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Voltage Controller for Radial Distribution Networks with Distributed Generation

Christopher Kigen [*], Dr. Nicodemus Abungu Odero[*]

[*] University of Nairobi, Department of Electrical & Information Engineering, P.O. Box 30197-00100 Nairobi, Kenya

Abstract- This paper presents a coordinated network controller whose objective is to maintain an optimal voltage profile across radial distribution networks with distributed generation. This is done by varying the output of the distributed generators. The controller was modeled as an optimization problem which was solved using Particle Swarm Optimization. The IEEE 33-bus and 69-bus test networks are then used to verify the effectiveness of the controller. The results obtained show that this controller can improve the voltage profile of a power network.

Index Terms- *radial distribution networks, particle swarm optimization, modified backward-forward sweep*

I. Introduction

Distributed generation (DG) is the term used to describe small scale generation of power usually connected directly to distribution networks. Most distribution systems are radial feeders, with a point of common connection, usually a substation. The introduction of distributed generation in distribution systems causes a voltage rise within the radial network. This is undesirable, as network operators must supply customers with voltages within a specific band of magnitude. There are various methods described in literature of mitigating this effect, and maintaining a suitable voltage profile.

This research is an extension of previous research done [1]. It is seen that Newton-Raphson load flow may not converge when applied to radial distribution networks. The controller developed in this research addresses this problem by using a modified backward-forward load flow.

Le, et al. (2005) [2] develop a technique to optimize voltage by effectively placing DG based on voltage sensitivity of the power lines. The authors develop a location index for DG placement. The index indicates proximity of each bus to voltage collapse. The DGs are located at buses closest to collapse (least stable).
Musa and Sanusi (2012) [3] describe a method called Ranked Evolutionary particle swarm optimization which is a hybrid of Evolutionary Programming and PSO. The method uses a "Ranking process" to find the best particle in a population. The method improves voltage profile in the radial network by optimal DG sizing and placement.
Rao and Raju (2010) [4] describe a voltage regulator placement method that uses Plant Growth Simulation Algorithm. Together with a candidate location technique, the method places voltage regulators at optimal locations in the radial network. In this way, optimal voltage profile is achieved.
Shivarudraswamy and Gaonkar (2011) [5] perform a voltage sensitivity analysis to determine the outputs of multiple DGs in radial networks for the best voltage profile. This enables coordinated voltage control of the network.
Lantharthong and Rugthaicharoencheep (2012) [6] propose a method of reconfiguring radial networks for optimal operation. Tabu search is used to allocate DGs and place capacitors in the radial networks.
Sharma and Vittal (2010) [7] propose a Network Performance Enhancement Index and heuristic rules for location and sizing of DG. In this way, an overall improvement in radial network performance is achieved. Voltage profile is measured using a voltage profile improvement index.
Naik, et al. (2012) [8] propose a method of network optimization based on optimal location of DG through voltage sensitivity index analysis. The method uses the forward-backward sweep method for power flow analysis. This method is effective in load flow of radial networks.
Kumar and Navuri (2012) [9] demonstrates a method of optimal placement and sizing of DG in a radial distribution network. The optimal position of DG is found through the use of loss sensitivity factors. These factors help to reduce the search space within which the optimal buses are located. A search method known as simulated annealing is used to determine size of DG at the optimal location.
Abu-Mouti and El-Hawary (2012) [10] proposes a radial network optimization method, that performs placement and sizing of DG in the network. This is done through the use of the artificial bee colony algorithm.
Chenning and Xuequin (2012) [11] presents an improved backward/forward sweep network load flow method. The method calculates load flow, without reactive flow update. Examples of various sizes and locations of DG within test networks are presented with results. A comparison is made between the results of this research and those obtained by the authors' previous work.
These different methods all attempt to control the voltage profile of the network. Most commonly, this is done by placement of the DG at the optimal bus. The sizing and output of the DG will also be varied to obtain the best result. In this research work, the voltage profile is optimized by usng a particle swarm optimization-based controller, together with a modified backward forward sweep load flow.

II. FORMULATION

A. Particle Swarm Optimization

Power system optimisation problems have multiple dimensions because of their numerous variables and constraints. This type of problem is best solved by meta-heuristic methods. The improvement in system performance is based on reduction in cost of power generation and active power loss.

