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Reactive Power and Voltage Control of the Nigerian Grid System Using Micro-Genetic Algorithm

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Abstract-- **In this paper, a micro-genetic based approach to the optimization of reactive power and voltage profiles improvement and real power loss minimization is presented. The reactive power control devices such as generators, tap positions of on-load tap changer of transformers, shunt reactors are used to correct voltage limits violations while simultaneously reducing the system real power losses. Genetic Algorithms (GAs) are well-known global search techniques anchored on the mechanisms of natural selection and genetics. Because of the time intensive nature of the conventional GA, the micro-GA is proposed as a more time efficient alternative. The feasibility and effectiveness of the developed algorithm is tested and verified on the Nigerian grid power system for three case studies scenarios preset in the power world simulator. The far-reaching simulation results that validate the effectiveness of the developed tool are presented and discussed in depth.**

***Index Terms*-- Voltage/reactive power control, micro-genetic algorithm, varying fitness function, Nigerian grid.**

I. INTRODUCTION

ONE of the important operating tasks of power utility operator is to maintain the voltage profile within specified limits for high quality of services at each consumer load point. The variations in load and generation profiles during normal and abnormal operating states of a power system may worsen the voltage profile at different nodes. This is so because sustained or intermittent over-voltages ultimately lead to equipment insulation failure. On the other hand, under-voltages impact adversely on the system voltage stability margin and bulk power carrying capacity of transmission lines which, if left unchecked, can lead to steady state or dynamic voltage collapse phenomenon. Consequently, the power utility operator in the control center re-dispatch the reactive power control devices such as generators, tap positions of on-load tap changer of transformers, static shunt capacitors and shunt reactors. As a result not only the voltage profiles are kept within the desired limits but also the power losses are reduced.

Over the years, many useful studies [1-3] based on classical techniques for solving reactive power dispatch problem have been carried out. This includes nonlinear programming (NLP), successive linear programming, mixed integer programming, Newton and quadratic techniques. Most of these approaches can be broadly categorized as constrained optimization techniques.

Even though these techniques have been successfully utilized in some sample power systems, there are still several issues to be addressed with regard to real power systems. Undoubtedly, the reactive power control problem is essentially a global optimization with several local minima. The first obvious problem is where a local minimum is returned instead of a unique global minimum. The second difficulty is the inherent integer nature of the problem. Most control devices (transformer tap positions, shunt capacitor and reactor banks) have pre-specified discrete values. Thus no matter the accuracy of the continuous solution, it is impossible, without making some reasonable approximations, in order to assign these values directly to the physical control devices. Mixed integer programming could be helpful in dealing with these variables, but it seems to be more complicated than conventional continuous methods.

Recently, some new stochastic search techniques have been developed to solve global optimization problems [4-8] in an attempt to circumvent the extant computational complexity and other limiting mathematical assumptions. These search techniques include expert system (ES), genetic algorithm (GA), tabu search, simulated annealing (SA), particle swarm optimization (PSO), etc. However, the most popular among these search techniques is the application of GAs to power system operational problems.

The work considered here explores the application of genetic algorithms (GAs) for controlling the reactive power for the improvement of the voltage profiles and reduction of system losses. The reactive power control devices such as generators, tap positions of on-load tap changer of transformers, shunt reactors were considered in this work. Genetic algorithms are stochastic search techniques based on the mechanism of natural selection and survival of the fittest. Also, they combine solution evaluation with randomized, structured exchange of information among solutions to obtain optimality. As a robust and powerful adaptive tool for solving

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search and optimization problems they have been proposed for various applications in the power systems [9].

One recognized disadvantage inherent in conventional GAs (CGA) is the large number of function evaluation resulting in long computational time. The application of micro-genetic algorithm (µGA) has been reported in [12] as an effective search technique. To take advantage of its efficient computational time, a µGA based approach is proposed in this paper to solve the reactive power / voltage control problem of the Nigerian grid system. Herein, a relatively small population size is utilized when compared with conventional GAs and furthermore premature convergence is avoided by frequent call of a "start and restart" procedure, through which a diversity of the population string is introduced.

The proposed GAs tools have been tested on a Nigerian grid power system modeled on the power world simulator in detail and thus giving an opportunity to preset a multitude of scenarios under operational situation. Three case studies are then considered and it is demonstrated that the micro-GA is an effective tool in removing the voltage problem while simultaneously reducing the losses at reduced computational time.

