and reduction of losses as a result of micro GA considering all the controllers (Duisburg power system)

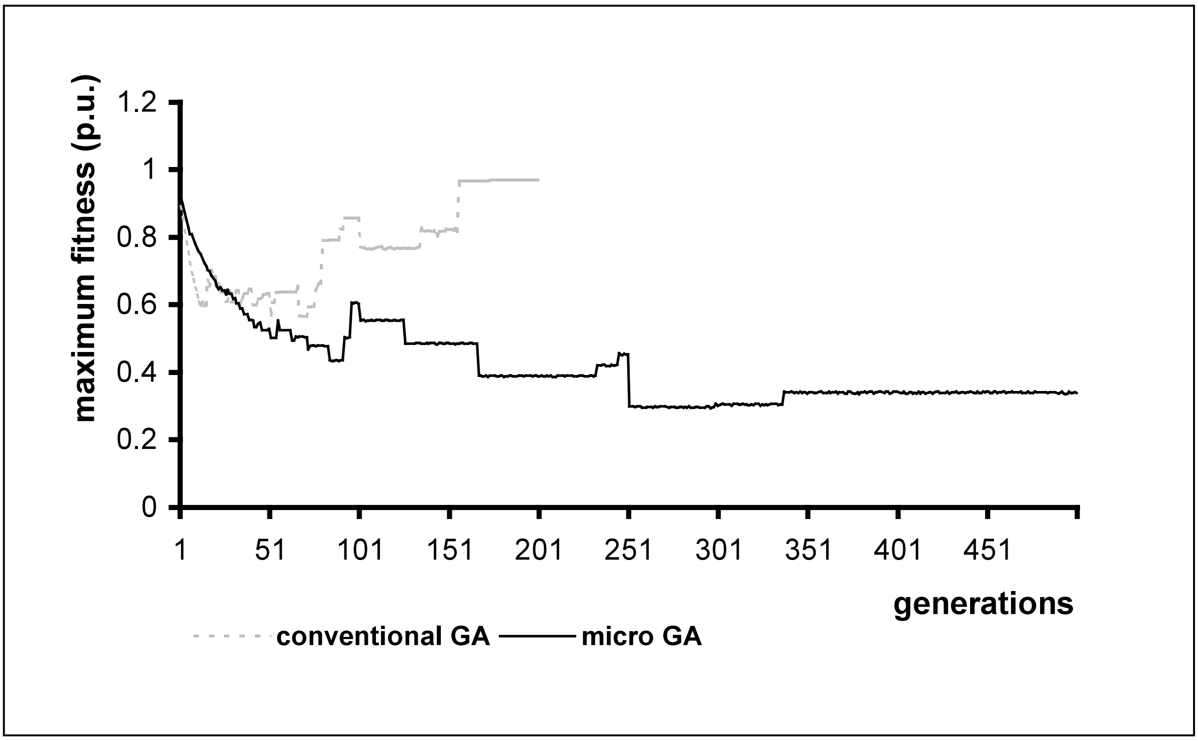

Figure 5.6 Convergence behavior of both conventional - and micro - GA for case 1 (Duisburg power system)

In contrast to the conventional GA approach, the micro GA was unable to solve the same problem and failed even at 500 generations, see figure 5.6. The resulting voltage profile is as shown in figure 5.5; the losses reduction is only 9.6% at this stage.

Case 2:

In this case, both conventional - and micro - GA were applied to the same scenario considered above but the controller pre-selection mechanism was additionally incorporated. This module selects 2 of the 4 synchronized generating units (**'''HKW2 ''BLA** and **'''HKW3 ''DT**) at substations HKW2 and HKW3 respectively, and 6 of the available 35 tap changing transformers (two 110/25/10 kV and one 110/10 kV at substation MEIDE, two 25/10 kV at substation RUHR and one 110/10 kV at substation U36), see figure 7.1. These selected controllers were passed on to the GA reactive power dispatch to determine their optimal settings. Results of voltage profile improvement and loss reduction for both methods are comparatively presented in figures 5.7 and 5.8.

It can be seen that in this case, both conventional GA (figure 5.7) and micro GA (figure 5.8) approaches succeeded in improving the voltage profile while minimizing the total system real losses. The conventional GA approach achieved a higher loss reduction (34.4%) compared with the micro GA approach (27.5%).

