University of Nairobi
School of Engineering
Department of Electrical and Information Engineering

IMPROVING THE VOLTAGE STABILITY OF A DISTRIBUTION SYSTEM WITH RENEWABLE DISTRIBUTED GENERATION USING A THREE METHOD HYBRID.

Thesis submitted in partial fulfillment of the requirements for the award of the Degree of Master of Science in Electrical and Information Engineering, in the Department of Electrical and Information Engineering of the University of Nairobi.

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Abstract

Owing to the increased advocacy on clean energy sources worldwide, the integration of Renewable Distributed Generators (RDGs) in to the grid has been increasingly adopted in meeting increased electrical load demand. RDGs are intermittent in nature posing a great problem to the system's voltage stability due to their variable power output. Therefore the study of voltage stability with Renewable Distributed Generation integrated in the distribution system is very critical in modern power system operation. The formulation and solution of the voltage stability problem of a radial distribution system with Renewable Distributed Generation (RDG) is crucial. Earlier research works show that optimal penetration of RDGs to the grid near the load centers can improve the system reliability, voltage stability and power quality through reduced transmission line losses. However, a further increase in RDG penetration distorts the system's voltage stability.

This thesis work comprised of a multi-objective problem formulation aimed at reducing the total line losses (both real and reactive) and the total voltage deviation of a radial distribution system with Photovoltaic Solar sources and wind sources. A three method hybrid approach of Index Based Planning, Adaptive Genetic Algorithm and Simulated Annealing was applied in solving this problem.

Results show that the three method hybrid can be used to optimally size and locate two RDGs in a radial distribution system while reducing the total line losses and total voltage deviation simultaneously. The integration of two PV Solar RDGs into the IEEE 33 Bus System reduced the total line losses and total voltage deviation by 62% and 73% respectively. The integration of two wind RDGs into the IEEE 33 Bus System reduced the total line losses and total voltage deviation by 76% and 70% respectively. Integration of a third RDG in to the system did not have any significant effect to the system's total voltage deviation and total line losses.

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Nomenclature

ABM-Agent Based Modeling

AC-Alternating Current

AGA-Adaptive Genetic Algorithm

AVR-Automatic Voltage Regulator

BPSO- Binary Particle Swarm Optimization

DC-Direct current

DES-Distributed Energy Storage

DE-Differential Evolution

DFIG- Doubly Fed Induction Generator

DG-Distributed Generation

DSTATCOM-Dynamic Static Compensator

EHV- Extra High Voltage

FACTS-Flexible AC Transmission System

FVSI-Fast Voltage Stability Index

GA-Genetic Algorithm

GSA- Gravitational Search Algorithm

HDPSO- Hybrid Discrete Particle Swarm Optimization

IA-Improved Analytical

IEEE-Institute of Electrical and Electronic Engineers

IHS-Improved Harmony Search

IPSO-Improved Particle Swarm Optimization

IRS-Intermittent Renewable Source

LQP-Line Stability Factor

MATLAB-Matrix Laboratory

MOPSO-Multi Objective Particle Swarm Optimization

OPF-Optimal Power Flow

PF-Power Factor

PSO-Particle swarm Optimization

PV-DG-Photo voltaic Distributed Generation

PV-Photo Voltaic

RDG-Renewable Distributed Generation

RE-Renewable Energy

RES-Renewable Energy Storage

RMS- Root Mean Square Value

SA-Simulated Annealing

STATCOM- Static Compensator

SVCs-Static VAR Compensator

THD-Total Harmonic Distortion

TRSC- Thyristor Controlled Series capacitor

TS- Tabu Search

UFLS- Under Frequency Load shedding

UPDC-Unified Power Flow Controller

VSI-Voltage Stability Indices

VSM- Voltage Stability Margin

CHAPTER 1

1 INTRODUCTION

This chapter gives a general background of the power system stability, an overview of the effects of grid integrated Renewable Distributed Generators (RDGs) on voltage stability, problem statement, research objectives, research questions related to the research objectives, research justification, scope of the research work and a description of the thesis organization.

1.1 Background

Voltage stability is a power system's ability to maintain acceptable voltage levels at all the buses under normal conditions and after a disruption [1]. Voltage stability enables the utility company to supply reliable and quality power to consumers. This is because all electrical loads have a specific voltage rating beyond which any variation of the voltage would permanently damage them or reduce their life span. In addition, voltage instability would lead to a voltage collapse which may further result in undesirable power blackouts. These black outs result in reduced revenue generation by the utility company and undesirable power interruptions to power consumers. Hence it is very important to maintain the voltage levels of a power system within acceptable limits (+/-6%).

