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Optimal Allocation of Dynamic Voltage Restorer in Distribution System Using Water Cycle Algorithm for Power Quality Enhancement

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ABSTRACT
The current trend of integrating sensitive loads and renewable energy sources (RES) at the Distribution corridor require urgent attention for dealing with associated power quality problems in the system, ranging from losses which decreases efficiency, voltage sags, voltage swells and flickers to other voltage instabilities. In this research a dynamic voltage restorer (DVR) was considered for solving these problems. Forward/backward flow algorithm techniques was considered in determining the system parameters. Water Cycle Algorithm Techniques was employed in this optimization work due its many advantages over other meta-heuristics algorithm, such as speed of convergence, ability to dodge premature convergence and not easily being trapped by local minima. The Optimization problem was formulated for the minimization of the voltage deviation and power loses by using water cycle algorithm in an IEEE 33-bus system and the real network of Nigeria Agriculcural and Cooperative Bank (NACB) distribution system. The work was implemented in MATLAB/Simulink environment. The results obtained shows that the WCA placed the DVR in the IEEE 33-bus network at bus 18, thereby reducing the real and reactive power losses by 21%, 13.2% respectfully, and improving the voltage profile by 12.27%. Similarly the method was demonstrated on a real-distribution network at NACB feeder 58-bus with 57 line network. The WCA optimally placed the DVR at bus 29, thereby reducing the real and reactive power by 27%, 6% respectfully, and improving the voltage profile by 4.92%.

Keywords: Dynamic Voltage Restorer (DVR), Power Quality, Distribution System

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I. INTRODUCTION

Delivery of quality and reliable electrical power to the customers in a cost-effective manner is the major concern of utility companies. With the rapid growth and development of power grids, the distribution network is faced with power quality problems ranging from losses which decrease efficiency, voltage sags, swells and flickers, reliability problems to other voltage instabilities [1]. Also Power quality issues in modern power distribution systems have gained significant attention due to the increased deployment of sensitive electrical equipment, distributed generation, and renewable energy sources. Voltage disturbances such as sags, swells, harmonics, and flickers disrupt the performance of sensitive devices, leading to inefficiencies and financial losses. Addressing these challenges is essential to ensure reliable and stable power delivery [2]

The degree of any variation from the nominal voltage magnitude and frequency values is known as electrical power quality. When variable power is applied to the load, power quality is a critical component of the power system. The low power quality therefore affects the industrial and residential consumers with sensitive loads. Even though there are many different kinds of loads on the distribution side, sensitive loads are more negatively impacted by low power quality than others. In modern power systems, the problem of power quality presents serious obstacles that have a negative impact on utility providers as well as users.A concentrated effort is being made to provide end consumers with high-quality power due to an increase in demand and increased competition among electric supply suppliers. Customers in the residential and commercial sectors are thus disproportionately affected by low power quality, particularly those with sensitive loads [3].

Therefore, since electrical energy is an essential ingredient upon which any country depends for its development, researchers and utility companies continue to look for ways to improve the quality, reliability and safety of the power system [4]. Among the solutions that draw considerable attention are integration of distributed generation (DG) technologies [5], reconfiguration of the network structure [6],[7] and application of distribution flexible alternating current transmission system (D-FACTS) devices [8].

The FACTS devices have been applied widely for increasing thermal loading capacity, post contingency and voltage control, power system conditioning, mitigation of flicker on the line, increasing reliability and security of the system and reactive powers compensation. Those devices applied at distribution network are referred as distribution FACTS (D-FACTS) devices. They are evolving technology-based solution that offers a superior adaption to varying operational conditions and enhances the usage of existing distribution installations.

Amongst the various FACTS devices, Dynamic Voltage Restorer (DVR) has a unique ability to provide a flexible control of the bus voltage magnitude and power reactive flowing through the branch where it is connected. To enhance the performance of the FACTS devices, are usually tuned using heuristic or meta-heuristic optimization algorithm. Not only are the device parameters optimally tuned, the location to install the FACTS device within the network as well as their respective sizes are often optimally computed for the enhancement of the network condition [8].

Dynamic Voltage Restorers (DVRs) have proven to be an effective solution for mitigating voltage-related disturbances in distribution systems. A DVR, a power electronic device, stabilizes voltage by injecting compensatory voltage during disruptions. Its effectiveness is influenced by optimal placement and sizing in the distribution network to maximize system stability and minimize costs [9].

Optimization techniques have been widely applied to determine the best configuration of DVRs. Traditional gradient-based methods struggle with the non-linear and complex nature of modern power systems, making them less effective in solving multi-objective optimization problems. This limitation has led to the adoption of meta-heuristic algorithms, which are more suited to handling complex optimization tasks. For instance, meta-heuristics have been highlighted for their scalability and flexibility in solving energy resource allocation challenges [10].

The Water Cycle Algorithm (WCA), inspired by natural hydrological processes such as evaporation, precipitation, and river flow, is a recent meta-heuristic optimization technique that has gained traction. Its ability to perform global searches and achieve fast convergence makes it an attractive option for power system optimization problems, including DVR placement and sizing. Studies have demonstrated WCA's superiority over conventional methods such as Genetic Algorithms (GA) and Particle Swarm Optimization (PSO) in terms of computational efficiency and solution quality [11].

Several studies have explored optimization algorithms for enhancing power quality. Research shows DVRs' effectiveness in mitigating harmonics and voltage sags, emphasizing the importance of strategic placement [12]. Other works highlight DVRs' role in improving the reliability of renewable energy-integrated systems, providing insights into their deployment for stable grid operation [13]. Advanced optimization techniques have also been reviewed, showcasing their application in solving power system challenges, including DVR allocation [14].

II. LITERATURE

2.1 Review of Theoretical Concept

The theoretical foundation of this study revolves around power quality, Dynamic Voltage Restorers (DVRs), and optimization techniques, particularly the Water Cycle Algorithm (WCA). These concepts are critical for understanding the methodology and objectives of the proposed work.

2.1.1 Electricity Distribution System

Distribution network is one of three main components of power system, electric power system can be defined as interconnection of electrical components/devices technically, with the aim of converting some forms of energy into electrical energy and transmitting it from the point of generation to load centres with the purpose of providing electricity to the consumers in a reliable and economical way [15].

2.1.1.1 Types of Distribution Network

The most commonly used distributed network architectures are.

1. Radial network
2. Ring network
3. Mesh network and
4. parallel network structure

2.1.1.1.1Radial Network Structure

The distribution system typically has a mesh structure, but by opening their connecting connections, it can function in a radial configuration. Simple relay coordination, protection plans, and lower short-circuit currents are to blame for this. Several feeders originate from the injection substation in this configuration, giving the consumer a single power source [16].

The feeder is composed of a circuit breaker and the entire line connected to the circuit breaker, from the distribution injection substation to the various substations (load buses) of the customer end. The main idea of

designing a feeder is how much current it can carry. The following are characteristics of a radial distribution network;
1. The limitations and uncertainties of network parameters.
2. High resistance to reactance ratio (X / R)
3. Numerous nodes and branches.
4.Load changes continuously [16],
Figure 2.1 shows a simple 10-Bus radial system with two Tie-Switches.

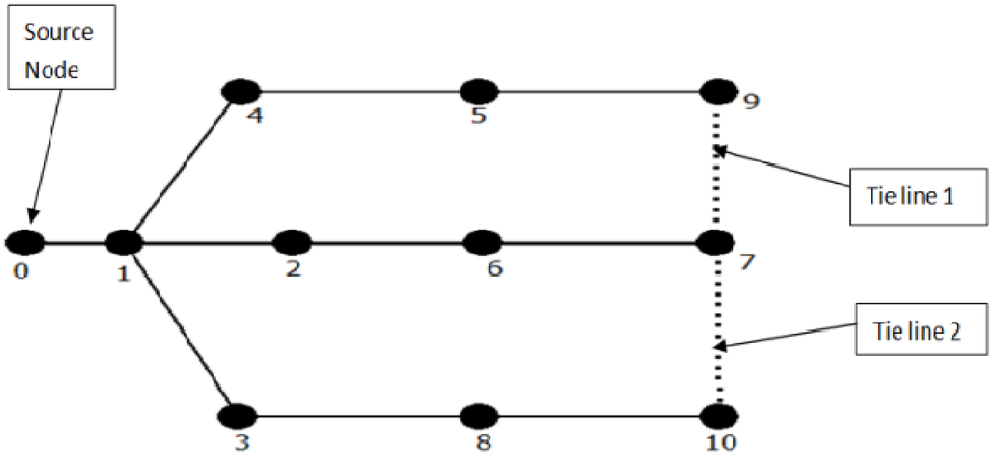

Figure 2.1: A Simple 10-Bus Radial System with Two Tie-Switches [16]

2.1.2 Power Flow Analysis in Distribution System

One of the most important and fundamental techniques for power system operation and planning in recent decades is load flow analysis. This is used to guarantee consistent, cost-effective, and dependable electrical power transfer from generators to consumers via the grid network. In the power system, it is the movement of both active and reactive power from the source to the load. A rational mathematical method for calculating multiple bus voltages, their phase angle, and the active and reactive power flows over different nodes, branches, generators, and loads under steady state conditions is provided by load flow analysis[17].

Load flow calculations are classified into two, which the first category is the ladder network method which comprises of basic laws of circuit theories like Kirchhoff's voltage Law (KVL) and Kirchhoff's current Law (KCL). The other category includes Newton-Raphson, Decoupled Newton-Raphson and Gauss-Seidel methods for transmission schemes and are typically built on nodal analysis method. But because of the complexity of distribution networks, it has continually been shown that these methods may turn out to be ineffective in the analysis of distribution schemes due to the different features of systems, such as; radial structure, high R/X ratio, very huge number of nodes and branches, unbalanced loads, and un-transposed lines [18], the backward-forward sweep is being used.

2.2 Backward-Forward Sweep (BFS) Technique for Power Flow Analysis

Power flow analysis was performed using the backward-forward sweep power flow technique for radial distribution systems. In essence, the backward sweep is a power or current flow solution with potential voltage updates. It begins with the last layer's branches and advances to the branches that are attached to the root node. By taking into account the node voltages from the previous iteration, the backward propagation computation yields the updated effective power flows in each branch [19].

In contrast, the forward sweep is a voltage drop computation that may include updates on current or power flow. Beginning with branches in the first layer and working towards those in the last, nodal voltages are updated in a forward sweep. Calculating the voltages at each node, beginning at the feeder source node, is the aim of forward propagation. The real value of the feeder substation voltage is set [19].
A radial distribution system is considered having 'n' buses as shown in Figure 2.2 below [20].