To compare the convergence behavior, figure 5.9 shows the maximal fitness values of individuals within generations according to equation (5.8) for both conventional - and micro - GA approaches applied to the same sample scenario from where figures 5.7 and 5.8 were obtained. The micro GA needs more generations to converge than the conventional GA and provides little lower fitness values due to the frequent restart procedure within the algorithm as there is no need for mutation (see figure 5.3). Also the number of generations needed to satisfy the convergence criteria outlined in section 5.2.1.3 (i.e. voltage at all nodes within limits and no improvement in incumbent maximum fitness after 30 generations) and reduction in transmission losses as noted in figures 5.7 and 5.8 is lower for the conventional GA (100 generations) than in case of the micro GA (192 generations). Subsequent generations are required for further reduction of transmission real power losses. On the other hand, since the micro GA processes four individuals for every generation and the fifth one is copied from the previous generation, the computational time demand per generation is considerably reduced; but due to the additional genotype convergence check

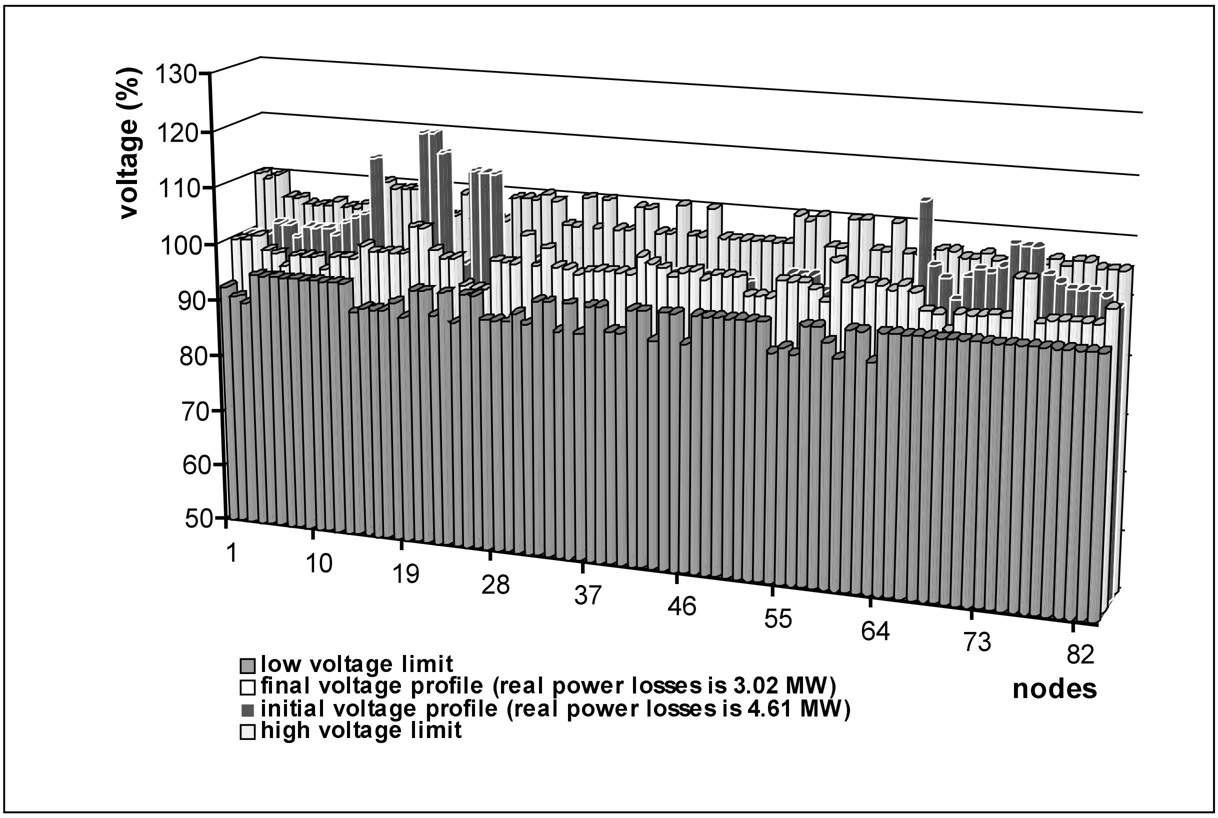

Figure 5.7 Voltage profile correction and reduction of losses as a result of conventional GA incorporating the controller pre-selection mechanism (Duisburg power system)