Renewable Distributed generation (RDG) refers to having various renewable energy generating units interconnected to a power distribution system and located close to the load centres so as to cater for increased electric load demand without making significant changes to the distribution system such as creating a new substation or uprating existing network and equipment [2] [3]. However, research has shown that interconnecting improperly sited and sized RDGs to the distribution system may result in increased power loss and consequently reduce the voltage stability of the system. Therefore it is crucial to obtain the optimal location and size of the RDGs.

The following are the benefits of increased use of RDGs that have resulted in increased research on it [3] [4] [5]:

(i) Incorporation of RDGs at the distribution network results in reduced cost in meeting increased power demand as compared to the conventional methods of expanding the existing network, uprating the existing substations or setting up new distribution substations.

(ii) They reduce line losses which result from long transmission lines because they are located at/near the load centres.

(iii) They reduce transmission line congestion because the RDGs are placed near the power consumers.

(iv) They lead to increased system reliability when properly interconnected to the grid. This occurs due to the variable production of power by the RDG units where at some times the RDG units output power is less than the demand and the load has to be powered from the utility company and there are other times when the RDG units produce higher power output than the load and thus the extra power is sent to the utility company.

(v) RDG sources can be used in providing emergency power supply to emergency units such as hospitals in case of a contingency in the distribution system which would lead to a power failure.

Distributed Generation (DG) can be done using renewable or non-renewable sources. Renewable Distributed Generators (RDGs) have minimal environmental pollution and are infinitely available therefore, incorporating them to the distribution network has been increasing in the recent past. However, integration of RDGs to the distribution system adds an extra challenge of ensuring that the voltage stability is maintained. This is because they are intermittent and cannot generate an instantaneous power at all times. Therefore voltage stability with RDG is still an active research area and various methods have been used to solve this problem.

1.2 Problem Statement

Previous research has indicated that the electric load profile in Kenya is time-varying and the loading affects voltage profile in the distribution systems. It is therefore suitable to consider incorporation of RDGs in solving this issue. Studies indicate that wrong RDG placement and sizing may violate voltage limits resulting in a poorer voltage profile. Optimal allocation of RDGs can improve the system’s voltage profile and reduce system losses. Therefore, optimal sizing and placement of RDG units is necessary in the modern power system. RDG sources are unpredictable and volatile in nature and they generate fluctuating power over time. In order to curb this, it is important to integrate Renewable Energy Storage (RES) at the RDG sources. RES allocation should be able to supply the required load when the RDG power output is low and hence enhance the system's reliability. RES are costly and recently research has shown that optimal RES assignment can be used in RDGs to make them more reliable. This thesis solved the multi-objective problem of minimization of total line losses and enhancement of the voltage stability of the distribution system with RDGs including RES allocation.

1.3 Objectives

The main objective of this thesis was to reduce total line losses and to improve the voltage stability of a radial distribution system incorporating RDGs and RES.

The specific objectives are:

(i) To formulate a multi-objective function considering voltage profile improvement and line loss reduction in a distribution system with RDGs.

(ii) To develop optimal locations and sizes of RDGs and RES using a hybrid of Index based planning, Adaptive Genetic Algorithm and Simulated Annealing.

(iii) To test the results obtained in the IEEE 33 Bus radial system and compare them to those obtained by other researchers using different optimization methods.

1.4 Research Questions

The following research questions were addressed in order to achieve the objectives stated above:

(i) How can the problem of increased and time varying electrical load be met in Kenya?

(ii) What are the effects of grid connected RDGs to the system's voltage stability and line losses?

(iii) How can suitable sites and sizes of the RDGs and RES be determined to improve the voltage profile and reduce the power losses?

(iv) How can a multi-objective problem of system's voltage stability with RDGs be formulated considering total voltage deviation and total line losses with RES allocation?

(v) How can a suitable hybrid algorithm be determined to solve the multi-objective function formulated?

(vi) How shall the results of this research work be tested and analyzed?

1.5 Justification for the Study

Renewable Distributed Generator technologies are on the rise due to their ability to solve the problem of time varying loads and increased energy demand at the distribution system level without making major alterations to the transmission system. RDG technologies have been a continuous trend due to their ability to generate clean energy, they are inexhaustible and they also solve the problem of volatility of fuel costs associated with fossil fuels which directly affects the cost of energy [6]. The use of RDGs is therefore seen as the emergent trend in meeting future electrical load growth. When these RDGs are interconnected to the grid they add an extra challenge of ensuring voltage stability is maintained because they generate a variable power output.