The paper is organized as follows: After the introduction, the general concept of genetic algorithm is presented in section II. In section III, the concept of micro-genetic algorithm is briefly described. Section IV deals with the realization of GA based reactive power/ voltage control problem. Several case studies are set forth in section V. Some conclusions are made based on the key results obtained.

II. GENETIC ALGORITHMS

Genetic algorithms are stochastic search techniques based on the mechanism of natural selection and survival of the fittest [10]. Further, they combined function evaluation with randomized and/or well-structured exchange of information among solutions to arrive at global optimum. More importantly, GAs appear attractive because of their superior robust behavior in nonlinear environment vis-à-vis other optimization techniques. The architecture of GA implementation can be segregated into three constituent phases namely: initial population generation, fitness evaluation and genetic operations which are sequentially linked as delineated in the flow chart of Fig. 1. Central to GA optimization process is binary encoding which concerns the specification of the number of bits of each string to simulate the genes of an individual chromosome. In what follows, the key computational tasks of the constituent phases of GA are briefly highlighted whilst full details can be found in [14].

The GA controls parameters, such as population size, crossover and mutation probabilities are selected, and an initial population of binary strings of finite length is randomly generated. Each of these individuals, comprising a number of chromosomes, represents a feasible solution to the search problem. The strings are then decoded back into their control variables to assess their fitness. Basically, average, minimum and maximum fitness of all individuals within a generation are computed. If a pre-defined convergence criterion is not satisfied, then the genetic operations comprising selection and reproduction, crossover and mutation are carried out.

Fundamentally, the selection and reproduction mechanism attempts to apply pressure upon the population in a manner similar to that of natural selection found in biological systems. A new population is created with poorer performing individuals eliminated whilst the most highly fit members in a population are selected to pass on information to the next generation. The widely used selection strategies are stochastic tournament and roulette wheel selection [10]. But the tournament selection is preferred because of its computational efficiency as further discussed in sequel.

Conceptually, pairs of individuals are chosen at random from the population and the most fit of each pair is allowed to mate. Each pair of mates creates a child having some mix of the two parents' characteristics according to the crossover method discussed later. The process of randomly selecting pairs and mating the stronger individuals continues until a new generation of the same number of individuals is reproduced.

The crossover previously mentioned is the kernel of genetic operations. It promotes the exploration of new regions in the search space using randomized mechanism of exchanging information between strings. Two individuals previously placed in the mating pool during reproduction are randomly selected. A crossover point is then randomly selected and information from one parent up to the crossover point is exchanged with the other parent. This is specifically illustrated below for the widely used uniform crossover technique, which was adopted in this work.

parent 1: 1011 1110 offspring 1: 1010 1111
⇨
parent 2: 1010 1011 offspring 2: 1011 1010

Also considered in this work, is the mutation process of randomly changing encoded bit information for a newly created population individual. Mutation is generally considered as a secondary operator to extend the search space and cause escape from a local optimum when used prudently with the selection and crossover schemes. As an additional innovation, the creep mutation is employed to assist the GA search for optimum solution based on an intelligent mechanism. It leaps incrementally in a random direction and always within the feasible region of parameter space.

Due to the probabilistic nature of the generation process, the possibility exists that the genetic operations may destroy the highest fit individual. The elitist strategy ensures that the fittest individual generated actually is reproduced in the subsequent generation. Elitism can rapidly increase the GA performance by using the best solution as a seed for further optimization thus accelerating its convergence speed to global optimum.

III. MICRO-GENETIC ALGORITHMS

It is expected of GAs to be able to find an acceptable solution within a reasonable time when solving the optimization problem. One of the features that distinguish

GAs from other conventional search methods is the characteristics to simultaneously deal with a population of points (solutions), thus leading to the disadvantage of requiring a relatively large number of function evaluations. A survey of the existing population studies [10] shows that a reasonable population (20-200) is generally thought to be able to find a global optimum in few generations. The application of this approach has been reported in [12], proving to be conceptually simple and easy to implement.

The major difference between the micro-GA and the conventional GAs lies in the choice of the population size. In the micro-GA, an initial very small population, typically four or five individuals is randomly generated and processed by the three main GA operators with the mutation rate fixed at 0.0. The algorithm usually converges quickly within a few function evaluations.