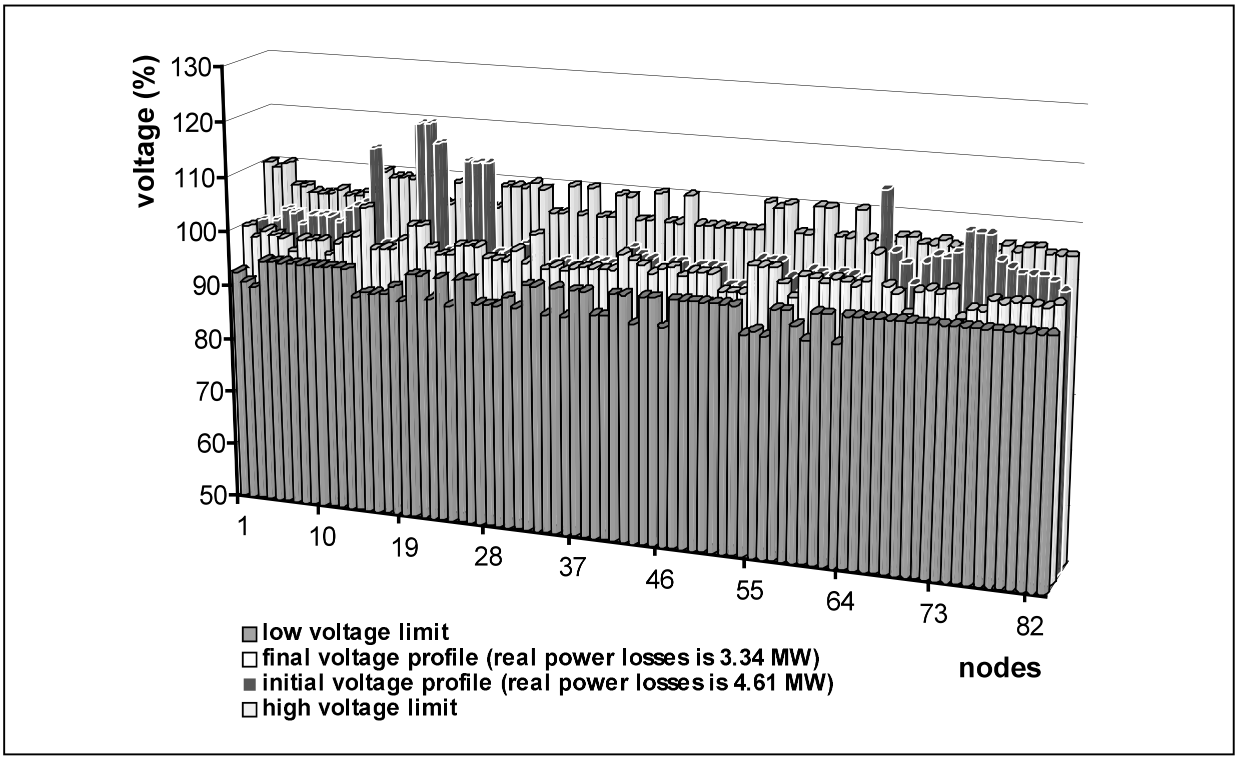

Figure 5.8 Result of micro GA for the same initial scenario incorporating the controller pre-selection mechanism (Duisburg power system)