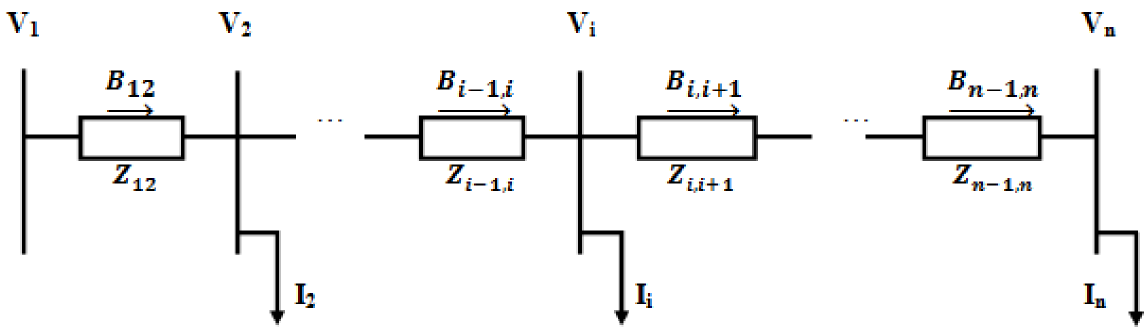

Figure 2.2: Single Line Diagram of n-Bus Radial Distribution System [20]

The system is assumed to be a balanced one, with (n-1) load buses which are treated as load buses and bus 1 as slack/swing bus. The general bus 'i' current injection at*kth* iteration is given by the following equation.

$$I_i^k = \left(\frac{S_i^{sch}}{V_i^k}\right) \tag{2.1}$$

WhereS_i^{sch} is the scheduled complex power at bus i, $V_i^k$is the bus 'i' voltage at the kth iteration. Now, Kirchhoff's current law (KCL) is applied by backward current sweep starting from the last bus 'n' to the source bus 1 to obtain the branch currents. In this step we obtained the first of the two matrices given by:

$$\begin{bmatrix} B_{12} \\ \vdots \\ B_{i-2,i-1} \\ B_{i-1,i} \\ B_{i,i-1} \\ \vdots \\ B_{n-1,n} \end{bmatrix} = \begin{bmatrix} 1 \ldots 1\ 1\ 1 \ldots 1 \\ : \ldots \ldots \ldots \ldots \ : \\ 0 \ldots 1\ 1\ 1 \ldots 1 \\ 0 \ldots 0\ 1\ 1 \ldots 1 \\ 0 \ldots 0\ 0\ 1 \ldots 1 \\ : \ldots \ldots \ldots \ldots \ : \\ 0 \ldots 0\ 0\ 0 \ldots 1 \end{bmatrix} \begin{bmatrix} I_{12} \\ \vdots \\ I_{i-1} \\ I_i \\ I_{i+1} \\ \vdots \\ I_n \end{bmatrix} \tag{2.2}$$

Equation 2.2 in a compact form is given as:

$$[B] = [BIBC][I] \tag{2.3}$$

Where$[BIBC]$ is the relationship matrix between branch currents and bus current injections.

In the forward voltage sweep, Kirchhoff's voltage law (KVL) is applied to obtain the bus voltages and second relationship matrix given by:

$$\begin{bmatrix} V_2 \\ \vdots \\ V_{i-1} \\ V_i \\ V_{i+1} \\ \vdots \\ V_n \end{bmatrix} = \begin{bmatrix} V_1 \\ \vdots \\ V_1 \\ V_1 \\ V_1 \\ \vdots \\ V_1 \end{bmatrix} - \begin{bmatrix} 1 \ldots 1\ 1\ 1 \ldots 1 \\ : \ldots \ldots \ldots \ldots \ldots : \\ 0 \ldots 1\ 1\ 1 \ldots 1 \\ 0 \ldots 0\ 1\ 1 \ldots 1 \\ 0 \ldots 0\ 0\ 1 \ldots 1 \\ : \ldots \ldots \ldots \ldots \ldots : \\ 0 \ldots 0\ 0\ 0 \ldots 1 \end{bmatrix} \begin{bmatrix} B_{12} \\ \vdots \\ B_{1-2,1-1} \\ B_{i-1,i} \\ B_{i,i-1} \\ \vdots \\ B_{n-1,n} \end{bmatrix} \tag{2.4}$$

By rearranging equation (2.4), the change in voltage vector$[\Delta V]$ was obtained as followsequations (2.5) – (2.7):

$$[\Delta V] = [BCBV][B] \tag{2.5}$$

Where$[BCBV]$ is the relationship matrix between bus voltages and branch current

$$[\Delta V] = [BCBV][BIBC][I] \tag{2.6}$$

$$[\Delta V] = [DLF][I] \tag{2.7}$$

Where$[DLF]$ is the relationship matrix between voltage drops and bus current injection.

The Radial Distribution Power Flow (RDPF) solution is achieved by employing KCL and KVL respectively to form the matrices[BIBC] and [BCBV] and performing matrix multiplications. Moreover, the following equations (2.8) – (2.10) are solved iteratively to get the power flow solution [19]:

$$I_i^k = \left(\frac{P^{sch} + jQ^{sch}}{V_i^k}\right) \tag{2.8}$$

$$[\Delta V^{k+1}] = [DLF][I^k] \tag{2.9}$$

$$[V^{k+1}] = [V_\circ] - [\Delta V^{k+1}] \tag{2.10}$$

Where $[V_\circ]$is initial bus voltage vector

The iterative process stops when the absolute of the difference between previous bus current injection and most recent bus current injection is less than or equal to a prescribed toleranceε:

$$\left|I_i^{k+1} - I_i^k\right| \leq \varepsilon \qquad (2.11)$$

Finally, the total active power loss can be calculated by the following equations (2.12) – (2.13):

$$Ploss = \sum_{i=1}^{br} |B_i|^2\, R \qquad i = 1,2,\dots,br \qquad (2.12)$$

Where $[B_i]$is magnitude of the *ith* branch current, R is the *ith*branch resistance and *br*is the number of branches in Radial Distribution System. The total active power loss can be written in terms of $[BIBC]$ as follows [19]:

$$Ploss = [R]^T[BIBC][I]^2 \qquad (2.13)$$

2.3 Dynamic Voltage Restorer (DVR)

Dynamic Voltage Restorer was define by [21] as a specialized power device that is actually utilized to correct for the distribution network's harmonic, drooping, and swelling of voltage. It is crucial to the sensitive load's operation. According to [22], In order to inject a controlled voltage into the electric distribution network, a solid-state custom power device called a dynamic voltage restorer (DVR) is connected in series with the load voltage. Additionally, DVR is a voltage source converter that increases the load voltage by injecting a dynamically controlled voltage in series to supply voltage via three single phase boosting transformers.[23] provided a further definition, describing it as a series compensator that regulates load side voltage by introducing voltage into the distribution system. In order to adjust for transient reduction, line voltage harmonics, and voltage sags and swells, it is connected between the supply and the sensitive load. When there is a voltage issue, such as compensating for voltage swells and sags, limiting fault current, eliminating harmonics, or reducing voltage transients, the basic idea is to inject a voltage of the appropriate amplitude and frequency to restore the load voltage. The control circuit, which regulates the system's load voltage within predetermined bounds, and the power circuit, which supplies the required voltage, are essential parts of the DVR [23].

The DVR consists of four major parts:

a. Voltage source inverter (VSI),
b. Injection transformers,
c. Passive filters,
d. DC-link energy storage.

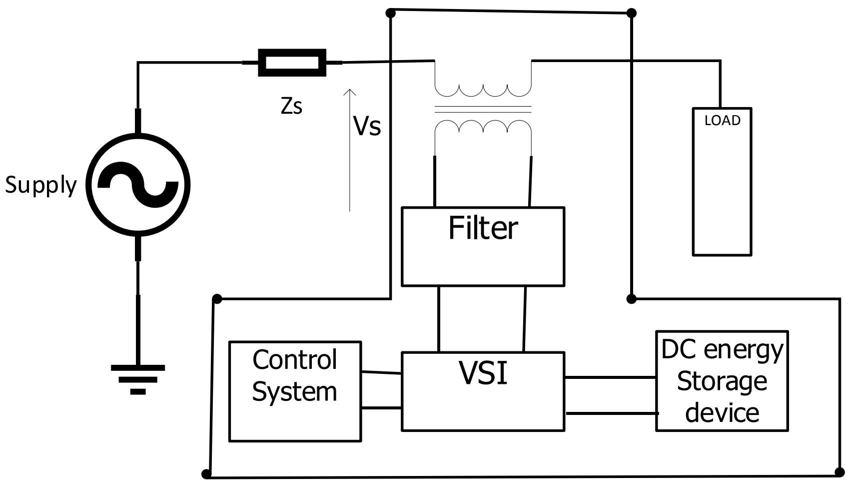

Figure 2.3: Schematic Diagram of DVR [26]

III. METHODOLOGY

3.1 Proposed Methodology

The step by step methodology for the actualization of this research objectives are outlined herein, these comprises the power flow analysis, Siting and sizing of DVR using water cycle optimization algorithm, their respective algorithmic procedures are shown below.

3.2 Load Flow Mathematical Model and Analysis of a Radial Network

Load flow in a radial distribution system depends on component specifications, power supply bus loads, and system voltage at the supplying bus. The designs, computations, and optimization for system control of power distribution systems provide the foundation of mathematical models and frequency in a typical steady-state setting. A sample mathematical model of a radial network used in this study is shown below.

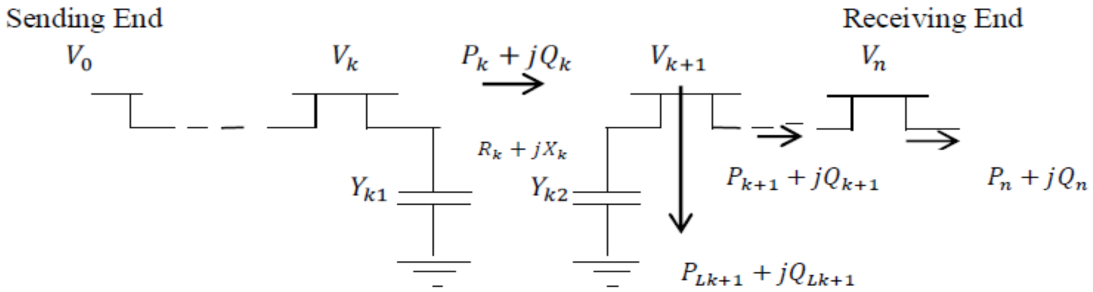

Figure 3.1 Single Line Diagram of a Radial Network

The power losses and magnitude of voltage for a radial network can be found by using load flow analysis. The real and reactive power of this system can be derived from the one-line diagram of a radial distribution system of Figure. 3.1, which is given as follows:

$$P_{k+1} = P_k - P_{loss,k} - P_{Lk+1} \quad 3.1$$

$$Q_{k+1} = Q_k - Q_{loss,k} - Q_{Lk+1} \quad 3.2$$

Where,
P_k- real power that is emanating from the bus,
Q_k- reactive power that is emanating from of the bus,
P_{Lk+1} - load real power of bus k+1,
Q_{Lk+1} - load reactive power of bus k+1.

The loss of power for line unit between buses k and k+1 can be computed as follows;

$$P_{loss}(k, k+1) = \frac{R_k({P_k}^2+{Q_k}^2)}{{V_k}^2} \quad 3.3$$

$$Q_{loss}(k, k+1) = \frac{X_k({P_k}^2+{Q_k}^2)}{{V_k}^2} \quad 3.4$$

Above equation give the losses of real power and reactive power in line section between buses k and k+1. Now the total real power loss and total reactive loss can be calculated by summing the losses of every section of the feeder. Hence the value of total real and reactive power loss can be expressed as [24]:

$$P_{T,loss}(k, k+1) = \sum_{k=1}^{n} P_{loss}(k, k+1) \quad 3.5$$

$$Q_{T,loss}(k, k+1) = \sum_{k=1}^{n} Q_{loss}(k, k+1) \quad 3.6$$

Equations (3.5) and (3.6) are the total real power loss and total reactive power loss respectively in section of line between k and k+1.

Now, the reformulation of backward forward method to perform the load flow analysis is done for convergence analysis of iterative process. Consider branch in between node 'k' and 'k+1' and by backward propagation effective power flows is calculated. The effective real and reactive powers is given as [24].

$$P_k = P'_{k+1} + \frac{\boldsymbol{R_k({P_{k+1}}^2+{Q_{k+1}}^2)}}{\boldsymbol{{V_{k+1}}^2}} \quad 3.7$$

$$Q_k = Q'_{k+1} + \frac{\boldsymbol{X_k({P_{k+1}}^2+{Q_{k+1}}^2)}}{\boldsymbol{{V_{k+1}}^2}} \quad 3.8$$

Where,

$$P'_{k+1} = P_{k+1} + P_{LK+1} \quad 3.9$$

$$Q'_{k+1} = Q_{k+1} + Q_{LK+1} \quad 3.10$$

Where, P_{k+1} is effective real power from 'k+1' node
Q_{k+1} is effective reactive power from 'k+1' node

The value of voltages and voltage angle at each node are evaluated in forward propagation. Let the voltage at node 'k' k' is $V_k<\delta_k$and voltage at node 'k+1' is $V_{k+1}<\delta_{k+1}$. The impedance connected between 'k' and 'k+1' is $z_k= r_k+ jx_k$and the current in this section is given as

$$I_k = \frac{V_k<\delta_k - V_{k+1}<\delta_{k+1}}{r_k + jx_k} \quad 3.11$$

To find the values of voltage and the voltage angle at all nodes the recursive equations are used. Primarily assume 1.0 p. u. voltage at all node. A detailed power flow calculation operation is given by the backward forward algorithm [25].