A restart procedure in which new individuals are randomly generated while keeping a copy of the best individual of the previous converged generation ensures the infusion of new genetic information and the retention of the previous best individual. The genotype convergence is said to occur when less than 5% of the bits of other individuals differ from the best individual. The flow chart of fig. 1 shows a comparison of the conventional GA approach and the micro-GA depicting their differences.

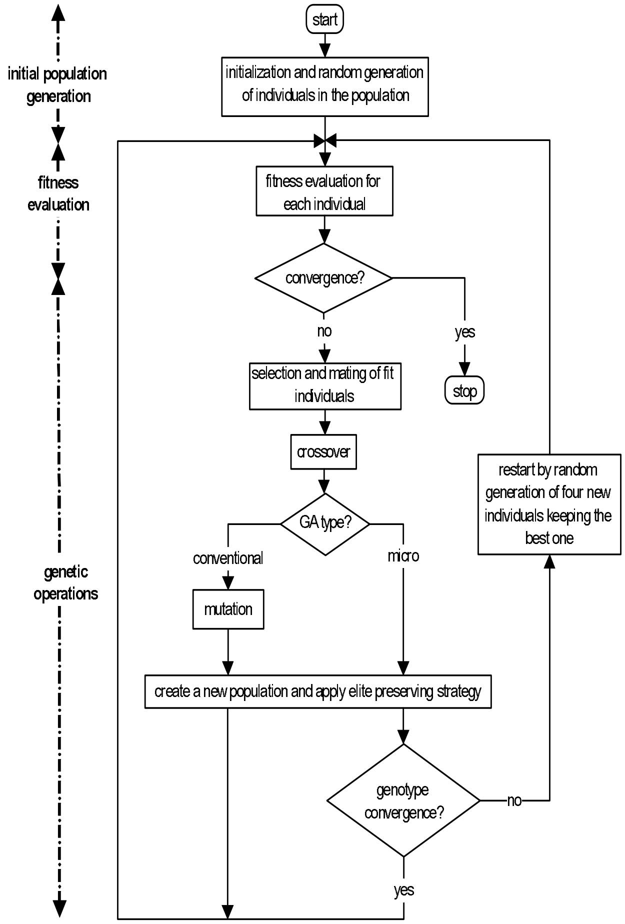

Fig. 1. Combined flowchart of micro-GA/conventional GA.

IV. REALIZATION OF GA BASED REACTIVE POWER / VOLTAGE CONTROL

The overall architecture of the proposed GA based reactive power dispatch is shown in Fig.2. It comprises several modules sharing common data and sequentially linked so as to minimize the execution time.

At the initialization phase of any GA implementation procedure, the relevant parameters must be defined as summarized in Table I. Furthermore, all the necessary power system data required for the computational process are actualized from the data files.

TABLE I
APPLIED PARAMETERS FOR GA BASED REACTIVE POWER DISPATCH

I. **PARAMETER**	***Conventional GA***	Micro GA
Population size (n_p) individuals	25	5
Mutation rate (σ_m) per bit	$\sigma_m = 1.75/l_c \cdot n_p$ *	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
Control device resolutions	3-bits for generators & transformers and 1-bit for the reactor step	3-bits for generators & transformers and 1-bit for the reactor step
Maximum number of generations (g_{max})	100	100
Voltage dev. tolerance (ε_V)	0.0	0.0
Slope of the penalty function (α)	10.5	10.5
Penalty threshold factor constraint satisfaction parameter (β)	1.005	1.005

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

Binary string representation is used to code the control device. A string consists of sub-strings; the number of sub-strings is equal to the number of control devices. The encoding parameters are the control devices earlier mentioned. A 3-bit length adequately codes a generator terminal voltage in the range of 0.9 to 1.1 p.u. at a step change of 0.025. In the encoding process of tap changing transformer, however, the bit length is adapted using the nearest integer value of the required string length:

$$b_T^i = \log_2\left(1 + \frac{T_i^{max} - T_i^{min}}{T_i^{step}}\right) \tag{1}$$

Where: T_i^{min} and T_i^{max} are the minimum and maximum tap ratios, respectively and T_i^{step} is the tap ratio step.

In the case of reactors, the total number available is retrieved from the data file to establish the number of bits required in the string representation of chromosomes. The switching on and off state of the reactor is represented in the genetic simulation process as either 1 or 0.