Voltage stability is important in a distribution system because all the equipment and loads are rated at specific voltage levels which if not maintained may cause permanent damage or shorten their life spans. Low voltages may result to a voltage collapse and eventually a power blackout which is undesirable [1] [7]. Therefore, a research on improving the distribution system's voltage stability upon incorporation of RDGs to increase system stability and reliability was deemed necessary.

1.6 Scope of Work

This thesis considered using Wind RDGs and Photovoltaic Solar RDGs interconnected to a radial distribution system due to the following reasons;

(i) They have less carbon emissions and therefore cause minimal environmental pollution.
(ii) Kenya is located at the equator and hence does not have severe climatic changes that may severely affect the PV Solar output. Therefore this would not have a significant impact on the solar generation throughout the year.
(iii) Exploration has shown that there are potentially suitable sites for wind power generation in Kenya.
(iv) The distribution system in Kenya is radial.

PV Solar sources produce DC power only and hence rectifiers and inverters are required to convert the DC power output into AC power output before interconnecting them to the grid. This power is injected at unity power factor resulting in a high system Power Factor. PV-DGs supply more active power to the grid for the same reactive power and therefore inverters with reactive power controls that can be configured to produce active and reactive power simultaneously can be used or static compensators can be employed.

This thesis involved using RDGs to enhance the system's voltage profile. A three method hybrid technique was used to design optimal siting and sizing of the RDGs and to determine optimal RES allocation to reduce total line losses and improve the voltage profile. Hybrid techniques were considered because they enhance the strengths of each individual base method, suppress the weaknesses of each base method and result to more accurate and reliable results.

The results from this work were analysed and compared to those obtained from other research works using other optimization techniques.

1.7 Thesis Organization

This thesis contains five major chapters; Chapter 1 contains an introduction, problem statement, research objectives, justification of the study and scope of work that was carried out. Chapter 2 contains an overview of Power System Stability, a review previous related works, effects of grid integrated RDGs to system's voltage stability and the problem formulation. Chapter 3 describes the proposed method, applied methodology and the validation method. Chapter 4 contains the results and analysis tested in the IEEE 33 Bus radial distribution System. Chapter 5 consists of a conclusion and a recommendation for future research work.

CHAPTER 2

2 LITERATURE REVIEW

This chapter contains an overview of the Power System Stability, a review of various voltage stability indices, methods used to restrain voltage instability, effects of grid interconnected Renewable Distributed Generators to Voltage stability, a review of previous research works and the problem formulation.

2.1 Power System Stability

It the Power System's ability to remain in a state of operating equilibrium under normal operating conditions or to get back to the state of equilibrium after being subjected to a disturbance. RDGs integration to the distribution network would affect the voltage stability of the distribution system. Figure 2.1 shows the classifications of power system stability.

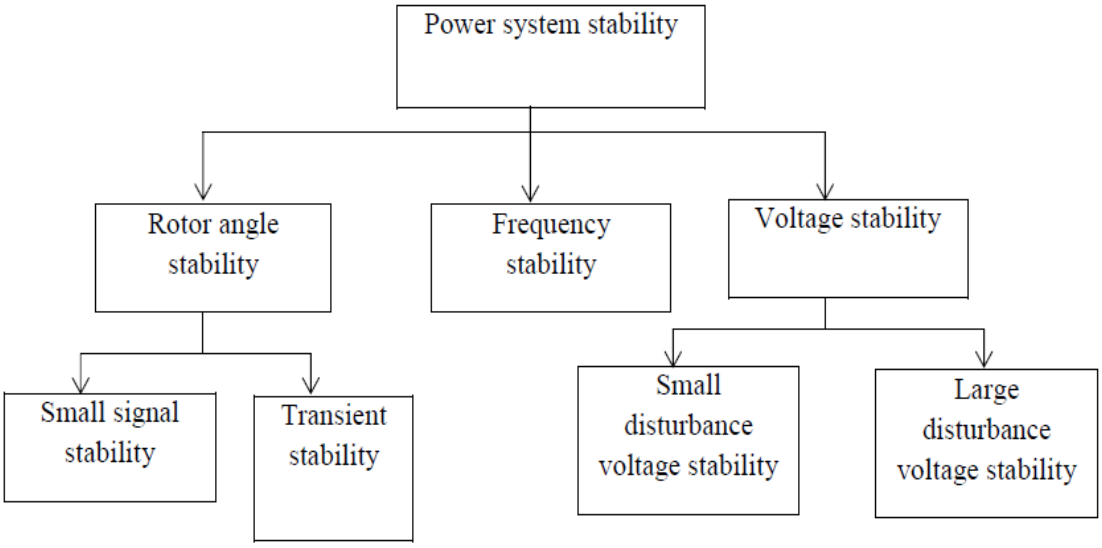

Figure 2.1 Classification of the power system stability [1]