3.3 Base-Case Power Flow Analysis

The pseudo-code used in developing the algorithm for running the base case load flow analysis for the distribution systems are presented below.

Step 1: Read bus data and line data of the distribution system and also base MVA and base KV.

Step 2: Evaluate the injected active and reactive power at each node, i.e.

$P_{inj} = P_{gen} - P_{load}$ 3.12
$Q_{inj} = Q_{gen} - Q_{load}$ 3.13
Step 3: Set k=1, the iteration count.
Step 4: For convergence criterion set ε=0.001, ΔP_{max}= 0.0 and ΔQ_{max}= 0.0.
Step 5: Evaluate the value of nodal current injection at node 'i' as
$I_i^{(k)}=(S_i/V_i^{(k-1)})^*-Y_iV_i^{(k-1)}$ i=1,2,3……. n 3.14
Step 6: Apply backward sweep and calculate the branch current using KCL.
Step 7: Forward sweep is applied to calculate the voltage at each node using KVL.
Step 8: Now calculate the power injection at node 'i' as
$S_i^k=V_i^k(I_i^k)^*-Y_i|V_i^k|^2$ 3.15
Step 9: Check convergence, if $\Delta P_{max} \leq \varepsilon$and$\Delta Q_{max} \leq \varepsilon$, then go to step 11, else step 10.
Step 10: Then set k=k+1 and go to step 4.
Step 11: In 'k' iteration print that problem is converged.
Step 12: Stop.

3.4 Backward-Forward Sweep (BFS) Technique for Power Flow Analysis

In essence, the backward sweep is a power or current flow solution with potential voltage updates. It starts from the branches in the last layer and move towards the branches connected to the root node. The updated effective power flowing in each branch is obtained in the backward propagation computation by considering the node voltages of previous iteration. The forward sweep is basically a voltage drop calculation with possible current or power flow updates. Nodal voltages are updated in a forward sweep starting from branches in the first layer toward those in the last. The method is achieved through the following steps:

i. The network line data and load data is loaded.
ii. A voltage profile of 1.0pu is assumed at the source node.
iii. The branch current of all branches is computed using the backward propagation with equation (2.2).
iv. The node voltages are updated using the forward propagation with equation (2.4).
v. The active power loss is calculated using equation (2.12)

Below is the flow chart for basic operation of the Backward/Forward sweep

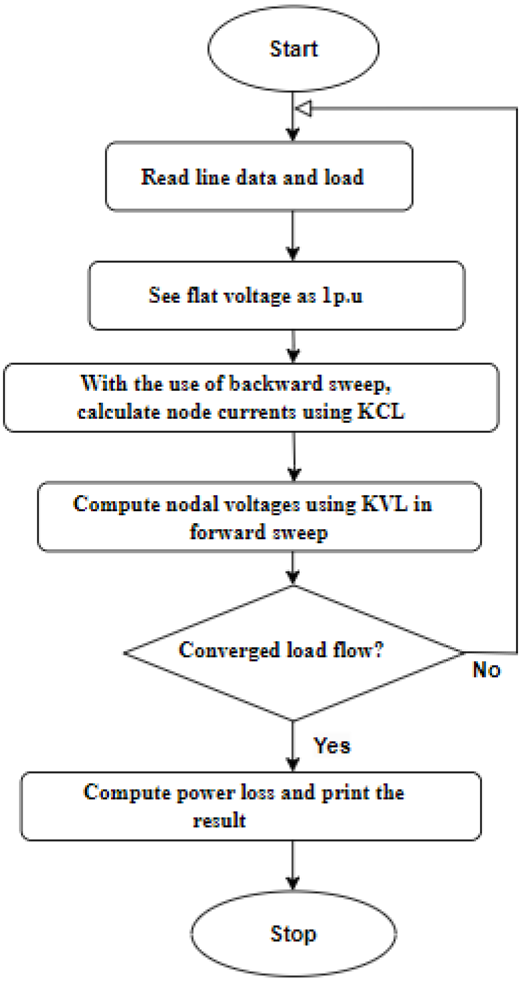

Figure 3.2 Flow Chart for Basic Operation of the Backward/Forward Sweep [20]

3.5 Objective Function Formulation

The power loss in the system is defined as:

$$P_{loss} = \sum_{j=1}^{Nbr} R_j \times \left(\frac{P_j^2+Q_j^2}{V_j^2}\right) \tag{3.16}$$

Where

$Nbr$is the number of the branches

$R_j$is the resistance of the j-th branch

$P_j$is the active power flowing through the terminal of j-th branch

$Q_j$is the reactive power flowing through the terminal of j-th branch

$V_j$is the terminal node voltage of the j-th branch

These objective function f_1 is subjected to constraint:

i. Node voltage constraint

$$V_{min}(j) \le V(j) \le V_{max}(j) \tag{3.17}$$

ii. Branch Power constraint

$$P_j \le P_{jmax} \tag{3.18}$$

$$Q_j \le Q_{jmax}$$

Secondly the objective function f_2 of total voltage deviation can be written as:

$$min\{f_2\} = \left[\sum_{i=1}^{nb}\{(Vi - Vmin)^2 + (Vi - V\ max)^2\}\right] \tag{3.19}$$

Where,

V_{min}= Minimum permissible voltage limits

V_{max} = Maximum permissible voltage limits

nb: total number of buses in the system.

and is subject to voltage limits constrains the bus voltages must be maintained around the nominal value and is given by;

$V_{imin} \leq V_{inom} \leq V_{imax}$ i= {1,2,3,……, N_b} (3.20)

Where, V_{imin},V_{imax} = minimum and maximum voltage limits of i^{th} node respectively.

$\boldsymbol{V_i}$= voltage at i^{th} node and $\boldsymbol{N_b}$= number of buses.

Aggregate Objective Function proposed for this work can be then be described

$fi = (w_1 f_1 + w_2 f_2)$ (3.21)

Output = min ($\sum_{i=1}^{Nbr} f_i$) (3.22)

Where

$f_1$is given as equation (3.16) and f_2 is given as equation (3.19)

$w_1$is the weight assigned to f_1 and w_2 is the weight assigned to f_2

3.6 Water Cycle Optimization Algorithm

The WCA mimics the flow of rivers and streams toward the sea and was derived by observing the water cycle process. Let us assume that there are some rain or precipitation phenomena. An initial population of design variables (i.e population of streams) is randomly generated after the raining process. The best individual (i.e, the best stream), classified in terms of having the minimum cost function (for minimization problems), is chosen as the sea [27]. Then, a number of good streams (i.e, cost function values close to the current best record) are chosen as rivers, whereas the remaining streams flow into the rivers and the sea. Starting the optimization algorithm requires the generation of an initial population representing a matrix of streams of size $N_{pop} \times D$, where D is the dimension. Hence, this matrix, which is generated randomly, is given as (the rows and column represent the population size (N_{pop}) and the number of design variables, *D*, respectively):

$Raindrop$ = $[x_1, x_2, x_3, ...x_N]$ (3.23)

$$\text{Total population} = \begin{bmatrix} Sea \\ River_1 \\ River_2 \\ River_3 \\ . \\ . \\ . \\ Stream_1 \\ Stream_2 \\ Stream_3 \\ . \\ . \\ . \\ Stream_{Npop} \end{bmatrix} = \begin{bmatrix} & x_1^1 x_2^1 & x_3^1 & \dots & x_D^1 & \\ & & x_1^2 x_2^2 x_3^2 & \dots & x_D^2 & \\ . & . & . & . & . \\ . & . & . & . & . \\ . & . & . & . & . \\ x_1^{Npop} & x_2^{Npop} & x_3^{Npop} & \dots & x_D^{Npop} \end{bmatrix} \quad (3.24)$$

The cost of raindrop can be given as:

C_i = $Cost_i$ = (x_1^i, x_2^i , x_3^i, ...x_D^i) (3.25)

whereN_{pop} is numbers of raindrop and *D*number of designed variables. Raindrop having the minimum value is taken as sea.

N_{sr} is the sum of river and sea which is given as:

N_{sr} = Number$of rivers$ + 1(sea) (3.26)

$N_{raindrop} = N_{POP} - N_{sr}$(3.27)

In the first step, N_{pop} streams are created. Then, a number of best individuals N_{sr} (minimum values) are selected as the sea and rivers. The stream which has the minimum value (objective function) among the others is considered as the sea. In fact, Nsr is the summation of the number of rivers (which is defined by the user) and a single sea. The rest of the population (N_{stream}) are considered as streams flowing into the rivers or may alternatively flow directly into the sea. Depending on the magnitude of the flow, each river absorbs water from streams. Hence, the amount of water entering a river and/or the sea varies from stream to stream. In addition, rivers flow to the sea, which is the most downhill location.

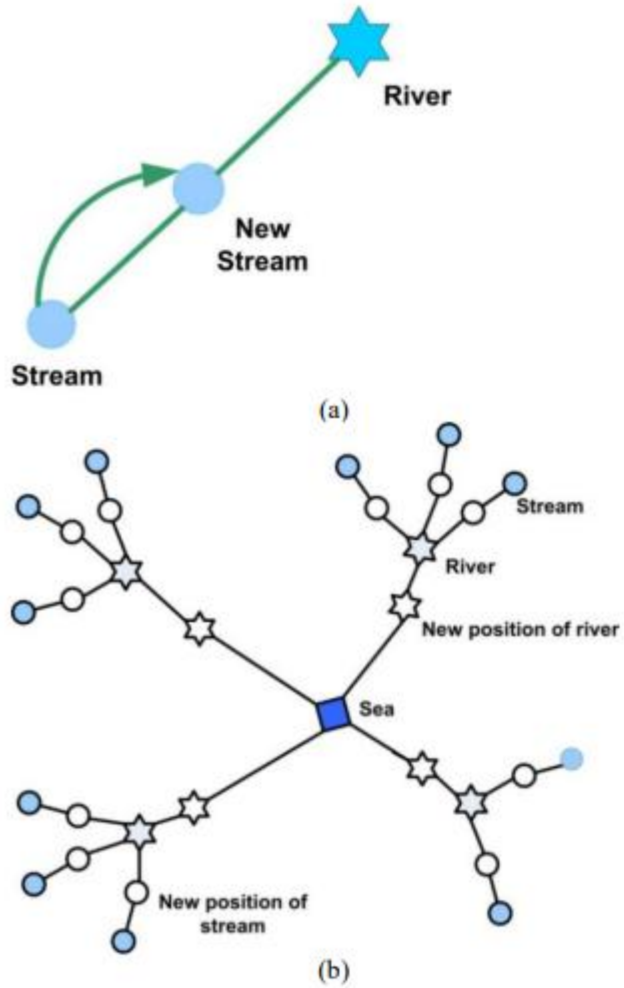

Figure. 3.3; Schematic Illustration of (a) Streams Flowing into a Particular River; (b) the WCA Optimization Process [27]

The designated streams for each river and the sea are calculated using the following Equation [28]:

NS_n = round$\left\{\left|\frac{Cost_n - Cost_{N_{sr}+1}}{\sum_{n=1}^{N_{sr}} C_n}\right| \times N_{streams}\right\}$ n = 1, 2, 3,..., N_{sr} (3.28)