The initial population is randomly generated from the sets of available control devices within their feasible range into a series of fixed length binary strings. They are then concatenated to form a complete chromosome. The sub-strings of each selected generating unit terminal voltage and transformer taps of specified bits length are extracted from the concatenated strings. They are decoded into their decimal equivalent and mapped into parameter values in the corresponding search space. The reactors are decoded by taking the number of ones as those to be switched on.

The main objective of a reactive power dispatch problem is to minimize the objective function of real power losses in the system while fulfilling the task of keeping the voltage within the feasible range. In order to achieve the latter, the varying fitness function technique of handling the constraints using penalty function proposed by [13] is adopted in this work. Here, the system real power losses are determined via the Newton-Raphson power flow with the admissible control devices imbedded. In order to form the penalty function for the violation of constraint, a measure of the degree of voltage limit violations d_V^m for the n_B buses of m^{th} individual is computed using:

$$d_v^m = \sum_{k=1}^{n_B} \left|(V_k - V_k^{\lim})\right| \tag{2}$$

Where:

$$V_k^{\lim} = \begin{cases} V_k^{\max} & \text{if} \quad V_k > V_k^{\max} \\ V_k & \text{if} \quad V_k^{\min} \le V_k \le V_k^{\max} \\ V_k^{\min} & \text{if} \quad V_k < V_k^{\min} \end{cases} ;$$

$V_k, V_k^{\min} \& V_k^{\max}$, are the actual, minimum and maximum voltage of node *k*. The generator reactive power constraint violations are taken into account during the load-flow by changing the corresponding voltage controlled bus to the load bus before a new iteration is performed. The varying fitness function of the m^{th} individual can be computed using:

$$f_{ind}^m = \frac{1.0}{\left(1.0 + P_L^m + \left\{\alpha \frac{g^{act}}{g^{\max}} d_v^m + (P_L^{\max} - P_L^{\min})\beta \frac{g^{act}}{g^{\max}}\right\} y^m\right)} \tag{3}$$

Where $P_L^{\min}$ and $P_L^{\max}$ are respectively the minimum and maximum p.u. values of the objective function of minimizing the power losses in a population; $g^{\max}$ is the maximum value of generation and g^{act} is the actual generation. The appropriate values of α and β are empirically determined for this problem.

$$y^m = \begin{cases} 0.0, & \text{if } d_v^m < \varepsilon_v \\ 1.0, & \text{otherwise} \end{cases}$$

After computing the fitness of each individual in a population, the convergence criterion of the maximum number of generations is checked. If this condition is not met, the GA undergoes the genetic operations of tournament selection, uniform crossover, binary and creep mutations, as well as generation replacement with elitist strategy enabled. The parameters of the fittest individual of this generation are returned as the desired optimum settings. These optimal settings of control devices are used in the power flow program to compute the corresponding voltage profile and system real power losses.