2.1.1 Rotor Angle (synchronous) Stability

It is the ability of interconnected synchronous machines of a power system to remain in a state of synchronism under normal operating conditions and even after being subjected to a disturbance. It is determined by its ability to maintain or regain the system equilibrium between mechanical and electromagnetic torque of all the machines in the system. Increasing the angular swings of some generators may cause instability with other generators. Equation (2.1) governs the rotor motion on the basis of the accelerating torque (T_a) which is a product of the total moment of inertia (J) and its angular acceleration ($\alpha=\frac{d^2\theta}{dt^2}$)

$$T_a=J\,\frac{d^2\theta}{dt^2}=T_m-T_e \tag{2.1}$$

Where, T_m is the mechanical torque less retarding torque due to losses due to rotation and T_e is the electrical torque.

Figure 2.2 gives the diagram of a machine rotor showing the direction of rotation, the mechanical and torque of the motor and the electrical torque of the generator.

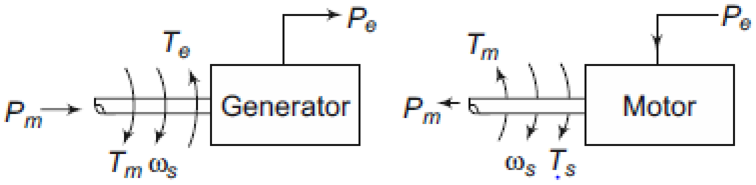

Figure 2.2 Diagram of a machine rotor [8]

Under steady-state conditions, T_m is equal to T_e and T_a is zero and synchronous speed is achieved. Any disturbance in the system causes the machines rotors to decelerate or accelerate depending on the laws of motion of a rotating body. Consequently, when a generator is made to run at a faster speed than the other, its rotor angular position will advance in relation to that the other machines resulting into an angular difference which triggers the transfer of load from the slower machine to the faster one based on the power-angle relationship. This is done in an attempt to regain synchronism by reducing the speed difference and the angular separation. Since the power-angle relationship is nonlinear , an increase in angular separation would lead to reduced power transfer which would further increase the angular separation causing instability after exceeding a given limit [1] [8].

Rotor angle stability can be categorized into two main categories:

(i) Small signal stability: is the power system's ability to maintain synchronism under small disturbances like small variations in load. Linearization of the system equations can be done when these disturbances arise.

(ii) Large disturbance rotor angle stability: is the power system's ability to sustain synchronism after a severe transient disturbance. This form of disturbance affects the system's the pre-disturbance and post-disturbance steady state operations by causing large changes to generator rotor angles.

The main concern for rotor angle stability is the integration of remote power plants to a large system over long transmission lines.

2.1.2 Frequency Stability

It is the ability of a power system to maintain steady frequency within the required nominal range (±0.5Hertz) under normal operating conditions and even after a major system disturbance resulting to a mismatch between generation and load. When this mismatch occurs, the speed and/or frequency of the machine varies and this would result in frequency instability. It is therefore important to properly control the system generation to ensure that it matches with the load.

When electrical power demanded (load) is more than the mechanical input, the power difference is compensated by stored kinetic energy in the rotor leading to a decline in turbine speed in order to maintain a constant alternator output. This leads to a corresponding reduction in the generator frequency as shown in equation (2.2)

$$\omega = 2\pi f \tag{2.2}$$

Where; ω is the turbine speed in radians per second, and f is the system frequency in Hertz.
In case of a significant load and generation mismatch, the generator controls, system controls and system protections are critical and failure to coordinate them well may vary the system frequency significantly from the acceptable value causing the loads or generators to trip. This would possibly result in a major system blackout.

2.1.3 Voltage Stability

Voltage stability is the ability of a power system to maintain acceptable voltages (+/-6%) at all buses in the system under normal conditions and even after a disturbance. Voltage instability occurs when the disturbance gives rise to a progressive and uncontrollable decline in voltage. This may lead to partial or total blackouts if there is inadequate reactive power compensation from generators and devices placed along the transmission lines. The relationship between real and reactive power absorbed by the load can be given by the following equations;

$$\mathrm{P_R} = |\mathrm{V_R}||\mathrm{I_R}|(\cos\theta_\mathrm{R}) \tag{2.3}$$

$$\mathrm{Q_R} = |\mathrm{V_R}||\mathrm{I_R}|(\sin\theta_\mathrm{R}) \tag{2.4}$$

Where; $\mathrm{P_R}$ *and* $\mathrm{Q_R}$ represent the real and reactive power absorbed by the load,
$\mathrm{V_R}$ *and* $\mathrm{I_R}$ are the voltage across the load and the current flowing through the load and θ_R *is* the angle by which $\mathrm{V_R}$ leads $\mathrm{I_R}$.