Particle swarm optimization (PSO) technique consists of a population of particles refining its knowledge of the given search space. The dimensions of the search space are determined by the number of decision variables and the particle population. The coordinates of each particle within the search space represent a possible solution. Each particle moves with adaptable velocity through the search space. The velocity of a particle depends on the particle's historical best position, the best position of other particles in the swarm, and a pre-determined fitness function. Each particle retains a memory of the best position it has encountered. The best position encountered by all of the particles is also remembered and is called the global best position.

To implement a PSO solution, a swarm of particles representing possible solutions is first initialized randomly.

The position of the particles changes from one iteration to the next, determined by the following variables. The position of a particle, $X_i(t)$, is a vector of the value of decision variables in a particle during iteration 'i'. The best previous position of particle 'i' is given by P_i. This variable represents the level of attraction of the particle towards its best solution so far. The best previous position of all particles (global best) is denoted by P_{gb}. This represents the attraction of the particle towards the best solution found by other particles in the swarm. The velocity of a particle during iteration 't' is given by $V_i(t)$. This represents the tendency of the particle to continue moving in a particular direction. This is a vector whose members are determined by evaluating a velocity update equation. For a general PSO, the vector update equation is given by

$$V_i^{t+1} = wV_i^t + C_1 \times r_1 \times (P_i - X_i^t) + C_2 \times r_2 \times (P_{gb} - X_i^t) \quad (1)$$

where C_1 and C_2 are acceleration coefficients and r_1 and r_2 are random numbers introduced to add stochasticity to the model. w represents an inertia coefficient. Once the velocity is determined, the position vector is updated using the following equation.

$$X_i^{t+1} = X_i^t + V_i^{t+1} \quad (2)$$

Optimisation problems vary widely in their nature. To improve the implementation of PSO, and adapt the method to suit a particular problem, various adjustments to the algorithm can be made. The topology of the swarm is the degree to which nearby particles have an influence on the velocity of a particle. This is referred to as the neighbourhood of the particle. In general, if the particle is influenced by all particles in the swarm, the best solution of all particles is included in the velocity update equation. This is known as g_{best}. If the particle is influence by a neighbourhood of nearby particles, the best solution is known as l_{best}, and is included in the velocity update equation.

To prevent divergence of the swarm, constriction factors or inertia constants are added to the velocity update equation.

B. Modified Backward / Forward Sweep Load Flow

The Newton-Raphson method is inefficient in analysis of radial networks. This is because radial network data produces sparse matrices, which are time-consuming to process. Accordingly, there are a number of reported studies in the literature specially designed for solution of power flow problem in radial distribution networks.

The BW/FW Sweep algorithms use the Kirchhoff laws. Different formulations can be found in literature. Using these methods, power flow solution for a distribution network can be obtained without solving any set of simultaneous equations.

The backward forward sweep method used in this research was based on Alsaadi, and Gholami (2009) [12]. The special topological characteristics of distribution networks have been fully utilized to make the direct solution possible. Two matrices are used to obtain power flow solutions. These are the bus-injection to branch-current (BIBC) matrix and the branch-current to bus-voltage (BCBV) matrix.

The BIBC presents the relationships between branch currents flowing through the radial network and node currents injected at each bus.

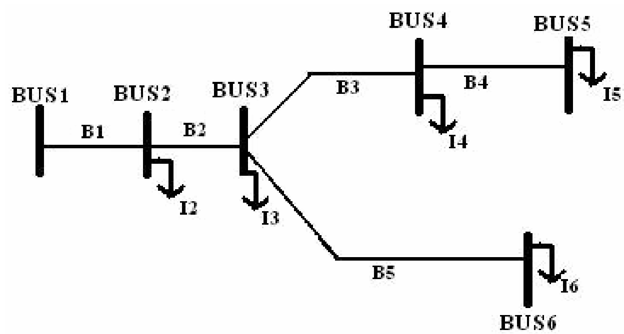

Figure 1: Sample Radial Network

In the figure above, the branch currents are denoted by the symbol 'B' and injected currents by symbol 'I'. Taking current B_5,

$$B_4 = I_5 \quad (3)$$

Also,

$$B_3 = I_4 + B_4 \quad (4)$$

Substituting (3) into (4),

$$B_3 = I_4 + I_5 \quad (5)$$

Similarly,

$$B_2 = I_3 + I_4 + I_5 + I_6 \quad (6)$$

By taking all the equations for branch currents simultaneously, we form the matrix equation,

$$\begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ B_4 \\ B_5 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \\ I_5 \end{bmatrix} \quad (7)$$