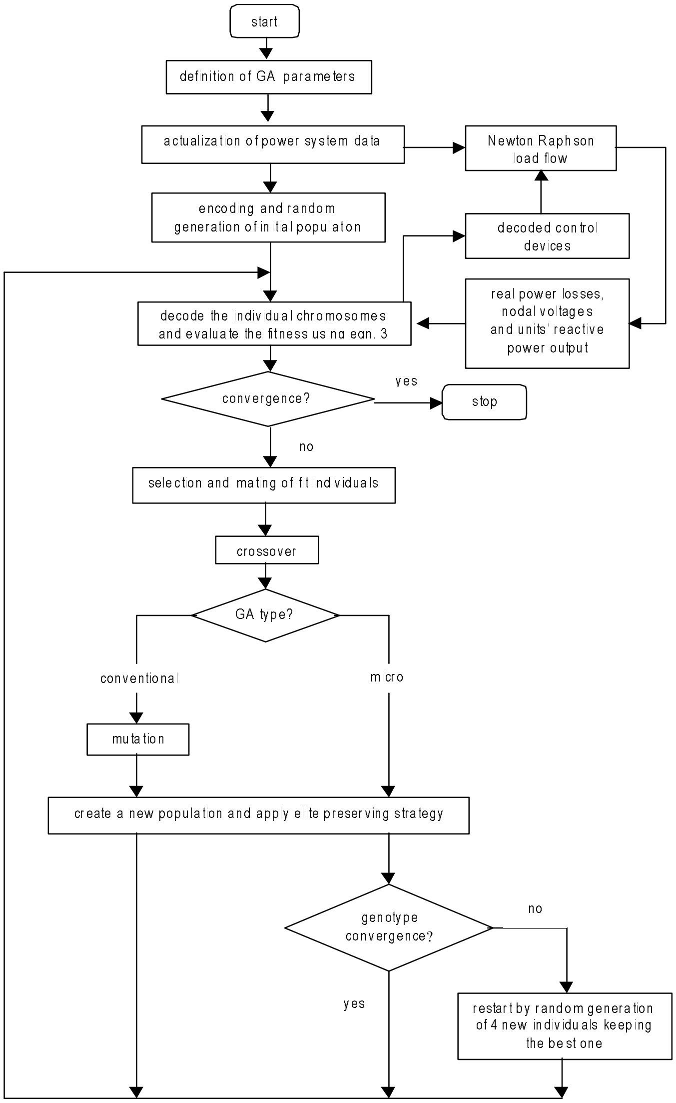

Fig. 2. Flow chart of combined micro/conventional GA based reactive power dispatch.

V. CASE STUDIES

In order to verify the feasibility and effectiveness of the developed tool, Nigerian 330-kV, 31-node grid power system replicated on the power world simulator is used. It consists of: 7 generating units (4 thermal units and 3 hydro), 7 generator transformers equipped with tap changers, and compensation reactors of different discrete values located at 8 different nodes. The single line diagram of the network is shown in Fig.3 and the complete system data not shown here can be obtained in [15]. Three samples of the various studies conducted on this power system are presented to illustrate the effectiveness of the tool.

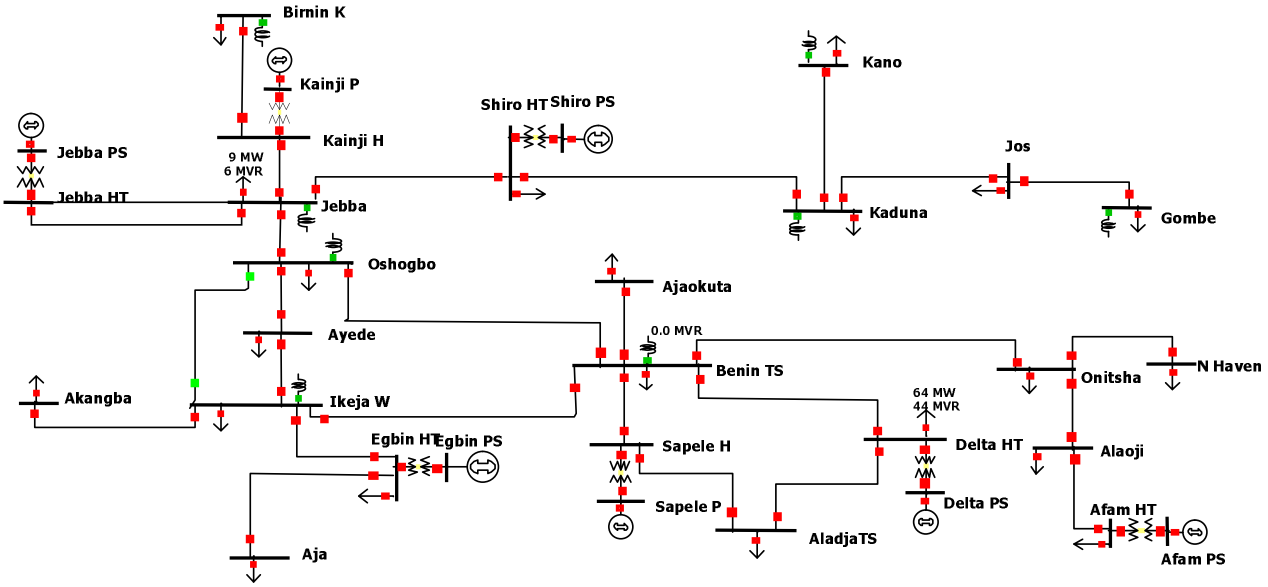

Fig. 3. Single line diagram of Nigerian 330-kV power system grid.

A. *Case Study 1: Load Modifications and Line Removal*

A number of loads at some nodes were changed in order to modify the load situation in the network and the excitation of the seven generating units randomly set at values ranging from 1.0 – 1.04 p.u The transformers taps were all set at the nominal values of 1.0. Two transmission lines: Oshogbo-Benin and Oshogo-Ikeja West were opened. Both under and over voltages problem was induced in the power system at five nodes as a result of these actions. Both the micro-GA and conventional GA based reactive power dispatch were used to solve the problem.