Equations (2.5)-(2.9) give the relationship between the active and reactive power and the voltage drop across a transmission line.

When V_R is taken as the reference voltage;

$$V_R = |V_R| < 0 \tag{2.5}$$

$$V_S = |V_S| < \delta \tag{2.6}$$

$$P_R = \frac{|V_S||V_R|}{X}\sin\delta \tag{2.7}$$

$$Q_R = \frac{|V_S||V_R|}{X}\cos\delta - \left(\frac{|V_R|^2}{X}\right) \tag{2.8}$$

Assuming δ is very small, $\cos\delta = 1$ and substituting it into equation (2.8), we obtain equation (2.9) given by;

$$Q_R = \frac{|V_R|}{X}\left(|V_S| - |V_R|\right) \tag{2.9}$$

Therefore, the real power transfer capability of a line can be increased by raising the voltage levels.

Equation (2.9) shows that reactive power is directly proportional to the magnitude of voltage drop across a transmission line and in most cases voltage instability occurs due to increased voltage drop that arises when reactive power flows through inductive reactance associated with the entire transmission system.

Voltage stability is categorized into two broad categories:

2.1.3.1 Large disturbance voltage stability

This is a system's ability to restore and maintain nominal voltage at all buses after the occurrence of large disturbances like sudden loss of a generating unit and a major system fault or contingency. It is affected by the system loading characteristics, operation of discrete and continuous controls and system protection operation.

2.1.3.2 Small disturbance voltage stability

It is the ability of a power system to control voltages to within nominal levels after small disturbances like an increase in the system load. It is determined by the load characteristics together with the operation of continuous and discrete controls at a given time instant.

A full and proper understanding of the voltage stability phenomena is crucial in the operation of a Power System and as a result, there is an increased active research on voltage stability of the Modern Power System worldwide and it is therefore a relevant active research area.

2.1.4 Voltage Profile and Voltage Stability Indices

A flat voltage profile ($1 < 0$) should be maintained in a power system at all times to ensure that voltage stability is achieved. In the Kenyan system the distribution system voltages are 33 KV, 11 KV, 415 V and 240 V and they should be maintained up to the load centers to avoid damage to equipment and appliances which could result to increased customer complaints. However, increased loading may result in voltage drop and hence affect the voltage profile. It is therefore, crucial to keep the voltage levels within acceptable margins of +/-6% of the nominal value. Poor voltage management could give rise to voltage collapse and consequently cause undesirable power blackouts. Therefore a continuous voltage assessment is key in a power system to ensure proper system performance and control.

Various voltage stability indices have been applied by researchers to analyze both static and dynamic voltage stability of a power system based on the power line model shown in Figure 2.3.

VSI has also been used to determine the critical buses for proper reactive power compensation [9] [10].

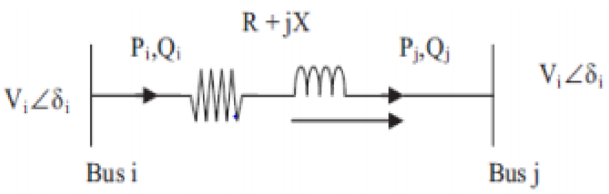

Figure 2.3 A power line model [9]

Voltage stability indices can be categorized into two categories; Line Voltage and Bus Voltage Stability Indices.

2.1.4.1 Line voltage stability indices

These indices provides information on the weakest branches in a distribution system and are highly effective in interconnected systems. They include the following;

(i) Fast Voltage Stability Index (FVSI)

This index is depended on the reactive power flow in the system and can be expressed as shown in equation (2.10).

$$FVSI_{ij} = \frac{4 * Z^2 * Q_j}{V_i^2 * X} \tag{2.10}$$

Where, Z is the line impedance; X is the line reactance; Q_j is the reactive power at the receiving end and V_i is the sending end voltage.

The most critical line will have a value of FVSI being close to 1.

(ii) Line Stability Index (Lmn)

This index is also based on reactive power as shown in equation (2.11).

$$\mathrm{Lmn} = \frac{4 * X * Q_j}{[V_i * \sin(\theta - \delta)]^2} \tag{2.11}$$

Where X is the line reactance; Q_j is reactive power at the receiving end, V_i is the sending end voltage, θ is the line impedance angle and δ is the angle difference between sending end and receiving end voltage.