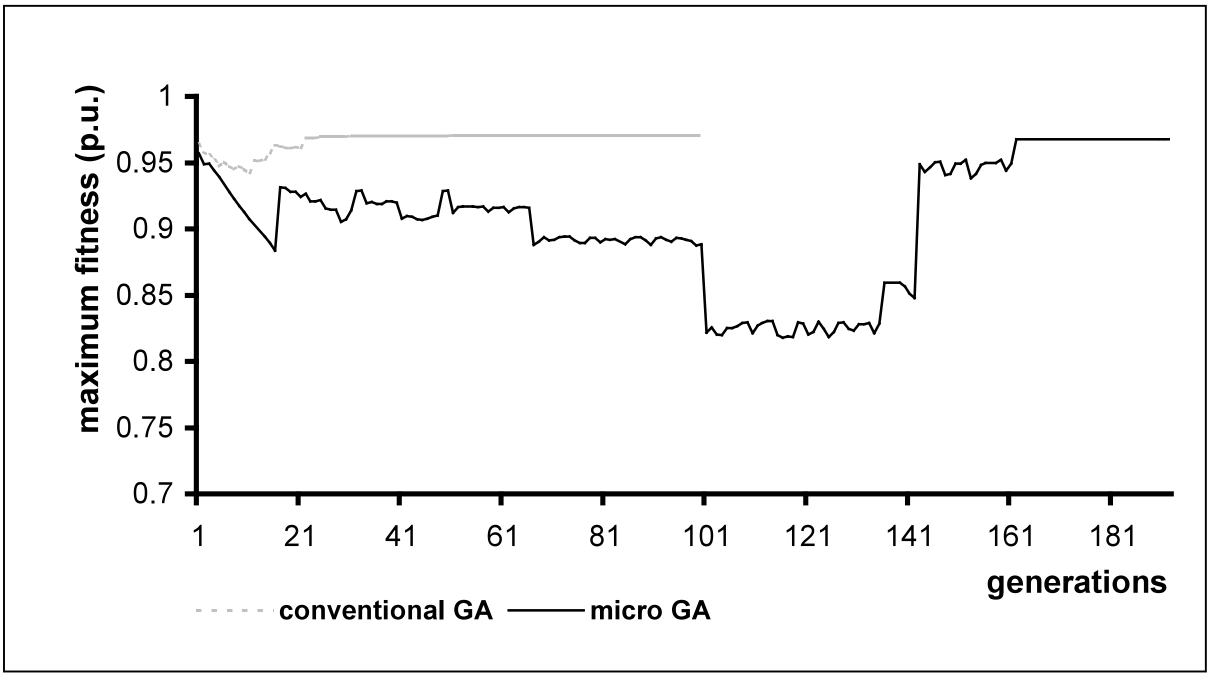

Figure 5.9 Convergence behavior of both conventional - and micro - GA for case 2 (Duisburg power system)

(see figure 5.3) there is no linear relationship between the computational time of the two approaches. As an example, to achieve a loss reduction of 27.5% from the same initial situation, the micro GA needs 215 seconds, while the conventional GA needs 542 seconds processing time to achieve a loss reduction of 34.4%.

A comparative analysis of cases 1 and 2 (see table 5.2) revealed that incorporation of the controller pre-selection mechanism is beneficial to both approaches of GA reactive dispatch in terms of performance (voltage profile improvement and losses reduction) and computation time. Both methods perform better in case 2 than in case 1. The micro GA was unable to solve the voltage problem in case 1. It can be seen that GA in conjunction with control variable pre-selection was able to eliminate the voltage problems faster than by considering all the control variables. There is an overall reduction in the computational time for this approach in that the number of control variables to be encoded is greatly reduced; thus this is amenable to large scale application. Eight control variables (i.e. two generating units and six tap changing transformers) were actually selected by the controller pre-selection module. In comparison, with regard to the execution of the final settings of the control devices, it would not be practicable and humanly possible to adjust all the 4 units and 35 transformers at a reasonable time granted that 10 seconds were required to execute each control device command: a considerable time of 390 seconds (!) would be needed. This is not desirable from practical application perspectives.

Table 5.2 Summary of results and comparison of conventional - and micro - GA based reactive power dispatch (Duisburg power system)

Results	Genetic Algorithm Approaches			
	Conventional		Micro	
	Case 1	Case 2	Case 1	Case 2
Total real power losses reduction (%)	26.3	34.4	9.6	27.5
Voltage problem solved?	yes	yes	no	yes
Generations required to converge	200*	100	500*	192
Processing time (seconds)**	1034	542	NM	215

*stopped at the maximum number of generations ; **measured on 25 MHz HP-Apollo workstation ; NM: Not Measured

5.3.2 Illustrative Example with 400/230/110 kV Transmission System

To further demonstrate the capabilities of the developed GA based reactive power dispatch, a part of the German high voltage transmission network presented above and briefly described in chapter 7 was considered. In this illustrative example, with the power system operating normally initially (i.e. there is no operating limits violation), one of the 13 generating units ('''SOL''E) was shut down and all the remaining 12 generating units terminal voltages were set at 100% and wrong tap setting of a tap changing transformer at substation BOC (see figure 7.3) was induced. As a result, voltages at five nodes violate the operating limits so that reactive power control is needed to recover the voltages. Both developed GA approaches were equally applied to solve this problem with and without incorporating the reactive power controllers pre-selection mechanism resulting also in two cases.

Case 1:

Here, both conventional GA and micro GA were applied to this problem considering all the 12 actually synchronized generating units and 69 tap changing transformers. Results of voltage profile improvement for the conventional GA and real power losses are presented in figure 5.10. Figure 5.11

depicts the related convergence behavior, which shows the maximal fitness values of individuals within generations according to equation (5.8) for the conventional GA approach applied to the above sample scenario.

From figures 5.10 and 5.11 it can be seen that at 200 generations the conventional GA approach was able to bring the voltage at all nodes within limits while at the same time a total real power losses reduction of 7.3% was achieved; rather the criterion of improvement of maximum fitness between generations was not yet fulfilled, thus stopping the algorithm at the maximum number of generations (200). A processing time of 2437 seconds was required by the conventional GA to procure the voltage recovery and real power losses reduction in this case.

In comparison, the micro GA applied to the same sample scenario was unable to solve the voltage problem even at 500 generations. Therefore, the results are not presented.