The results of the application of both approaches are comparatively depicted in Figs.4 and 5. It can be seen clearly that µGA approach fulfils the criterion of keeping the voltage at all buses within limits 100 generations. This is resulted in power loss reduction from 47.04356MW to 46.658MW, 0.81% active power loss reduction. Conventional GA yielded relatively less loss reduction from 47.04356MW to 46.888 MW (0.33%) and poor voltage limits violation correction capability. Since the micro-GA processes four individuals for every generation and the fifth one is copied from the previous generations, the computational time demand per generation is considerably reduced. The parameter suggestions are shown in the Table II.

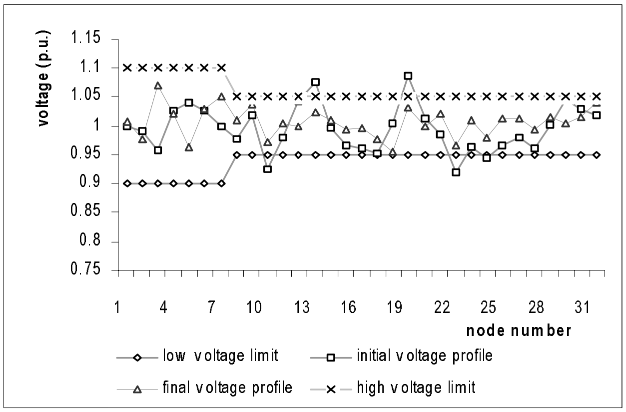

Fig. 4. Voltage profile correction using µGA reactive power dispatch.

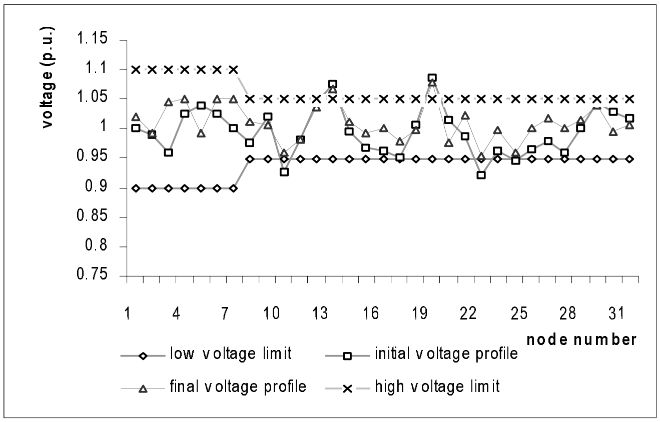

Fig. 5. Voltage profile correction using CGA reactive power dispatch.

TABLE II
SUMMARY OF CASE STUDIES SUGGESTED CONTROL DEVICE

no	Control device	Case 1		Case 2		Case 3	
		Initial	final	Initial	final	initial	final
1	Egbin PS	1.0	1.007	1.0	1.07	1.0	1.07
2	Sapele PS	0.99	0.975	0.99	0.957	0.99	0.957
3	Delta PS	1.0	1.05	1.0	1.014	1.0	1.014
4	Afam PS	1.027	1.0214	1.0	0.9857	1.0	0.9857
5	Shiroro PS	1.04	0.9643	1.03	1.043	1.03	0.957
6	Kainji PS	1.03	1.0	1.04	1.0142	1.04	1.0142
7	Jebba PS	1.0	1.05	1.03	0.957	1.03	0.957
8	25-1 (traf)	1.0	1.043	0.975	0.957	0.975	0.957
9	26-2 (traf)	1.0	1.043	1.0	1.100	1.0	1.10
10	27-3 (traf)	1.0	0.929	1.0	1.07	1.0	1.07
11	28-4 (traf)	1.0	1.014	0.95	1.10	0.95	1.10
12	29-5 (traf)	1.0	1.014	1.025	0.9571	1.025	0.9571
13	30-6 (traf)	1.0	0.957	0.95	1.014	0.95	1.014
14	31-7 (traf)	1.0	1.043	1.0	1.10	1.0	1.10
15	Benin TS (4no,75 Mvars)	0	4	2	1	2	1
16	Jebba (2no, 75Mvars)	0	2	0	1	0	1
17	Ikeja West (4no,75 Mvars)	0	2	2	2	2	2
18	Oshogbo (2no, 75Mvars)	0	1	0	1	0	1
19	Kaduna (1no, 75Mvars)	0	1	0	0	0	0
20	Gombe (1no, 75Mvars)	0	0	0	1	0	1
21	Birni Kebbi (1no, 50Mvars)	0	1	0	1	0	1
22	Ajaokuta (1no, 30Mvars)	0	0	0	1	0	1