This is generalized to,

$$[B] = [BIBC][I] \quad (8)$$

Similarly, the BCBV was formulated as the relationship between branch currents and node voltages.

By using a process similar to that used to form the BIBC, we get the BCBV of the illustrated network as follows.

$$\begin{bmatrix} V_1 \\ V_1 \\ V_1 \\ V_1 \\ V_1 \end{bmatrix} - \begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \\ V_5 \end{bmatrix} = \begin{bmatrix} Z_{12} & 0 & 0 & 0 & 0 \\ Z_{12} & Z_{23} & 0 & 0 & 0 \\ Z_{12} & Z_{23} & Z_{34} & 0 & 0 \\ Z_{12} & Z_{23} & Z_{34} & Z_{45} & 0 \\ Z_{12} & Z_{23} & 0 & 0 & Z_{56} \end{bmatrix} \begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ B_4 \\ B_5 \end{bmatrix} \quad (9)$$

This is generalized to,

$$[\Delta V] = [BCBV][B] \quad (10)$$

Substituting (8) into (10), we get the relationship between bus voltages and bus injection currents as,

$$[\Delta V] = [BCBV][BIBC][I] \quad (11)$$

The injected current at a bus 'i' is given by

$$I_i = \frac{(P_i - jQ_i)^*}{V_i} \quad (12)$$

This load flow method is used with passive networks. These are networks with a single source of power. However if DGs are connected to the networks, they become active.

In order to incorporate DGs into the radial load flow, they are considered as current sources. In a bus with a DG, the injected power is given as follows.

$$S_i = S_{Di} - S_{Gi} \quad (13)$$

Where S_i is injected power at bus 'i', and S_{Di} and S_{Gi} represent load power and generator power at bus 'i', respectively. Thus, injected current at a bus with DG is given by

$$I_i = \frac{[(P_{Di} - P_{Gi}) - j(Q_{Di} - Q_{Gi})]^*}{V_i} \quad (14)$$

The radial network loadflow can be carried out by solving the following equations iteratively.

$$[\Delta V^{k+1}] = [BCBV][BIBC][I^k] \quad (15)$$

$$[V^{k+1}] = [V^0] - [\Delta V^{k+1}] \quad (16)$$

Where V^{k+1} represents the voltage at each bus during the k+1'th iteration.

III. TEST NETWORKS

In order to test the effectiveness of the proposed controller, the algorithm was tested on two standard IEEE radial distribution networks. These are the IEEE 33-bus and 69-bus radial networks. These networks were chosen because they have been used extensively in literature for radial distribution network analysis. The proposed controller was first tested on the IEEE 33 bus network. Load and line data for this network are given in [13]. The total installed peak loads on the system are 3715 kW and 2290 kVAr. Base voltage is 12.66kv. The topology of the network is illustrated below.

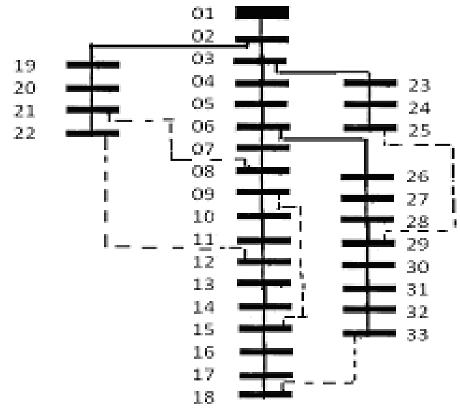

Figure 2: IEEE 33-bus Radial Network

The IEEE 69-bus radial distribution system has 70 branches and 7 laterals. Bus 1 is taken as the point of common coupling (substation). The test system is a 12.66 kV radial distribution system. The total loads for this test system are 3,801.89 kW and 2,694.10 kVAr. This network is used extensively in literature for testing and simulation of radial distribution feeder networks. Load and line data for this network are given in [6]. The topology of the network is illustrated below.