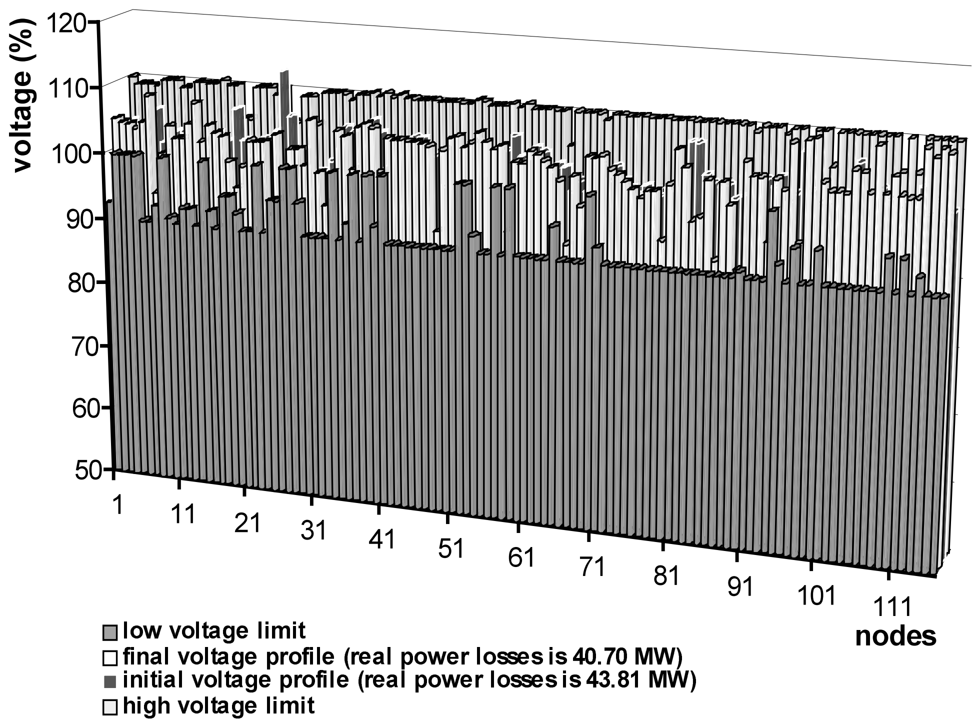

Figure 5.10 Voltage profile correction and reduction of losses as a result of conventional GA considering all the controllers (high voltage transmission system)

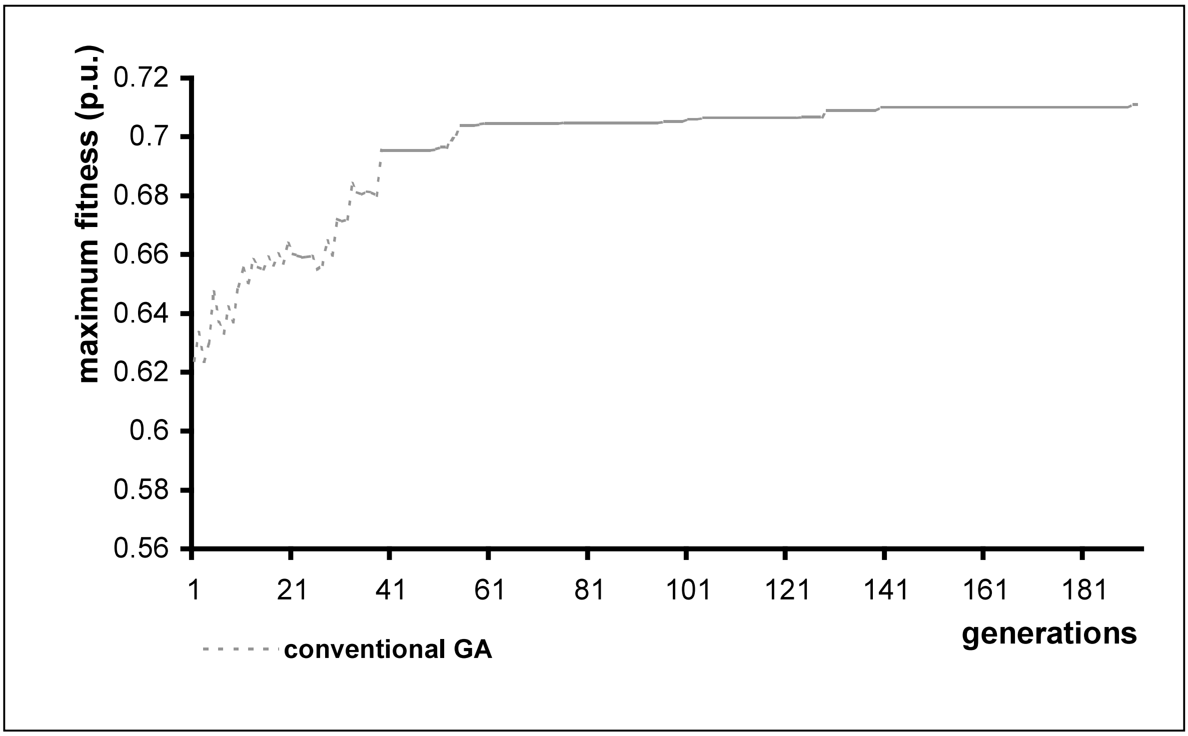

Figure 5.11 Convergence behavior of conventional GA for case 1 (high voltage transmission system)