B. Case Study 2: Wrong Tap Settings of Transformers and Switching Reactances

With all the 33 transmission lines closed, a scenario was preset on the power world simulator by heuristic based wrong tap settings of the machine transformer taps. Two of the four each 75 MVars reactors at bus 8 (Benin TS) and node 10 (Ikeja West) were wrongly switched on. These actions led to the voltage limits violations in 13 nodes. Micro-GA based reactive power dispatch is used to solve this voltage problem. The result of the application of this approach is presented in Fig.6. Simulation results show that the approach is able to keep the voltage at all buses within limits in 100 generations. Active power loss reduction of 7.51% (from 40.497MW to 37.456 MW) was achieved with this approach.

C. Case Study 3: Disconnection of a Transmission Line

Here, the system was initially operating in the scenario 2. Interrupting the transmission line between Ikeja West and Benin TS resulted in voltage limits violations at 14 nodes.

The micro-GA based reactive power is used to solve this problem. The algorithm was able to solve the voltage problem, which yielded 6.338757% (from 42.79MW to 40.77 MW) real power loss reduction. The voltage profile correction is as shown in Fig. 7. The recommended control devices for the above three cases are summarized in the Table II.

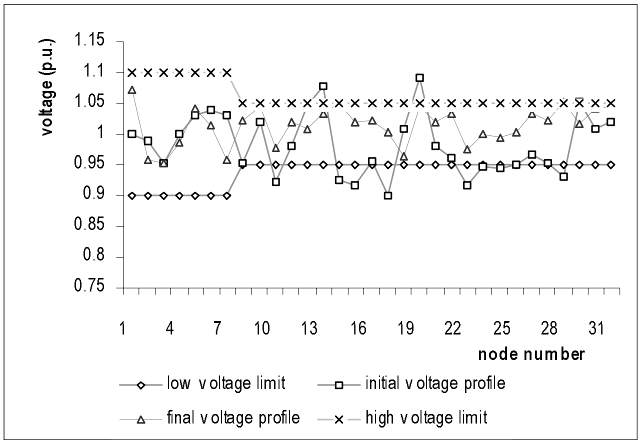

Fig. 6. Voltage profile correction using micro- GA for case 2.

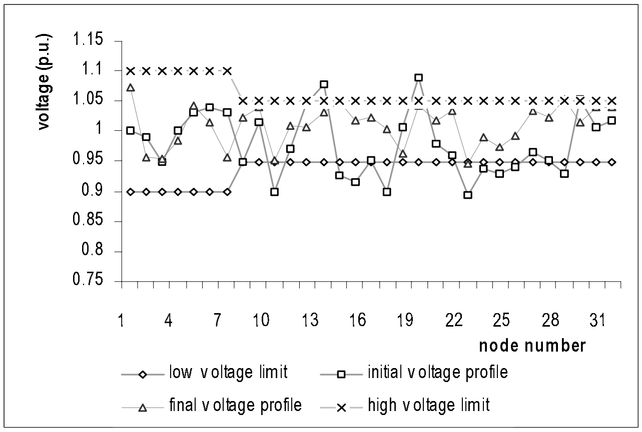

Fig. 7. Voltage profile correction using micro-GA for case 3.

VI. CONCLUSION

In this paper, a micro-GA and conventional GA based reactive power / voltage control has been proposed. The simulation studies on Nigerian grid power system have been replicated on power world simulator to solve the imposed reactive power / voltage control problem. The proposed approach was able to correct the resulting abnormal bus voltages to within the prescribed limits whilst returning lower system real power losses at significantly reduced processing time. From practical point of view, it is pertinent to curtail the number of control devices employed to alleviate bus voltage problems. It is also feasible to apply the proposed genetic algorithm with pre-selection mechanism to the Nigerian grid power system with distributed Flexible AC Transmission System (FACTS) devices. These are our research direction being pursued to incorporate intelligent computations.

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