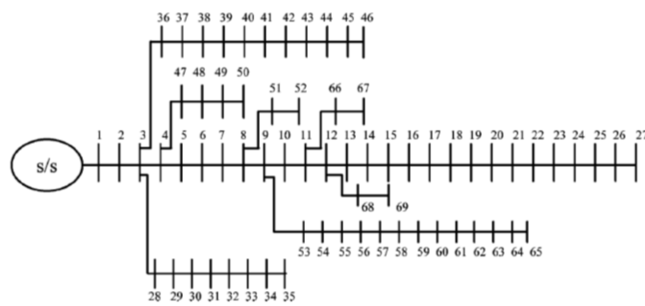

Figure 3: IEEE 69-bus Radial Network

IV. SIMULATION RESULTS

The controller algorithm was simulated in Matlab code. The parameters specified in various previous research works are used as inputs to the controller simulation program. The results obtained by running the program using these parameters are shown in graphical form below.

Test Case 1a: IEEE 33-Bus Network

A comparison was made with [7]. In this case, there was one DG in the network. The DG was placed on bus 30 has a real power output of 1470kW and reactive power of 500kVAr. The voltage profile of the network with these parameters is shown below.

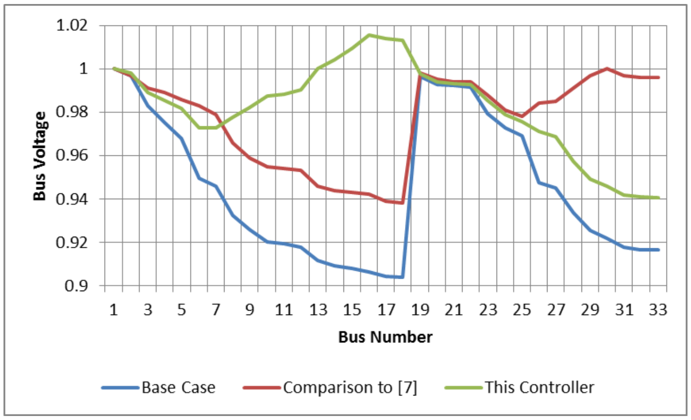

Figure 4: Test Case 1a

Test Case 1b: IEEE 33-Bus Network

A further comparison was made with [14]. In this case, there are three DG in the network. The first DG was placed on bus 15, and has a real power output of 50kW. The second and third DG are placed on bus 25 and 31 respectively, and have real power outputs of 250kW and 750kW, respectively. The voltage profile of the network with these parameters is shown below.

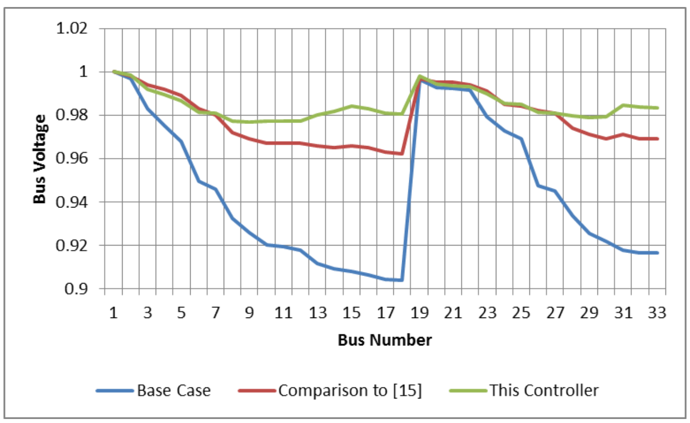

Figure 5: Test Case 1b

Test Case 1c: IEEE 33-Bus Network

A further comparison was made with [8]. In this case, there was one DG in the network. The DG was placed on bus 16, and has a real power output of 1350kW as well as reactive power of 654kVAr. The voltage profile of the network with these parameters is shown below.