Case 2:

Here, the controller pre-selection mechanism was additionally incorporated to select only voltage sensitive controllers. This module selected 2 of the 12 actually synchronized generating units (**'''KHER ''1** and **'''KNEP ''C**) and 5 of the available 69 tap changing transformers (three 220/30 kV at substation BOC, one 220/30 kV at substation RUH and a power unit block transformer 21/220 kV at substation SOL), see figure 7.3. These selected controllers were made available to the GA reactive power dispatch to determine their optimal settings. Results of voltage profile improvement and real power losses reduction for both methods are comparatively presented in figures 5.12 and 5.13.

It can be seen that both conventional GA (figure 5.12) and micro GA (figure 5.13) approaches succeeded in procuring the recovery of voltage profile while minimizing the total system real losses. Both approaches achieved a real power losses reduction of 1.9% at the convergence generation shown in figure 5.14. Subsequent generations, however are needed for further reduction in transmission losses.

Figure 5.14 shows the maximal fitness values of individuals within generations according to equation (5.8) for both conventional - and micro - GA approaches applied to the same sample scenario from where figures 5.12 and 5.13 were obtained in order to compare their convergence behavior. It can be seen that the micro GA needs more generations to converge than the conventional GA. The micro GA needs 266 seconds, while the conventional GA needs 660 seconds processing time to procure the voltage recovery and real power losses reduction shown in the figures 5.12 and 5.13. Summary of important results obtained showing the comparison of conventional - and micro - GA approaches are shown in table 5.3.

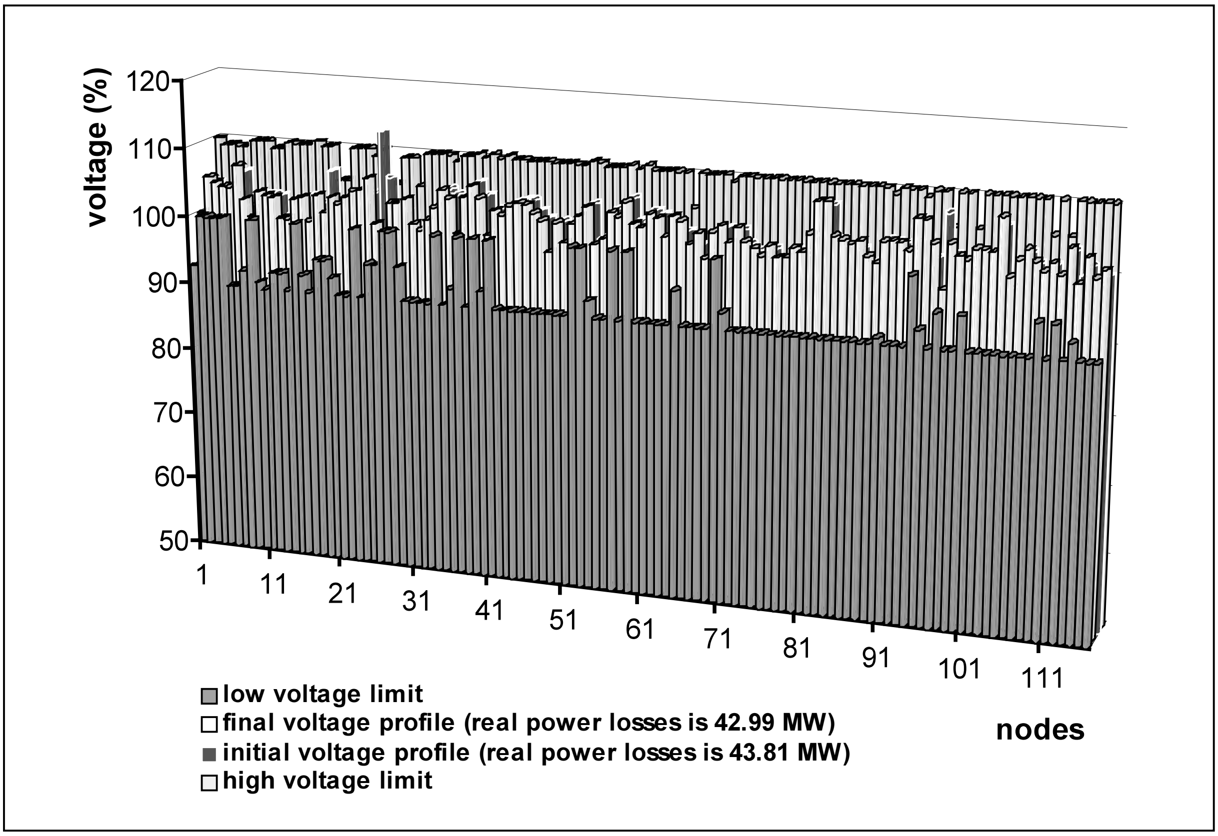

Figure 5.12 Voltage profile correction and reduction of losses as a result of conventional GA incorporating controller pre-selection mechanism (high voltage transmission system)