For a stable system, $Lmn \leq 1$.

(iii) Line Stability Factor (LQP)

This index is based on real and reactive power flow as shown in equation (2.12).

$$LQP = 4 * \left[\frac{X}{V_i^2}\right] * [\frac{X}{V_i^2} * P_i^2 + Q_j] \qquad (2.12)$$

Where, X is the line reactance; P_i is the real power at the sending node, Q_j is the reactive power at the receiving node, V_i is the sending end voltage.

2.1.4.2 Bus voltage stability indices

These indices provide information on the weakest nodes in the system. These indices include:

(i) Voltage Stability Index (VSI)

SI is used in determining the buses that are more proximate to voltage instability in a distribution network for effective compensation [11] [12]. VSI was formulated from Figure 2.4 which shows a two bus system.

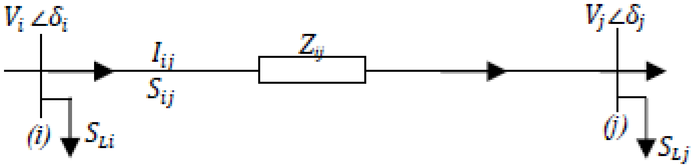

Figure 2.4 One line diagram of a two-bus distribution network [13]

$$VSI(j) = V_i^4 - 4V_i^2\left(P_{Lj}R_{ij} + Q_{Lj}X_{ij}\right) - 4\left(P_{Lj}X_{ij} - Q_{Lj}R_{ij}\right)^2 \qquad (2.13)$$

Where, $VSI(j)$ is the voltage stability index of the receiving end bus, V_i is the magnitude of the sending-end voltage, R_{ij} and X_{ij} represent the line resistance and line reactance respectively. P_{Lj} and Q_{Lj} are the total real load power and total reactive load power fed through node j.

Equation (2.13) can be used to determine the VSI for all the receiving end buses in a radial distribution system. The bus voltages and branch currents can be obtained from load flow studies. Consequently, P_{ij} and PQ_{ij} at the receiving end buses can be calculated. The bus with the minimum VSI is more prone to experiencing voltage instability [13].

(ii) L-index (L)

L-index is used to determine the most unstable buses in a power system. The L-index value is between 0 and 1. The closer the value is to 0, then the more stable the bus and the closer the L-index value to 1 the more unstable the bus. Equation (2.14) shows the L-index formulation. [14]

$$\mathrm{L} = \frac{4[\mathrm{V_i}\,\mathrm{V_j}\cos(\delta_i-\delta_j)-\mathrm{V_j}^2\cos^2(\delta_i-\delta_j)}{\mathrm{V_i}^2} \tag{2.14}$$

Where, $\mathrm{V_i}$ and V_j is the magnitude of the sending end and receiving end voltage respectively, $(\delta_i - \delta_{j)}$ Is the difference in phase angles at the sending and receiving end nodes respectively.

2.1.5 Methods Used to Contain Voltage Instability

Traditionally the following methods have been used to maintain the system's Voltage Stability;

(i) Using an AVR to increase generator's output under varying load conditions. Voltage regulation is achieved faster and efficiently as the regulation cycles are unlimited. The main disadvantage of AVR's is that they are very costly.

(ii) Raising transformer tap changer value so as to increase output voltage when the system is experiencing low voltages and when lowering the tap changer value to reduce the output voltages when there is an overvoltage in the system. Most primary substations have on load tap changers which are efficient and operate automatically based on the output voltage values detected by the relays. For distribution transformers, the tap changers are manually raised or lowered. This may not be timely done and hence result to damage of electrical appliances due to voltage fluctuations before manual intervention.

(iii) Applying load compensation or line compensation through injection of reactive power at an appropriate location by use of capacitors and reactors. They are expensive and require regular maintenance.

(iv) Strategic under frequency load shedding may be applied during low voltage conditions by switching off power supply to some customers. This however is disadvantageous as results in reduced network reliability.

2.2 Effects of RDGs to Voltage Stability

Renewable generation has various advantages over the conventional sources of power which has resulted to increased advocacy for their adoption worldwide. These include;

- They are not exhaustible.
- Minimal or no severe environmental impacts.
- Energy cost reduction.
- Energy security.

Interconnection of renewable sources to the grid adds an extra challenge of ensuring that voltage stability and rotor angle stability of the system is maintained. Frequency stability may be affected by unpredictable imbalances between generation and load as a result of forecast errors. The power injected from RDGs affects the system's power flows in a radial distribution network. When RDGs are located near the load centers and are used to locally provide power to those loads then the distribution line losses are significantly reduced. Reduction of line losses results in reduced voltage drop in the system.