Where NS_n is the number of streams which flow into the specific rivers and the sea. Figure 3.3a shows a schematic view of a stream flowing towards a specific river along their connecting line. For the exploitation phase of the WCA, new positions for streams and rivers have been suggested as follows [28]

$\vec{X}_{Stream}\,(t+1) = \vec{X}_{Stream}\,(t)$ + rand x C x ($\vec{X}_{Sea}\,(t)$ - $\vec{X}_{Stream}\,(t)$) (3.29)

$\vec{X}_{Stream}\,(t+1) = \vec{X}_{Stream}\,(t)$ + rand x C x ($\vec{X}_{River}\,(t)$ - $\vec{X}_{Stream}\,(t)$) (3.30)

$\vec{X}_{River}\,(t+1) = \vec{X}_{River}\,(t)$ + rand x C x ($\vec{X}_{Sea}\,(t)$ - $\vec{X}_{River}\,(t)$) (3.31)

Where *t* is an iteration index, *1 < C < 2*, and the best value for *C* may be chosen as 2, and rand is a uniformly distributed random number between zero and one. Eq. (3.29) and (3.30) are for streams which flow into the sea and their corresponding rivers, respectively. If the solution given by a stream is more optimal than that of its connecting river, the positions of the river and stream are exchanged (i.e., the stream becomes a river and the river becomes a stream). A similar exchange can be performed for a river and the sea. The evaporation process operator is also introduced to avoid premature (immature) convergence to local optima (exploitation phase) [27]. Basically, evaporation causes sea water to evaporate as rivers/streams flow into the sea. This leads to new precipitation. Therefore, we have to check whether the river/stream is sufficiently close to the sea to enable the evaporation process to occur. For that purpose, the following criterion is utilized for the evaporation condition between a river and the sea:

If $\left\|\overrightarrow{X^t}_{Sea} - \overrightarrow{X^t}_{Riverj}\right\| < d_{max}$ or rand < 0.1, where$j$ = 1, 2, 3, . . ., $N_{sr} - 1$

Perform raining process by uniform random search, end

Where d_{max} is a small number close to zero.After evaporation, the raining process is applied and new streams are formed in different locations (similar to mutation in the GAs). Indeed, the evaporation operator is responsible for the exploration phase in the WCA. Uniform random search is used to specify the new locations of the newly formed streams: A large value for d_{max} prevents additional searches and small values encourage the search intensity near the sea. Therefore, d_{max} controls the search intensity near the sea (i.e., best obtained solution). The value of d_{max} adaptively decreases as follows [28]:

$$d_{max}(t+1) = d_{max}(t) - \frac{d_{max}(t)}{Max.\ Iteretion} \quad t = 1, 2, 3, \ldots, \text{Max. Iteration} \qquad (3.32)$$

The development of the WCA optimization process is illustrated in Fig. 1b where the circles, stars, and the diamond correspond to streams, rivers, and the sea, respectively. The white (empty) shapes denote the new positions occupied by streams and rivers.

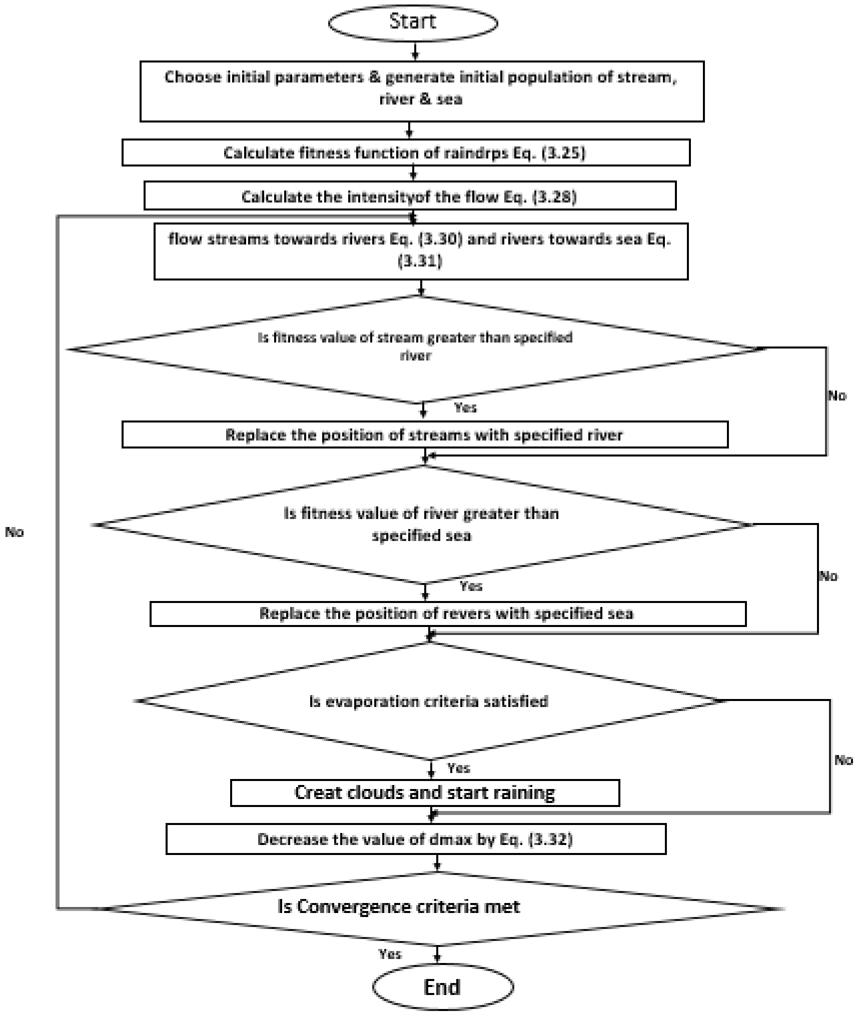

Figure 3.4: Flowchart for Water Cycle Algorithm Approach for Optimal Placement of DVR

IV. RESULTS AND DISCUSSION

4.1 Results of IEEE 33-Bus Standard Test System

The IEEE 33-bus radial distribution system consists of 33 buses and 32 branches as shown in PSAT simulation platform in Figure 4.1, the back and forward load flow analysis method is used to determine the power losses, voltage magnitude, and phase angle at various buses. For all the test systems, the substation voltage is considered as 1 p.u. The load is assumed to be constant power load.

4.1.1 Results of Power Flow Analysis for IEEE 33 Bus Network

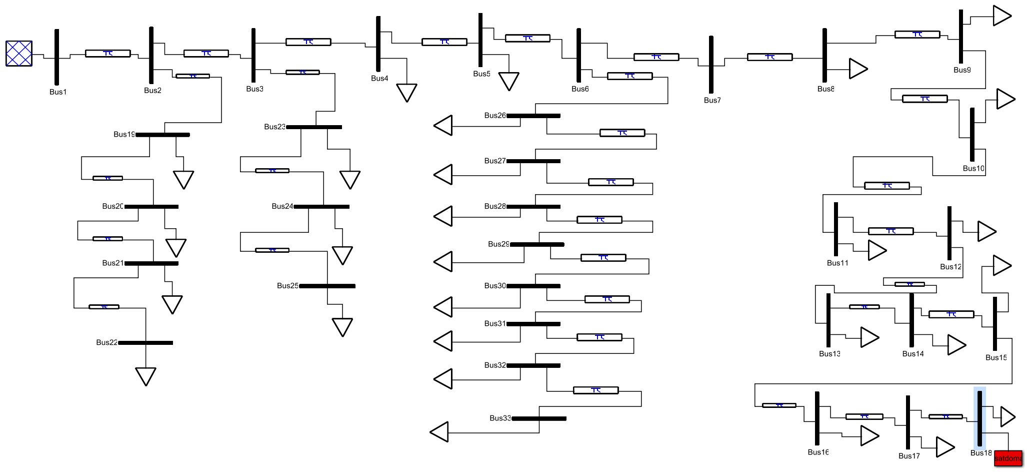

Figure 4.1: IEEE 33 Bus System in PSAT Simulation Platform

The radial distribution load flow analysis was done for the IEEE 33-Bus test system with and without DVR to determine the operating point of the network, these results comprises voltage magnitude in per unit with their phase angles, real and reactive power losses on lines.

The first scenario was without DVR and the minimum bus voltage has a value of 0.881 per unit at bus 18, the real and reactive power losses were found to be 227.4135kW and 151.4198kVAr respectively.

While the second scenario with DVR, the minimum bus voltage has a value of 0.998 per unit at bus 18, the real and reactive power losses were found to be 179.7382 kW and 131.0947 kVAr respectively. The numerical values of the results are in Appendix A4.

4.1.2 Results of Real and Reactive Power Loss Indices for IEEE 33 Bus System with and without DVR

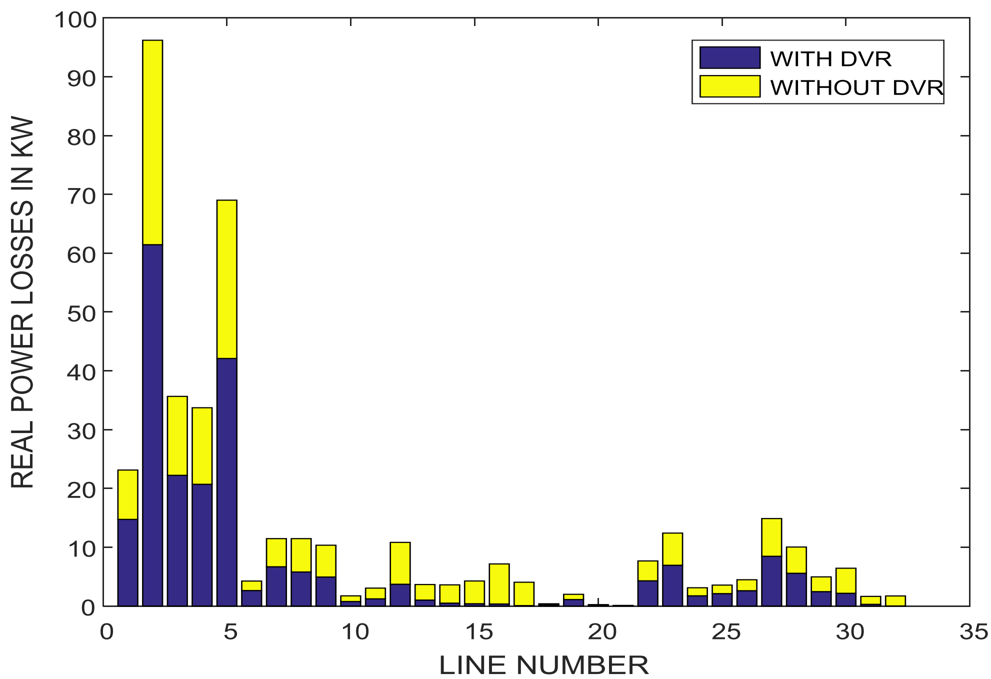

Figure 4.2: Real Power Loss Index of the 33-Bus Network with and without DVR

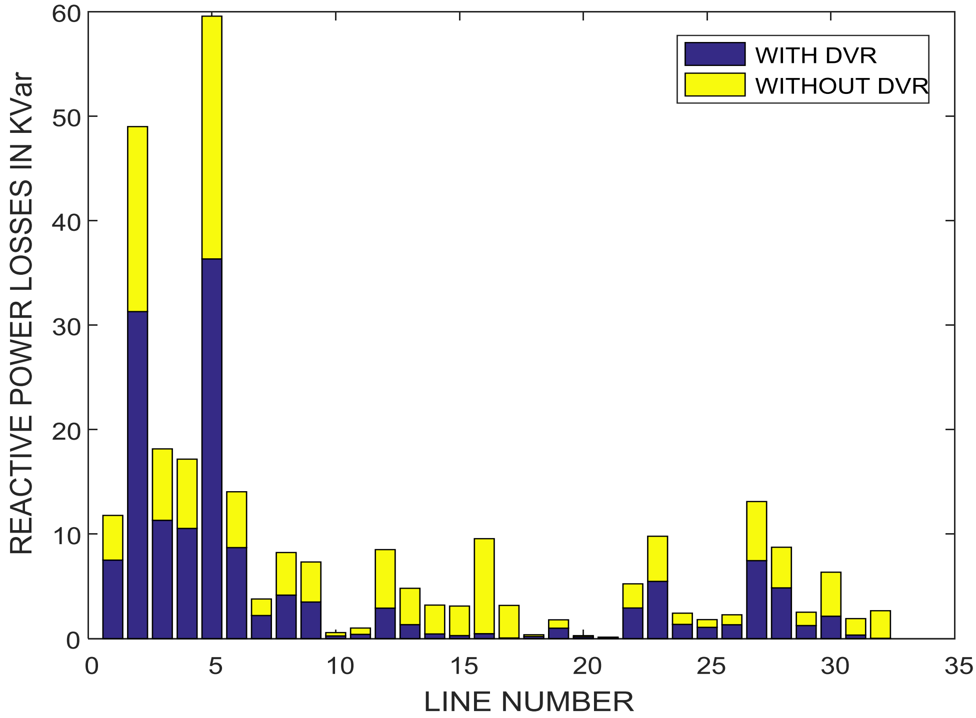

Figure 4.3: Reactive Power Loss Index of the 33-Bus Network with and without DVR

4.1.3 Voltage Profile for IEEE 33 bus System with and without DVR

Figure 4.4 shows the plots of voltage profile for IEEE 33 bus system with and without DVR. It is evident that the DVR has considerably improved the voltage profile lowest voltage which is bus 18.