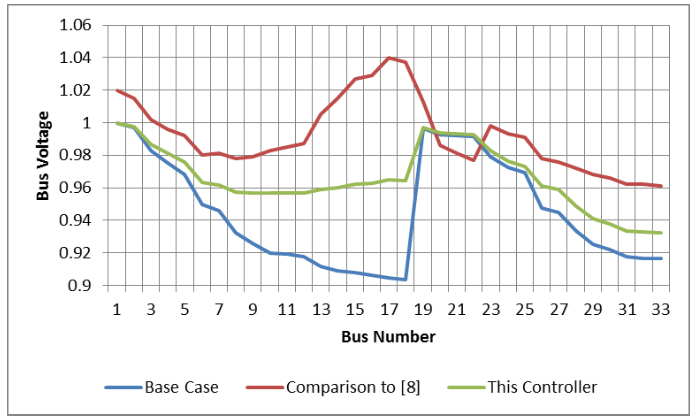

Figure 6: Test Case 1c

Test Case 1d: IEEE 33-Bus Network

A further comparison was made with [11]. In this case, there are two DG in the network. The DG are placed on bus 16 and 32, and have real power output of 400kW and 200kW, respectively. The voltage profile of the network with these parameters is shown below.

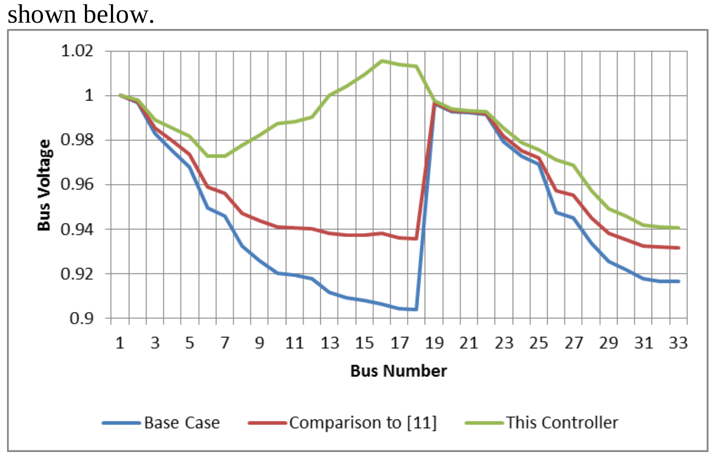

Figure 7: Test Case 1d

Test Case 1e: IEEE 33-Bus Network

A further comparison was made with [9]. In this case, there are three DG in the network. The DGs are placed on bus 17, 18 and 33, and have real power output of 719kW, 113kW and 1043kW, respectively. The reactive power outputs of the DG's are 415kVAr, 65kVAr and 6kVAr, respectively. The voltage profile of the network with these parameters is shown below.

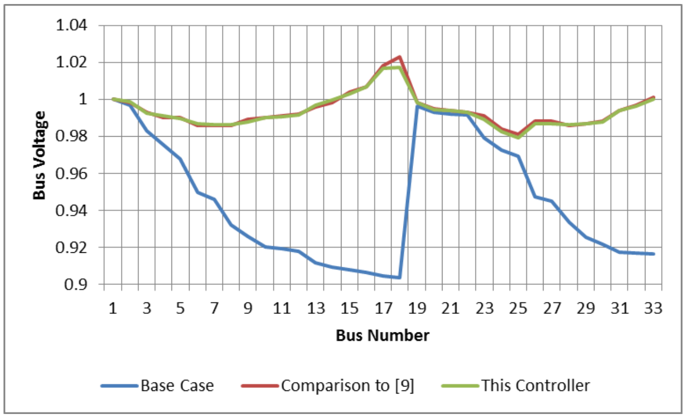

Figure 8: Test Case 1e

Test Case 2a: IEEE 69-Bus Network

A comparison was made with [9]. In this case, there are two DG in the network. The DG are placed on bus 26 and 65, and have real power output of 656kW and 1606kW, respectively. The reactive power outputs of the DG's are 378kVAr and 927kVAr, respectively. The voltage profile of the network with these parameters is shown below.