RDGs increase or reduce line losses based on the following factors; their locations, their generation capacities and the size of load and the network topology.

Equation (2.15) gives the "exact loss" formula which gives the total system's real power losses.

$$\sum_{i=1}^{n}\sum_{j=1}^{n}\big\{\propto_{ij}\ (P_iP_j+Q_iQ_j)\big)\}+\Big\{\beta_{ij}\,(Q_i\,P_j-P_iP_j)\Big)\} \qquad (2.15)$$

Where; $\propto_{ij} = \frac{r_{ij}}{V_iV_j}\cos(\delta_i-\delta_j)$ and $\beta_{ij} = \frac{r_{ij}}{V_iV_j}\sin(\delta_i-\delta_j)$ (2.15 a)

And;

$r_{ij}+jX_{ij}=Z_{ij}$ (2.15 b)

Representing the *ij*th elements of [Zbus] matrix [8].

RDGs sources are intermittent as they generate a variable power output. This poses uncertainty challenges to the system controller. Impacts of interconnecting RDGs to the grid cannot be investigated by steady state analysis but by performing a dynamic analysis. In addition, the impacts of RDGs integration to the grid are depended on their penetration level in the system.

RDG penetration level (PL) can determined from equation (2.16) as;

$$PL=\frac{\sum S_{RDG}}{\sum S_{PL}}*100\% \qquad (2.16)$$

Where S_{RDG} is the total complex power generation from the RDG and S_{PL} is the total complex peak load.

Research indicates that locating the RDG units at the load centers can enhance the system's voltage profile of a radial distribution system. The voltage profile can be enhanced further by increasing the RDG sizes. However, the RDG size should be limited by generator regulation to avoid inducing over voltages to the system. As a result, system losses are reduced by proper RDG integration at optimal locations and up to specific optimal penetration levels.

RDG integration alters the voltage profiles of the feeders by increasing voltages near the generating units leading to violation of the acceptable limits. This could trigger the operation of overvoltage protection schemes of the generating units. This thesis covers the effects of integrating PV Solar RDGs and Wind RDGs to the voltage stability of a radial distribution system.

2.2.1 Effects of Integrating PV Solar Sources to the Distribution Grid Voltage Stability

The output of PV Solar sources is at unity power factor with no reactive power component. Equation (2.17) shows the relationship between Power Factor and real and reactive power components based on the power triangle.

$$\cos(\theta) = \frac{P}{\sqrt{(P^2 + Q^2)}} \tag{2.17}$$

Where, $\cos(\theta)$ is the Power Factor, P and Q are the real and reactive power components.

Integration of PV Solar RDGs located at optimal sites in the grid can improve the system's power factor and reduce transmission losses.

Since Reactive power received at the Load node is proportional to the magnitude of voltage drop across a transmission line as seen in equation (2.9), interconnecting PV RDGs to the grid can modify the feeder voltage profiles by causing a significant increase in voltage especially near the generating units leading to violation of the acceptable voltage limits, increased consumer dissatisfaction and undesirable operation of overvoltage protection relays which may necessitate their modification. Also interconnecting large PV Solar RDGs at the end of long distribution lines that have small loads would cause over voltages as explained from the power balance equation (2.18).

$$P_{generated} = P_{load} + P_{losses} \tag{2.18}$$

If PV Solar RDGs are connected at the load centers, the power losses are negligible and can be ignored. Therefore, equation (2.18) can be modified to equation (2.19).

$$P_{generated} = P_{load} \tag{2.19}$$

Therefore, interconnecting large PV Solar RDGs to smaller load centers could result in high voltages at the load centers in a bid to maintain equation (2.19) which could damage the electrical equipment.

Increased penetration of single-phase PV Solar RDG may increase feeder/line currents which would result in major current and voltage imbalances as a result of a significant back feeding in one phase compared to the other two phases. PV Solar sources would result in increased total harmonic distortion (THD) arising from the power electronics interface equipment at the converter stations before connecting them to the grid. These include; as Renewable Energy Storage (RES), Inverter stations, and voltage regulators. Interaction of these equipment and the capacitor banks in the network may cause resonance and hence give rise to THD.

The power output from PV Solar RDGs is intermittent and this poses a challenge to the system controller due to the variability of the source. Increased penetration of PV Solar RDGs can lead to significant back feeding in the system which could affect the operation of over current protection schemes and the operation of the line voltage regulators, specifically those that have been set to forward operation mode. Major back feeding to the substation transformer affects their loading limits.