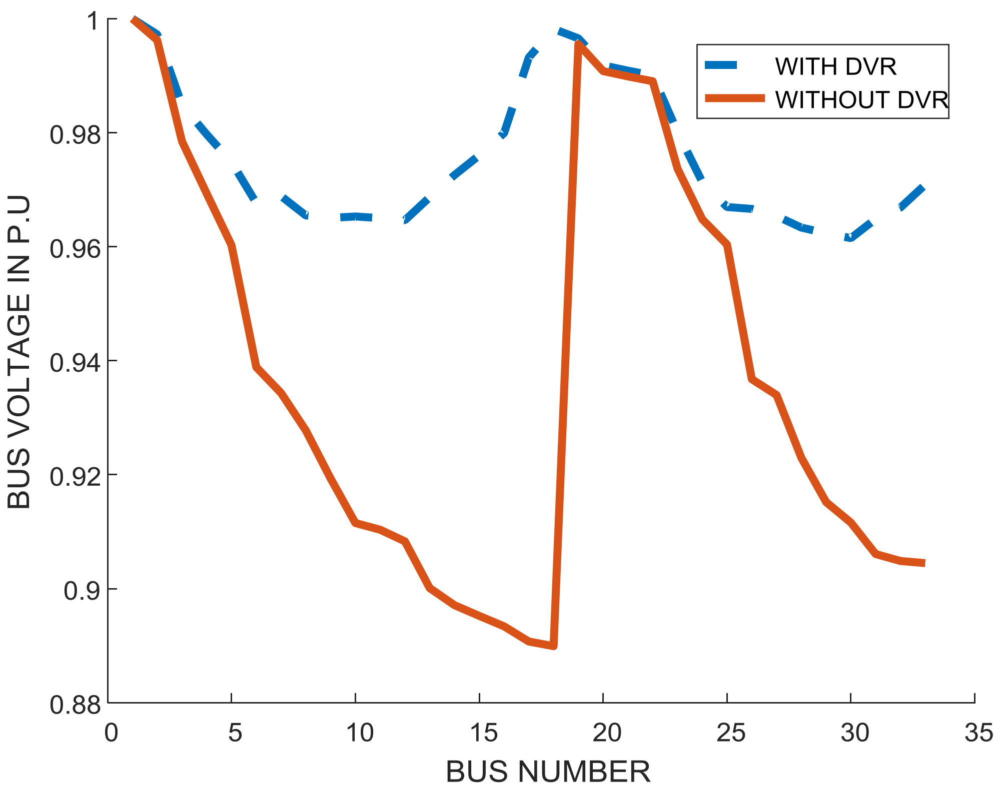

Figure 4.4 Voltage Profile of the 33-Bus Network with and without DVR

4.1.4 WCA Optimization Procedure
This Optimization Procedure shows how the voltage deviation on the line is been reduced as the optimization algorithm changes the values of DVR ratings. The total real and reactive power losses after DVR allocation was relatively reduced from 227.4135kW and 151.4198kVAr to 179.7382 kW and 131.0947kVAr respectively which indicate 21% and 13.2% reduction. The optimization procedure is shown in Figure 4.5. The codes for this results is in Appendix A3_2

The minimum sum of square of voltage deviation = 0.0833

This procedure is used to determine the maximum amount of voltage the DVR can inject to the line at its location which is bus 18 and no constraint will be violated (The value is 33- sum of the p.u voltages of the 33 buses)

The bus with minimum voltage is bus 18. The difference in voltage with and without DVR is 0.10827 p.u this is equal to 0.10827*11000= 1100Volts

Bus 18 voltage with DVR is 0.9981 p.u

Bus 18 voltage without DVR is 0.889 p.u

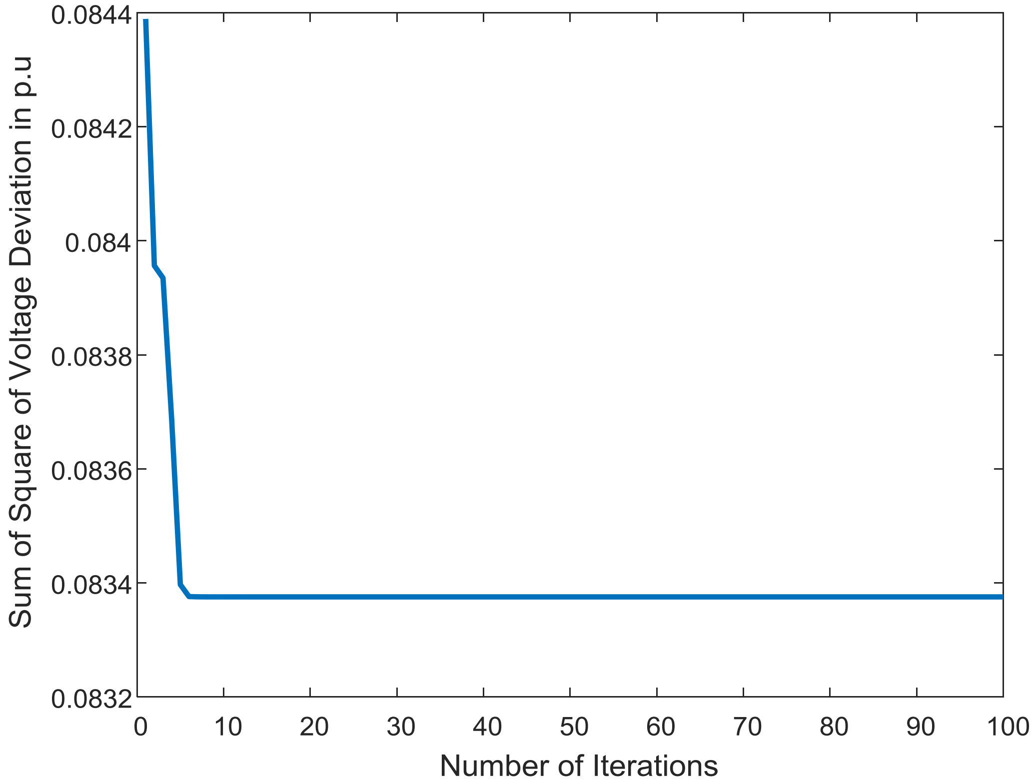

Figure 4.1: WCA Convergence Characteristics for IEEE 33 Bus Network

4.1.5 Summary of Result for IEEE 33 Bus System
The results were compared with and Without DVRs allocation on the 33-bus system to observe there was an improvement and was summarized in Table 4.1.

Table4.1: Summary of Result for IEEE 33 Buss Network

S/N	Parameter	Without DVR	With DVR Optimally Deployed	Improvement
1	DVR Location	-	Bus 18	-
2	Real Power Losses (kW)	227.4135	179.7382	21%
3	Reactive Power Losses (kvar)	151.4198	131.0947	13.2%
4	Voltage (pu)	0.889	0.9981	12.27%
5	DVR size (kV)	-	1.5	-

4.2 Results for NACB 11KV Feeder Radial Network
Theradial distribution load flow results for the 11KV NACB 58-bus with 57 linenetwork are shown in Appendix A2, while the network in PSAT simulation platform is shown in Figure 4.6. These results comprises graphical representation and numerical values recorded in the Appendix A5, the back and forward load flow analysis

method is used to determine the power losses, voltage magnitude, and phase angle at various buses. For all the test systems, the substation voltage is considered as 1 p.u. The load is assumed to be constant power load.

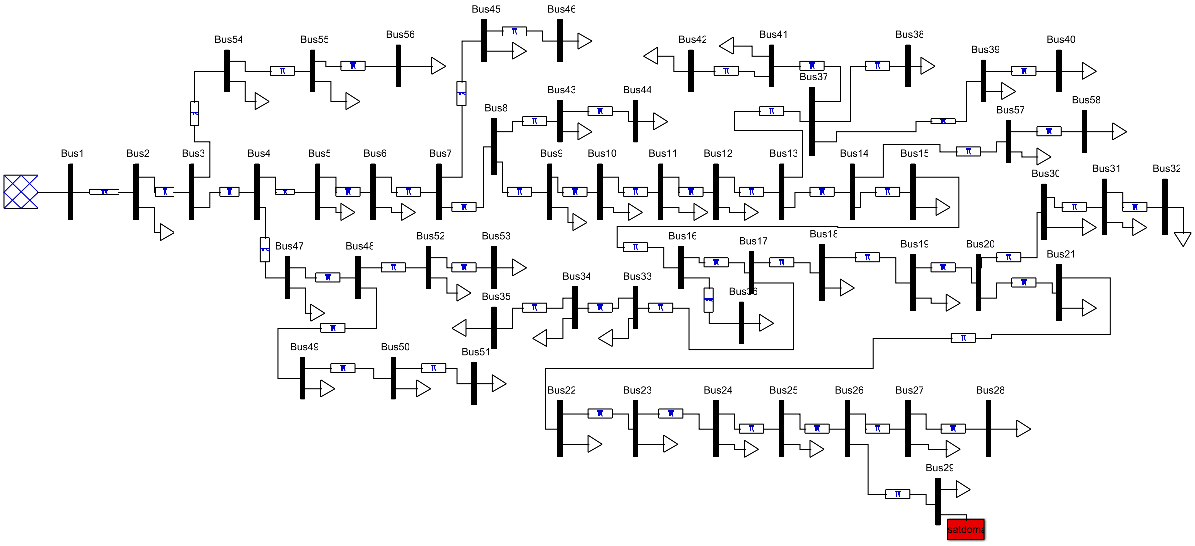

Figure 4.6: Simulation Diagram for NACB Feeder in PSAT Platform

4.2.1 Results of Power Flow Analysis for NACB Feeder Network

The radial distribution load flow analysis was done for the NACB Feeder network with and without DVR to determine the operating point of the network, these results comprises voltage magnitude in per unit with their phase angles, real and reactive power losses on lines.

The first scenario was without DVR and the minimum bus voltage has a value of 0.9245 per unit at bus 29, the real and reactive power losses were found to be 448.9871 kW and 421.4709kVAr respectively.

While the second scenario with DVR, the minimum bus voltage has a value of 0.970 per unit at bus 29, the real and reactive power losses were found to be 324.74 kW and 304.84kVAr respectively. The numerical values of the results are in Appendix A5.