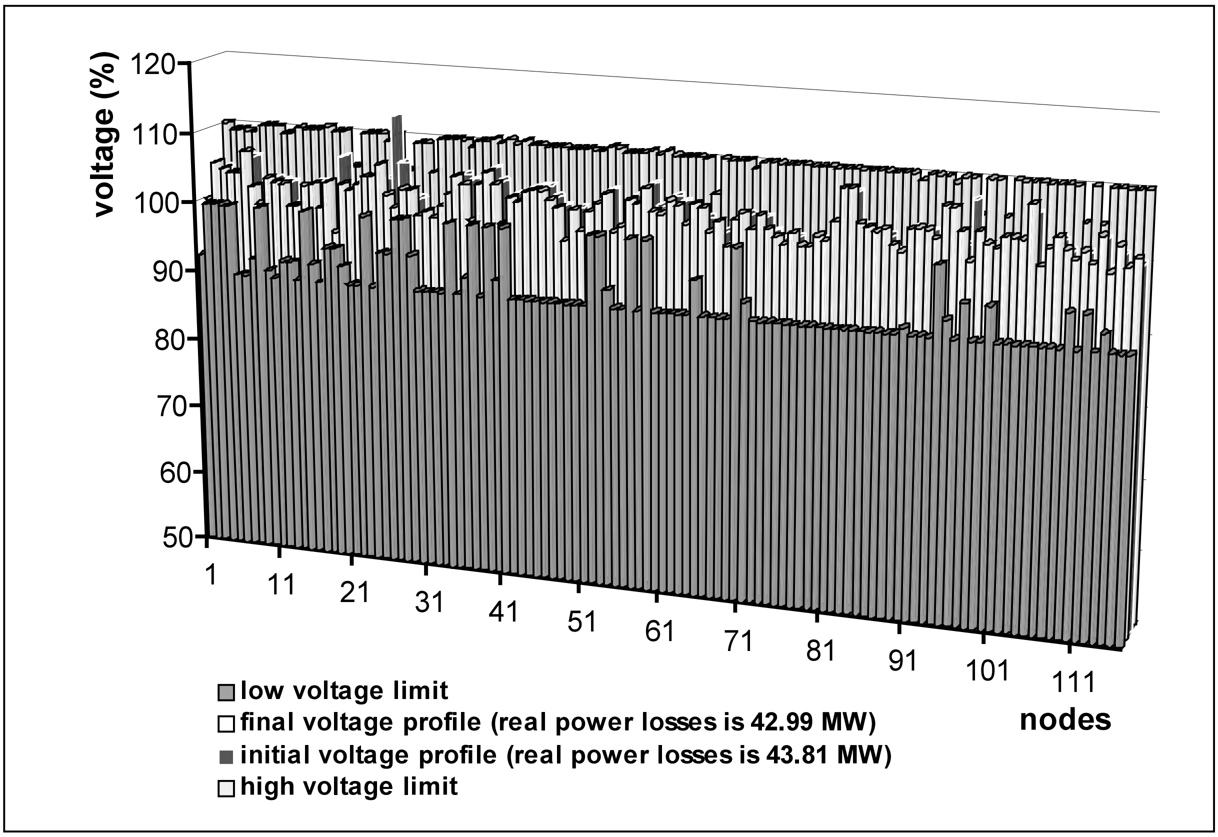

Figure 5.13 Result of micro GA for the same initial scenario incorporating the controller pre-selection mechanism (high voltage transmission system)