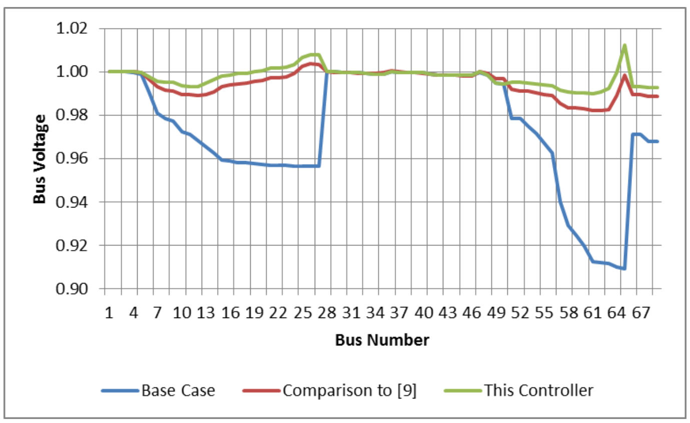

Figure 9: Test Case 2a

Test Case 2b: IEEE 69-Bus Network

A comparison was made with [10]. In this case, there was one DG in the network. The DG was placed on bus 61, and has real power output of 1870kW and reactive power output of 1159kVAr. The voltage profile of the network with these parameters is shown below.

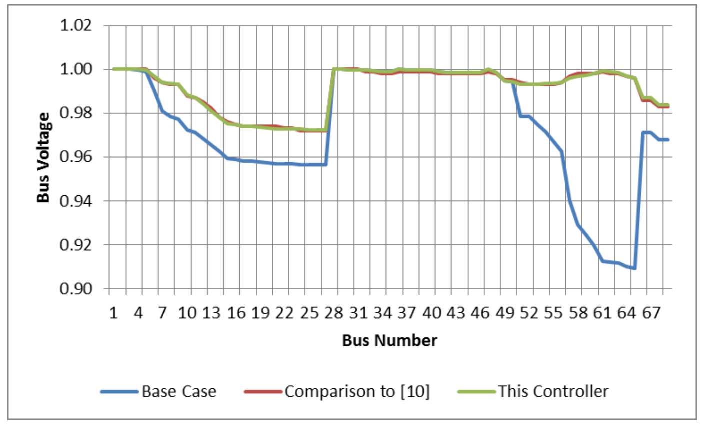

Figure 10: Test Case 2b

V. DISCUSSION

The results above are summarized in the table below.

Test Case	Reference Article	Reference Optimum Result	Optimum in This Research
1a	Sharma and Vittal (2010) [7]	0.762	0.698
1b	Sharma and Vittal (2010) [7]	0.708	0.504
1c	Naik, et al. (2012) [8]	0.7027	0.698
1d	Chenning and Xueqin (2012) [11]	1.3834	0.698
1e	Kumar and Navuri (2012) [9]	0.304	0.3021
2a	Kumar and Navuri (2012) [9]	0.3821	0.2473
2b	Abu-Mouti and El-Hawary (2011) [10]	0.608	0.598

The figures given represent the results of the objective function of the controller algorithm. This is given by,

$$f = \sum_{i \in N_L} |V_i - 1.0| \tag{17}$$

This function is a measure of the extent to which bus voltages – represented by V_i – deviate from unity. The lower the value of 'f', the better the voltage profile of the network. A lower value is a better result.

These results indicate that the controller consistently outperforms existing research in literature. By adjusting the output of DGs, a better voltage profile can be achieved.

VI. CONCLUSION

This paper has presented a controller that uses PSO and a modified backward / forward load flow to optimize voltage profile in radial distribution networks with distributed generation. This controller can be implemented in real-world networks with minimal additions to existing network devices.

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AUTHORS

First Author – Christopher Kigen, Postgraduate Student, University of Nairobi, Department of Electrical & Information Engineering, P.O. Box 30197-00100 Nairobi, Kenya.
Second Author – Dr. Nicodemus Abungu Odero, University of Nairobi, Department of Electrical & Information Engineering, P.O. Box 30197-00100 Nairobi, Kenya.

Correspondence Author – Christopher Kigen, Postgraduate Student, University of Nairobi, Department of Electrical & Information Engineering, P.O. Box 30197-00100 Nairobi, Kenya.