4.2.2 Results of Real and Reactive Power Loss Indices for NACBFeeder with and without DVR

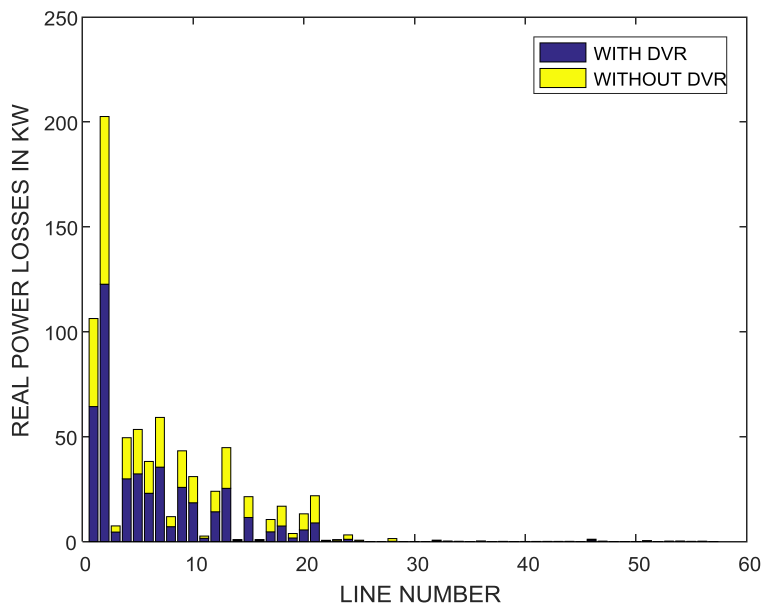

Figure 4.7: Real Power Loss Index of the NACB Feeder Network with and without DVR

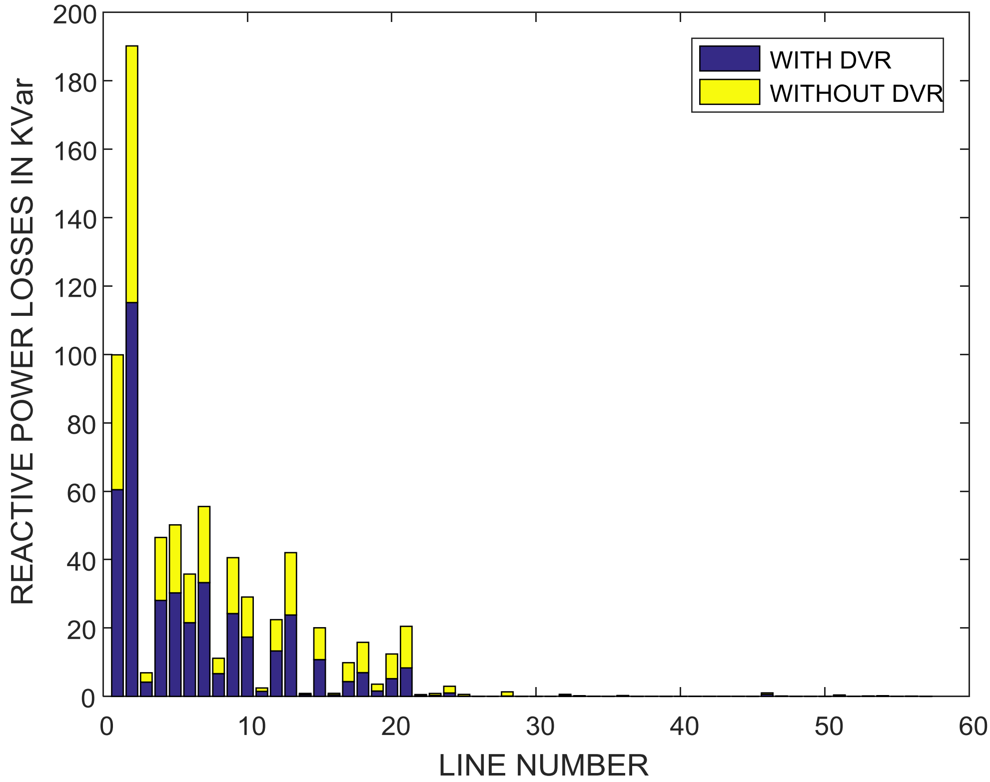

Figure 4.8: Reactive Power Loss Index of the NACB Feeder Network with and without DVR

4.2.3 Voltage Profilefor NACB Feeder Network with and without DVR

Figure 4.9 shows the plots of voltage profile for NACB Feeder network with and without DVR. It is evident that the DVR has considerably improved the voltage profile lowest voltage which is bus 29.

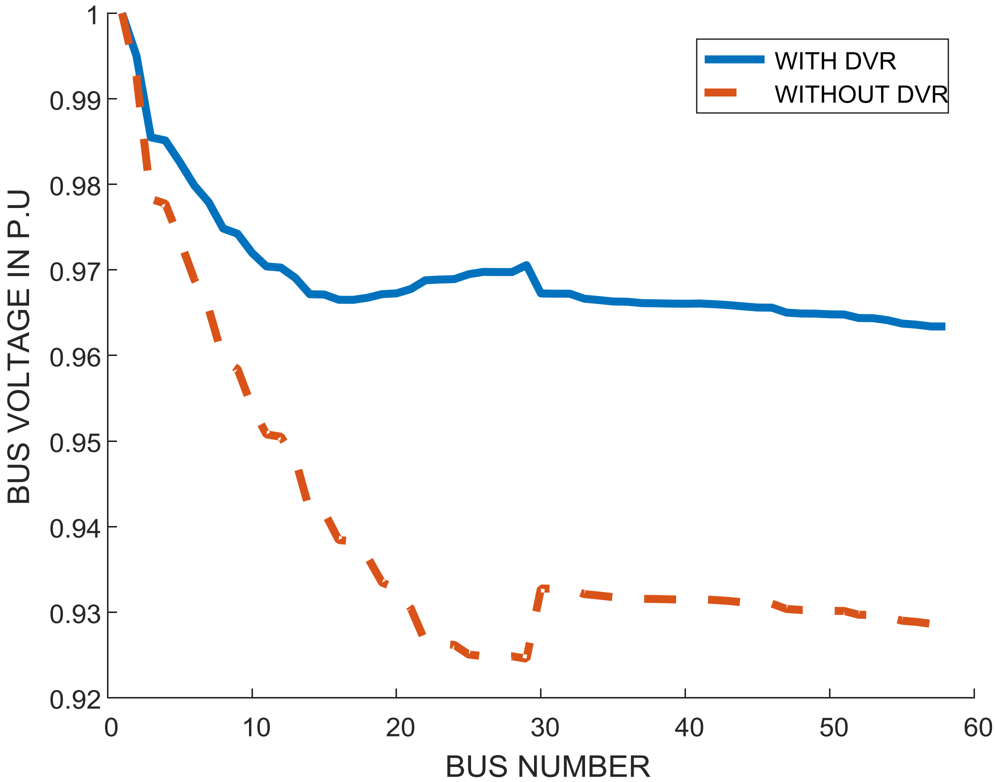

Figure 4.9 Voltage Profile of the NACB Feeder Network with and without DVR

4.2.4 WCA Optimization Procedure

This Optimization Procedure shows how the voltage deviation on the line is been reduced as the optimization algorithm changes the values of DVR ratings. The total real and reactive power losses after DVR allocation was relatively reduced from 448.9871 kW and 421.4709kVAr to 324.74 kW and 304.84kVArrespectively which indicate 27% and 6% reduction. The optimization procedure is shown in Figure 4.10. The codes for this results is in Appendix 3_1.

The minimum sum of square of voltage deviation = 1.77

The bus with minimum voltage is bus 29. The difference in voltage with and without DVR is 0.0459 Volt p.u this is equal to 0.0459 *11000= 504 Volts

Bus 29 voltage with DVR is 0.970 p.u

Bus 29 voltage without DVR is 0.9245 p.u

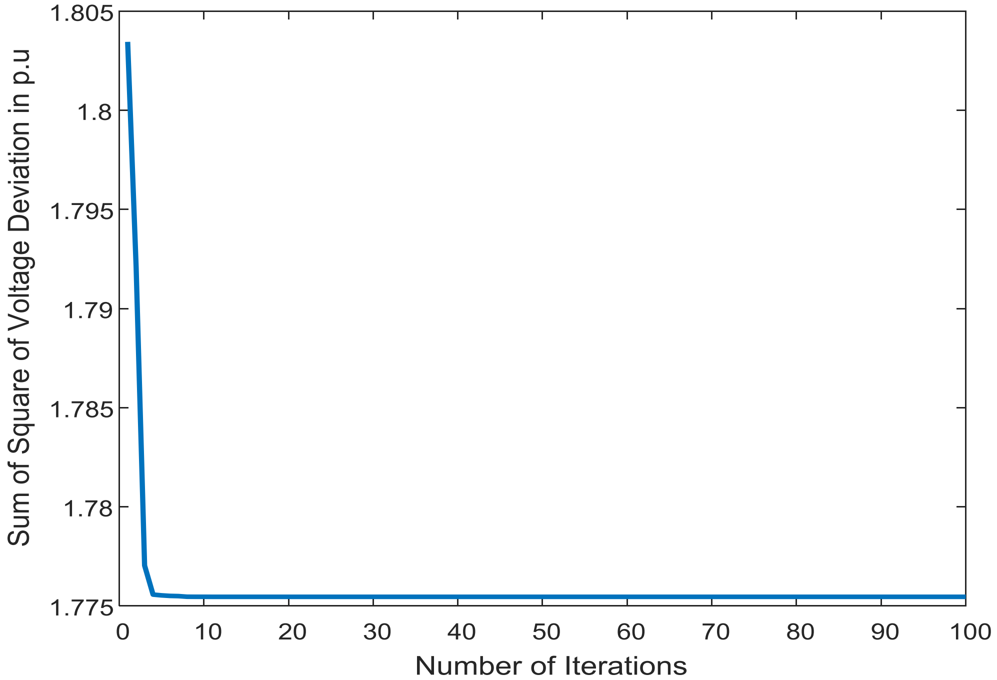

Figure 4.10: WCA Convergence Characteristics for NACB Feeder Network

4.2.5 Summary of Result for NACB Feeder Network

The results were compared with and Without DVRs allocation on the NACB Feeder to observe there was an improvement and was summarized in Table 4.2.

Table 4.2: Summary of Result for NACB Feeder 11KV Network

S/N	**Parameter**	**Without DVR**	**With DVR Optimally Deployed**	**Improvement**
1	DVR Location	-	Bus 29	-
2	Real Power Losses (KW)	448.9871	324.74	27%
3	Reactive Power Losses (kvar)	421.4709	304.84	6%
4	Voltage (pu)	0.9245	0.970	4.92%
5	DVR size (kV)	-	1	-

V. CONCLUSION

5.1 Conclusion

In this research work, a meta-heuristic optimization algorithm; water cycle algorithm (WCA) was used to optimally determine the location and size dynamic voltage restorer (DVR) in a distribution network with the aim of improving the system voltage profile and reducing the active and reactive power loss. The steady state model of DVR was derived and incorporated in forward/backward sweep load flow method in order to guide the WCA while determining the optimal location and size of the DVR. The performance of the proposed method was tested on IEEE 33-bus standard radial distribution systems in a MATLAB software. It was found that the proposed WCA placed the DVR in the IEEE 33-bus network at bus 18, thereby reducing the real and reactive power by 21%, 13.2% respectively and improving the voltage profile by 12.27%. To demonstrate the applicability of the technique ina real-life distribution system the DVR was optimally placed in NACB feeder, and the result shows that with the placement of the DVR, the WCA placed the DVR at bus 29 thereby reducing the real and reactive power loss by 27%, 6% respectively and improving the voltage profile by 4.92%.