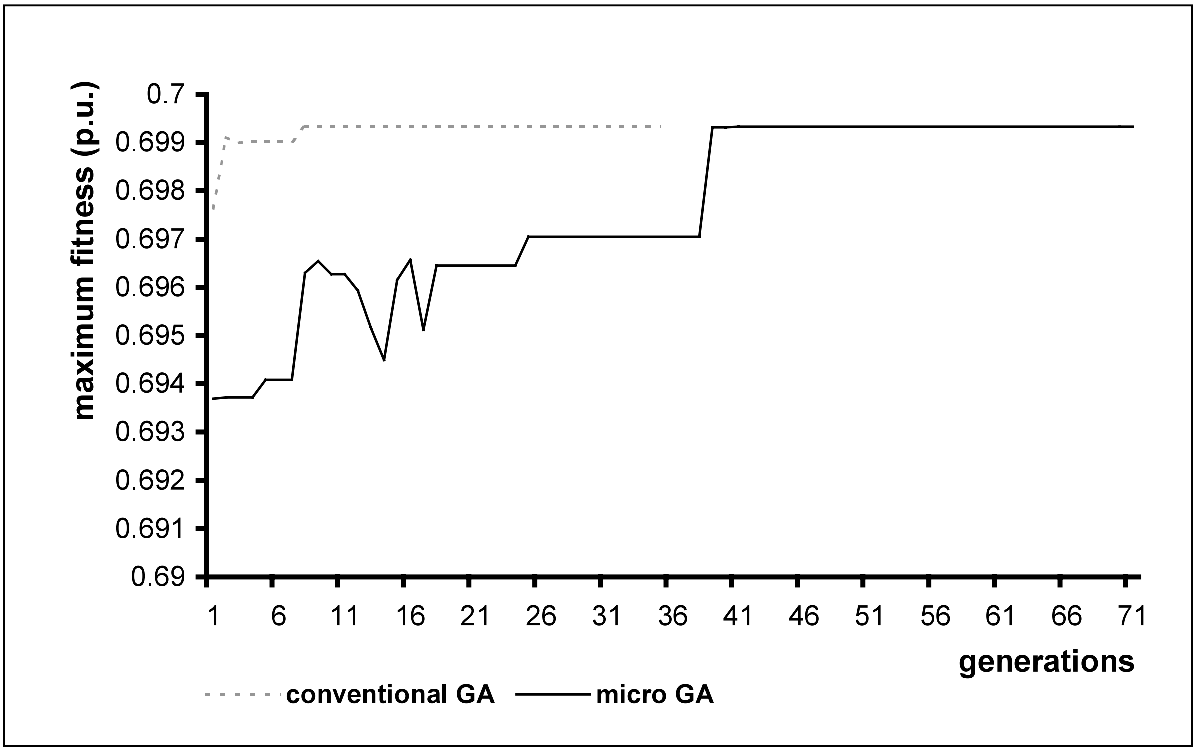

Figure 5.14 Convergence behavior of both conventional - and micro - GA for case 2 (high voltage transmission network)

Table 5.3 Summary of results and comparison of conventional - and micro - GA based reactive power dispatch (high voltage transmission system)

Results	Genetic Algorithm Approaches			
	Conventional GA		Micro GA	
	Case 1	Case 2	Case 1	Case 2
Total real power losses reduction (%)	7.3	1.9	NS	1.9
Voltage problem solved?	yes	yes	no	yes
Generations required to converge	200*	35	NS	71
Processing time (seconds)**	2437	660	NS	266

*stopped at the maximum number of generations ; **measured on 25 MHz HP-Apollo workstation ; NS: No Solution

5.4 Concluding Remarks

Both conventional and micro genetic algorithm based approaches for reactive power dispatch from the voltage profile correction and real power losses minimization point of view were comparatively investigated. They were implemented and successfully tested with several sample scenarios set on two real power systems replicated on the operator training simulator. Transformer taps, generator terminal voltages and shunt capacitors and reactors were considered as control variables.

From the results obtained (see tables 5.2 and 5.3), it was generally observed that:

- The conventional GA on principle was able to bring the voltages within limits, connected with considerable reduction of losses; however, the criterion of improvement in incumbent maximum fitness after 30 generations was not fulfilled in some cases.
- The micro GA approach failed in converging in some cases, caused by large chromosome length as a result of too many controllers to be coded.
- The application of the controller pre-selection mechanism was beneficial, especially to the micro GA.

For large scale and practical application in terms of controller commands execution it is necessary to select appropriate controllers and minimize the required chromosome length.

For both GA approaches tremendous processing time have been measured, excluding practical application. However, for the test implementation considered here (see tables 5.2 and 5.3) antiquated 25 MHz Apollo workstations were used (the reason is that the training simulator and all its environment is implemented on this hardware). A speed up factor of 20 can be realistically expected if today's computer hardware would be used, thus reducing the time demand to seconds or few minutes.

In general, the conventional GA approach proved to be superior to the micro GA approach with regard to robustness and accuracy. In view of this, the conventional GA reactive power dispatch with the control variable pre-selection mechanism were finally integrated into the hybrid state assessment and enhancement scheme as a sub-function to assist the operators' to improve the system state when there are voltage violations, see chapter 6.