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APPENDICES

APPENDIX A1

Table A1: Line and Bus Data for Standard IEEE 33-bus Distribution Network

Branch Number (ik)	**Sending Bus** (i)	**Receiving Bus** (k)	$R_{ik}\ (\Omega)$	$X_{ik}\ (\Omega)$	$P_{Dk}\ (kW)$	$Q_{Dk}\ (kVAr)$
1	1	2	0.0922	0.047	100	60
2	2	3	0.493	0.2511	90	40
3	3	4	0.366	0.1864	120	80
4	4	5	0.3811	0.1941	60	30
5	5	6	0.819	0.707	60	20
6	6	7	0.1872	0.6188	200	100
7	7	8	0.7114	0.2351	200	100
8	8	9	1.03	0.74	60	20
9	9	10	1.044	0.74	60	20
10	10	11	0.1966	0.065	45	30
11	11	12	0.3744	0.1238	60	35
12	12	13	1.468	1.155	60	35
13	13	14	0.5416	0.7129	120	80
14	14	15	0.591	0.526	60	10
15	15	16	0.7463	0.545	60	20
16	16	17	1.289	1.721	60	20
17	17	18	0.732	0.574	90	40
18	18	19	0.164	0.1565	90	40
19	19	20	1.5042	1.3554	90	40
20	20	21	0.4095	0.4784	90	40
21	21	22	0.7089	0.9373	90	40
22	22	23	0.4512	0.3083	90	50
23	23	24	0.898	0.7091	420	200
24	24	25	0.896	0.7011	420	200
25	25	26	0.203	0.1034	60	25
26	26	27	0.2842	0.1447	60	25
27	27	28	1.059	0.9337	60	20
28	28	29	0.8042	0.7006	120	70
29	29	30	0.5075	0.2585	200	600
30	30	31	0.9744	0.963	150	70
31	31	32	0.3105	0.3619	210	100
32	32	33	0.341	0.5302	60	40

APPENDIX A2

Table A2: Line and Bus Data for NACB Distribution Network

```
linedata = [1.0000    1.0000    2.0000    0.0662    0.0622
    2.0000    2.0000    3.0000    0.1324    0.1243
    3.0000    3.0000    4.0000    0.0055    0.0051
    4.0000    3.0000   54.0000    0.0475    0.0446
    5.0000    4.0000    5.0000    0.0523    0.0491
```

```
    6.0000    4.0000   47.0000    0.0414    0.0388
    7.0000    5.0000    6.0000    0.0766    0.0719
    8.0000    6.0000    7.0000    0.0169    0.0159
    9.0000    7.0000    8.0000    0.0616    0.0578
   10.0000    7.0000   45.0000    0.0441    0.0414
   11.0000    8.0000    9.0000    0.0038    0.0036
   12.0000    8.0000   43.0000    0.0396    0.0371
   13.0000    9.0000   10.0000    0.1167    0.1096
   14.0000   10.0000   11.0000    0.0028    0.0026
   15.0000   11.0000   12.0000    0.0747    0.0701
   16.0000   12.0000   13.0000    0.0041    0.0039
   17.0000   13.0000   14.0000    0.0607    0.0570
   18.0000   13.0000   37.0000    0.0973    0.0914
   19.0000   14.0000   15.0000    0.0221    0.0207
   20.0000   14.0000   57.0000    0.0822    0.0772
   21.0000   15.0000   16.0000    0.1410    0.1324
   22.0000   16.0000   17.0000    0.0167    0.0157
   23.0000   16.0000   36.0000    0.0268    0.0251
   24.0000   17.0000   18.0000    0.0979    0.0920
   25.0000   17.0000   33.0000    0.0267    0.0250
   26.0000   18.0000   19.0000    0.0093    0.0087
   27.0000   19.0000   20.0000    0.0701    0.0658
   28.0000   20.0000   21.0000    0.0649    0.0609
   29.0000   20.0000   30.0000    0.0099    0.0093
   30.0000   21.0000   22.0000    0.0659    0.0619
   31.0000   22.0000   24.0000    0.0410    0.0385
   32.0000   24.0000   25.0000    0.0848    0.0797
   33.0000   25.0000   23.0000    0.0228    0.0214
   34.0000   25.0000   26.0000    0.0658    0.0618
   35.0000   26.0000   27.0000    0.0367    0.0345
   36.0000   26.0000   29.0000    0.0137    0.0129
   37.0000   27.0000   28.0000    0.0263    0.0247
   38.0000   30.0000   31.0000    0.0128    0.0120
   39.0000   31.0000   32.0000    0.0384    0.0361
   40.0000   33.0000   34.0000    0.0168    0.0158
   41.0000   34.0000   35.0000    0.0302    0.0284
   42.0000   37.0000   38.0000    0.0416    0.0390
   43.0000   37.0000   39.0000    0.0868    0.0815
   44.0000   37.0000   41.0000    0.0506    0.0475
   45.0000   39.0000   40.0000    0.0219    0.0206
   46.0000   41.0000   42.0000    0.0499    0.0468
   47.0000   43.0000   44.0000    0.0139    0.0130
   48.0000   45.0000   46.0000    0.0157    0.0148
   49.0000   47.0000   48.0000    0.1747    0.1641
   50.0000   48.0000   49.0000    0.0512    0.0481
   51.0000   48.0000   52.0000    0.1022    0.0960
   52.0000   49.0000   50.0000    0.0081    0.0076
   53.0000   50.0000   51.0000    0.0670    0.0629
   54.0000   52.0000   53.0000    0.1314    0.1234
   55.0000   54.0000   55.0000    0.0508    0.0477
   56.0000   55.0000   56.0000    0.0679    0.0638
   57.0000   57.0000   58.0000    0.0139    0.0130];

loaddata1 = [1.0000         0         0         0
2.0000  240.0000  174.0000         0
3.0000  240.0000  174.0000         0
    4.0000         0         0         0
    5.0000   80.0000   58.0000         0
6.0000  400.0000  290.0000         0
```

7.0000	400.0000	290.0000	0
8.0000	80.0000	58.0000	0
9.0000	0	0	0
10.0000	0	0	0
11.0000	80.0000	58.0000	0
12.0000	400.0000	290.0000	0
13.0000	240.0000	174.0000	0
14.0000	40.0000	29.0000	0
15.0000	400.0000	290.0000	0
16.0000	400.0000	290.0000	0
17.0000	0	0	0
18.0000	0	0	0
19.0000	0	0	0
20.0000	40.0000	29.0000	0
21.0000	80.0000	58.0000	0
22.0000	240.0000	174.0000	0
23.0000	0	0	0
24.0000	80.0000	58.0000	0
25.0000	400.0000	290.0000	0
26.0000	40.0000	29.0000	0
27.0000	160.0000	116.0000	0
28.0000	0	0	0
29.0000	400.0000	290.0000	0
30.0000	80.0000	58.0000	0
31.0000	40.0000	29.0000	0
32.0000	0	0	0
33.0000	0	0	0
34.0000	400.0000	290.0000	0
35.0000	240.0000	174.0000	0
36.0000	80.0000	58.0000	0
37.0000	240.0000	174.0000	0
38.0000	80.0000	58.0000	0
39.0000	400.0000	290.0000	0
40.0000	40.0000	29.0000	0
41.0000	40.0000	29.0000	0
42.0000	240.0000	174.0000	0
43.0000	80.0000	58.0000	0
44.0000	160.0000	116.0000	0
45.0000	160.0000	116.0000	0
46.0000	80.0000	58.0000	0
47.0000	400.0000	290.0000	0
48.0000	80.0000	58.0000	0
49.0000	80.0000	58.0000	0
50.0000	0	0	0
51.0000	40.0000	29.0000	0
52.0000	240.0000	174.0000	0
53.0000	240.0000	174.0000	0
54.0000	40.0000	29.0000	0
55.0000	40.0000	29.0000	0
56.0000	240.0000	174.0000	0
57.0000	240.0000	174.0000	0
58.0000	40.0000	29.0000	0]

APPENDIX A5
RESULTS OF NACB FEEDER

RADIAL POWER FLOW RESULTS OF NACB FEEDER WITHOUT DVR

Bus No.	Voltage Mag.	Angle Degree	----Load---- kW	kVAr	---Substation--- kW	kVAr
1	1.0000	0.0000	0.0000	0.0000	8928.9871	3495.4709
2	0.9926	-0.0035	240.0000	87.0000	0.0000	0.0000
3	0.9783	-0.0104	240.0000	87.0000	0.0000	0.0000
4	0.9777	-0.0107	0.0000	0.0000	0.0000	0.0000
5	0.9735	-0.0128	80.0000	29.0000	0.0000	0.0000
6	0.9689	-0.0151	400.0000	145.0000	0.0000	0.0000
7	0.9654	-0.0168	400.0000	145.0000	0.0000	0.0000
8	0.9596	-0.0198	80.0000	29.0000	0.0000	0.0000
9	0.9584	-0.0205	0.0000	0.0000	0.0000	0.0000
10	0.9540	-0.0228	0.0000	0.0000	0.0000	0.0000
11	0.9508	-0.0245	80.0000	29.0000	0.0000	0.0000
12	0.9505	-0.0246	400.0000	145.0000	0.0000	0.0000
13	0.9479	-0.0260	240.0000	87.0000	0.0000	0.0000
14	0.9418	-0.0293	40.0000	14.5000	0.0000	0.0000
15	0.9417	-0.0293	400.0000	145.0000	0.0000	0.0000
16	0.9384	-0.0311	400.0000	145.0000	0.0000	0.0000
17	0.9383	-0.0312	0.0000	0.0000	0.0000	0.0000
18	0.9364	-0.0322	0.0000	0.0000	0.0000	0.0000
19	0.9334	-0.0338	0.0000	0.0000	0.0000	0.0000
20	0.9328	-0.0342	40.0000	14.5000	0.0000	0.0000
21	0.9304	-0.0355	80.0000	29.0000	0.0000	0.0000
22	0.9265	-0.0377	240.0000	87.0000	0.0000	0.0000
23	0.9263	-0.0379	0.0000	0.0000	0.0000	0.0000
24	0.9262	-0.0379	80.0000	29.0000	0.0000	0.0000
25	0.9250	-0.0386	400.0000	145.0000	0.0000	0.0000
26	0.9249	-0.0387	40.0000	14.5000	0.0000	0.0000
27	0.9248	-0.0387	160.0000	58.0000	0.0000	0.0000
28	0.9248	-0.0387	0.0000	0.0000	0.0000	0.0000
29	0.9246	-0.0388	400.0000	145.0000	0.0000	0.0000
30	0.9328	-0.0342	80.0000	29.0000	0.0000	0.0000
31	0.9327	-0.0342	40.0000	14.5000	0.0000	0.0000
32	0.9327	-0.0342	0.0000	0.0000	0.0000	0.0000
33	0.9321	-0.0346	0.0000	0.0000	0.0000	0.0000
34	0.9319	-0.0347	400.0000	145.0000	0.0000	0.0000
35	0.9318	-0.0348	240.0000	87.0000	0.0000	0.0000
36	0.9317	-0.0348	80.0000	29.0000	0.0000	0.0000
37	0.9316	-0.0349	240.0000	87.0000	0.0000	0.0000
38	0.9315	-0.0349	80.0000	29.0000	0.0000	0.0000
39	0.9315	-0.0349	400.0000	145.0000	0.0000	0.0000
40	0.9315	-0.0349	40.0000	14.5000	0.0000	0.0000
41	0.9315	-0.0349	40.0000	14.5000	0.0000	0.0000
42	0.9314	-0.0350	240.0000	87.0000	0.0000	0.0000
43	0.9313	-0.0350	80.0000	29.0000	0.0000	0.0000
44	0.9311	-0.0351	160.0000	58.0000	0.0000	0.0000
45	0.9310	-0.0352	160.0000	58.0000	0.0000	0.0000
46	0.9310	-0.0352	80.0000	29.0000	0.0000	0.0000
47	0.9304	-0.0356	400.0000	145.0000	0.0000	0.0000
48	0.9303	-0.0356	80.0000	29.0000	0.0000	0.0000
49	0.9302	-0.0356	80.0000	29.0000	0.0000	0.0000
50	0.9302	-0.0357	0.0000	0.0000	0.0000	0.0000
51	0.9301	-0.0357	40.0000	14.5000	0.0000	0.0000
52	0.9297	-0.0359	240.0000	87.0000	0.0000	0.0000
53	0.9297	-0.0359	240.0000	87.0000	0.0000	0.0000
54	0.9294	-0.0361	40.0000	14.5000	0.0000	0.0000
55	0.9290	-0.0363	40.0000	14.5000	0.0000	0.0000

56	0.9289	-0.0364	240.0000	87.0000	0.0000	0.0000
57	0.9286	-0.0365	240.0000	87.0000	0.0000	0.0000
58	0.9286	-0.0365	40.0000	14.5000	0.0000	0.0000

==

Total			8480.0000	3074.0000	8928.9871	3495.4709

FROM BUS	TO BUS	REAL POWER LOSSES	REACTIVE POWER LOSSES
1.0000	2.0000	64.3367	60.4492
2.0000	3.0000	122.6449	115.1417
3.0000	4.0000	4.5089	4.1810
3.0000	54.0000	29.8808	28.0565
4.0000	5.0000	32.2446	30.2717
4.0000	47.0000	22.9954	21.5512
5.0000	6.0000	35.4507	33.2755
6.0000	7.0000	7.0813	6.6623
7.0000	8.0000	25.8113	24.2190
7.0000	45.0000	18.4785	17.3472
8.0000	9.0000	1.5525	1.4708
8.0000	43.0000	14.1841	13.2887
9.0000	10.0000	25.3466	23.8045
10.0000	11.0000	0.5244	0.4870
11.0000	12.0000	11.4614	10.7556
12.0000	13.0000	0.4801	0.4567
13.0000	14.0000	4.6163	4.3349
13.0000	37.0000	7.3998	6.9511
14.0000	15.0000	1.6807	1.5743
14.0000	57.0000	5.5221	5.1862
15.0000	16.0000	8.8742	8.3329
16.0000	17.0000	0.2129	0.2002
16.0000	36.0000	0.3417	0.3200
17.0000	18.0000	1.0703	1.0058
17.0000	33.0000	0.1051	0.0984
18.0000	19.0000	0.0026	0.0024
19.0000	20.0000	0	0
20.0000	21.0000	0.1136	0.1066
20.0000	30.0000	0.0015	0.0014
21.0000	22.0000	0.0011	0.0011
22.0000	24.0000	0	0
24.0000	25.0000	0.3740	0.3515
25.0000	23.0000	0.1006	0.0944
25.0000	26.0000	0.0408	0.0383
26.0000	27.0000	0.0025	0.0024
26.0000	29.0000	0.1597	0.1504
27.0000	28.0000	0.0018	0.0017
30.0000	31.0000	0.0267	0.0250
31.0000	32.0000	0.0007	0.0006
33.0000	34.0000	0.0142	0.0134
34.0000	35.0000	0.0187	0.0176
37.0000	38.0000	0.0258	0.0242
37.0000	39.0000	0.0240	0.0225
37.0000	41.0000	0.0314	0.0295
39.0000	40.0000	0.0015	0.0014
41.0000	42.0000	0.6292	0.5901
43.0000	44.0000	0.0695	0.0650
45.0000	46.0000	0.0024	0.0023
47.0000	48.0000	0.0030	0.0028

48.0000	49.0000	0.0009	0.0008
48.0000	52.0000	0.2547	0.2393
49.0000	50.0000	0.0050	0.0047
50.0000	51.0000	0.0743	0.0698
52.0000	53.0000	0.1116	0.1048
54.0000	55.0000	0.0317	0.0298
55.0000	56.0000	0.0577	0.0542
57.0000	58.0000	0.0002	0.0002

Total 448.9871 421.4709

RADIAL POWER FLOW RESULTS OF NACB FEEDER WITH DVR

Bus No.	Voltage Mag.	Angle Degree	Load kW	Load kVAr	Substation kW	Substation kVAr
1	1.0000	0.0000	0.0000	0.0000	8885.9305	3487.1743
2	0.9950	-0.0054	240.0000	87.0000	0.0000	0.0000
3	0.9855	-0.0162	240.0000	87.0000	0.0000	0.0000
4	0.9851	-0.0167	0.0000	0.0000	0.0000	0.0000
5	0.9826	-0.0201	80.0000	29.0000	0.0000	0.0000
6	0.9799	-0.0240	400.0000	145.0000	0.0000	0.0000
7	0.9779	-0.0269	400.0000	145.0000	0.0000	0.0000
8	0.9748	-0.0321	80.0000	29.0000	0.0000	0.0000
9	0.9742	-0.0333	0.0000	0.0000	0.0000	0.0000
10	0.9720	-0.0373	0.0000	0.0000	0.0000	0.0000
11	0.9704	-0.0403	80.0000	29.0000	0.0000	0.0000
12	0.9703	-0.0405	400.0000	145.0000	0.0000	0.0000
13	0.9691	-0.0431	240.0000	87.0000	0.0000	0.0000
14	0.9672	-0.0496	40.0000	14.5000	0.0000	0.0000
15	0.9671	-0.0498	400.0000	145.0000	0.0000	0.0000
16	0.9665	-0.0537	400.0000	145.0000	0.0000	0.0000
17	0.9665	-0.0539	0.0000	0.0000	0.0000	0.0000
18	0.9667	-0.0566	0.0000	0.0000	0.0000	0.0000
19	0.9672	-0.0609	0.0000	0.0000	0.0000	0.0000
20	0.9673	-0.0619	40.0000	14.5000	0.0000	0.0000
21	0.9678	-0.0655	80.0000	29.0000	0.0000	0.0000
22	0.9688	-0.0716	240.0000	87.0000	0.0000	0.0000
23	0.9689	-0.0719	0.0000	0.0000	0.0000	0.0000
24	0.9689	-0.0721	80.0000	29.0000	0.0000	0.0000
25	0.9695	-0.0741	400.0000	145.0000	0.0000	0.0000
26	0.9698	-0.0746	40.0000	14.5000	0.0000	0.0000
27	0.9697	-0.0746	160.0000	58.0000	0.0000	0.0000
28	0.9697	-0.0746	0.0000	0.0000	0.0000	0.0000
29	0.9706	-0.0756	400.0000	145.0000	0.0000	0.0000
30	0.9672	-0.0619	80.0000	29.0000	0.0000	0.0000
31	0.9672	-0.0619	40.0000	14.5000	0.0000	0.0000
32	0.9672	-0.0619	0.0000	0.0000	0.0000	0.0000
33	0.9666	-0.0623	0.0000	0.0000	0.0000	0.0000
34	0.9665	-0.0624	400.0000	145.0000	0.0000	0.0000
35	0.9663	-0.0625	240.0000	87.0000	0.0000	0.0000
36	0.9663	-0.0625	80.0000	29.0000	0.0000	0.0000
37	0.9661	-0.0626	240.0000	87.0000	0.0000	0.0000
38	0.9661	-0.0626	80.0000	29.0000	0.0000	0.0000
39	0.9661	-0.0627	400.0000	145.0000	0.0000	0.0000
40	0.9660	-0.0627	40.0000	14.5000	0.0000	0.0000

41	0.9661	-0.0626	40.0000	14.5000	0.0000	0.0000
42	0.9660	-0.0627	240.0000	87.0000	0.0000	0.0000
43	0.9659	-0.0628	80.0000	29.0000	0.0000	0.0000
44	0.9657	-0.0628	160.0000	58.0000	0.0000	0.0000
45	0.9656	-0.0629	160.0000	58.0000	0.0000	0.0000
46	0.9656	-0.0629	80.0000	29.0000	0.0000	0.0000
47	0.9650	-0.0633	400.0000	145.0000	0.0000	0.0000
48	0.9649	-0.0634	80.0000	29.0000	0.0000	0.0000
49	0.9649	-0.0634	80.0000	29.0000	0.0000	0.0000
50	0.9648	-0.0634	0.0000	0.0000	0.0000	0.0000
51	0.9648	-0.0634	40.0000	14.5000	0.0000	0.0000
52	0.9644	-0.0637	240.0000	87.0000	0.0000	0.0000
53	0.9644	-0.0637	240.0000	87.0000	0.0000	0.0000
54	0.9641	-0.0638	40.0000	14.5000	0.0000	0.0000
55	0.9637	-0.0641	40.0000	14.5000	0.0000	0.0000
56	0.9636	-0.0642	240.0000	87.0000	0.0000	0.0000
57	0.9634	-0.0643	240.0000	87.0000	0.0000	0.0000
58	0.9634	-0.0643	40.0000	14.5000	0.0000	0.0000
Total			**8480.0**	**3074.0**	**8885.93**	**3455.06**

FROM BUS	TO BUS	REAL POWER LOSSES	REACTIVE POWER LOSSES
1.0000	2.0000	41.9561	39.4210
2.0000	3.0000	79.9384	75.0479
3.0000	4.0000	2.9398	2.7260
3.0000	54.0000	19.6121	18.4148
4.0000	5.0000	21.1789	19.8831
4.0000	47.0000	15.1760	14.2229
5.0000	6.0000	23.7030	22.2487
6.0000	7.0000	4.7813	4.4984
7.0000	8.0000	17.4278	16.3527
7.0000	45.0000	12.4767	11.7128
8.0000	9.0000	1.0512	0.9958
8.0000	43.0000	9.7671	9.1505
9.0000	10.0000	19.4125	18.2315
10.0000	11.0000	0.4208	0.3907
11.0000	12.0000	9.9206	9.3097
12.0000	13.0000	0.4719	0.4488
13.0000	14.0000	5.8857	5.5269
13.0000	37.0000	9.4346	8.8625
14.0000	15.0000	2.1429	2.0072
14.0000	57.0000	7.6829	7.2155
15.0000	16.0000	12.9517	12.1617
16.0000	17.0000	0.3656	0.3437
16.0000	36.0000	0.5867	0.5495
17.0000	18.0000	2.0858	1.9601
17.0000	33.0000	0.5307	0.4969
18.0000	19.0000	0.0019	0.0018
19.0000	20.0000	0	0
20.0000	21.0000	1.3055	1.2251
20.0000	30.0000	0.0011	0.0011
21.0000	22.0000	0.0008	0.0008
22.0000	24.0000	0	0
24.0000	25.0000	0.2782	0.2615
25.0000	23.0000	0.0748	0.0702
25.0000	26.0000	0.0304	0.0285

26.0000	27.0000	0.0019	0.0018
26.0000	29.0000	0.1188	0.1118
27.0000	28.0000	0.0013	0.0013
30.0000	31.0000	0.0199	0.0186
31.0000	32.0000	0.0005	0.0005
33.0000	34.0000	0.0106	0.0099
34.0000	35.0000	0.0139	0.0131
37.0000	38.0000	0.0192	0.0180
37.0000	39.0000	0.0178	0.0167
37.0000	41.0000	0.0234	0.0220
39.0000	40.0000	0.0011	0.0011
41.0000	42.0000	0.4678	0.4388
43.0000	44.0000	0.0517	0.0483
45.0000	46.0000	0.0018	0.0017
47.0000	48.0000	0.0022	0.0021
48.0000	49.0000	0.0007	0.0006
48.0000	52.0000	0.1894	0.1779
49.0000	50.0000	0.0038	0.0035
50.0000	51.0000	0.0553	0.0519
52.0000	53.0000	0.0830	0.0779
54.0000	55.0000	0.0236	0.0221
55.0000	56.0000	0.0429	0.0403
57.0000	58.0000	0.0002	0.0002
Total		**324.74**	**304.84**