Optimal PV Solar RDGs penetration at acceptable levels reduce the feeder currents especially in consumer centers where peak loading occurs at day time therefore reducing line losses. A further increase in penetration could increase reverse power flow, line currents, line losses, feeder and equipment loading.

2.2.2 Effects of Integrating Wind Power Sources to the Distribution Grid Voltage Stability

The main challenge associated with wind power generation is voltage variations which result from the following conditions:

(i) Steady state voltage (during continuous power production).
(ii) Voltage fluctuations (Flicker occurring during switching).

Equation (2.20) gives the relationship between the power output from a wind source and the speed of wind:

$$P = \frac{1}{2} \times \rho \times A \times V^3 \tag{2.20}$$

Where; P is the generated power (Watts), ρ is the density of wind/air(Kg/M^3), A is the frontal area and V is the wind velocity (m/s)

Voltage variations could arise from fluctuating frequency and magnitude of power output resulting in light flickering. Voltage flicker can occur in two instances; during continuous wind turbine operation or during generator and capacitor switching. Rapid variations in the wind turbine power output due to variations in the velocity of wind could result to variations in the root mean square value of the voltage. This therefore limits the maximum quantity of wind power that can be connected to the grid.

Wind generating units generate fluctuating power outputs which affects system stability and power quality. If a large proportion of the system's load is supplied by wind RDGs, a voltage fluctuation could arise due to a change in the load mainly where the wind generator is interconnected to the grid at a fixed speed.

Voltage dip is a form of power quality disturbance which affects the operation of sensitive power electronic equipment and industrial processes. It occurs due to adverse weather such as lightening, a large momentarily system's over load and over current faults. When this occurs it could trigger the disconnection of wind generators from the grid resulting in loss of generation and this could adversely affect the system's stability.

Harmonics can be generated at either the generation or load side. They result from nonlinear loads at consumer centers. The current from non-linear loads interacts with the system impedance to generate undesirable (voltage/current) harmonics which cause poor power quality, increased power losses and interference with communication systems. This causes the challenge of limiting the harmonics to acceptable levels at the point of grid integration.

2.3 Voltage Stability with Renewable Energy Sources.

Researchers [14]-[30] have applied various methods in solving the problem of voltage instability in distribution systems with RE sources. Lately, vigorous effort has been applied in the following areas:

(i) Optimal placement or siting of DGs to enhance voltage stability by utilizing various algorithms.
(ii) Optimization methods of controlling and improving bus voltage and current in grid interconnected systems.
(iii) Optimal RES assignment to improve voltage stability with RE penetration.

Optimal RDG placement and location can be formulated as an optimization problem and various algorithms have been applied in solving the problem. These include hybrid techniques incorporating various computational, heuristic and metaheuristic optimization methods. They have mostly combined two artificial intelligence methods or hybridized an artificial intelligent method with a deterministic or heuristic method.

From reviewed literature, most of the hybrid methods gave superior solutions and also improved on the computation time by enhancing the strengths and suppressing the weaknesses of each individual method by avoiding entrapment of the solutions into a local minimum.

2.3.1 Review of Related Works

H. Mantway et al [15] proposed a BPSO method of meeting both the operational and economical requirements of a system while using optimal DG placement to reduce the cost of expanding the distribution system to meet increased loading. This algorithm gave the optimal DG sizes and locations as well as the amount of the power bought from the distribution grid. This method is useful in solving non-continuous problems, however, its main limitation is confinement of solutions to a local optimum.

Parizad et al [16] modelled two scenarios for optimally placing DGs in a distribution system. In the first scenario he applied the exact loss formula to optimally size and site DGs while reducing total real power losses. In the second scenario he applied VSI to determine optimal DG placement in the system. Further, Distribution Power Flow Solution Algorithm which was based on equivalent current injection using bus injection to branch current (BIBC) and branch current to bus voltage (BCBV) matrices was used to size the DGs. These were tested on the IEEE 33 Bus and 30 Bus Systems. Results indicated that the distribution system's power losses were minimized, voltage stability was enhanced and in overall the system's efficiency was improved.
This research work determined optimal placement for Real Power Generating DGs only. It did not consider DGs with both Real and Reactive power generating capability.

N. Jain et al [11] presented a VSI based method for DG siting and a Multi-Objective Particle Swarm Optimization (MOPSO) technique to determine the optimal DG sizing. This method was tested on distribution test feeders with 30 and 41 buses while considering mixed type voltage depended loads. Results indicated that the method was effective for solving DG placement problem, where multiple pareto-optimal solutions were obtained in one simulation run. The solutions represented possible trade-offs between the multi-objective functions index and DG sizes.
This method required short computation time and its limitations were that the DG planner was required to choose one optimal solution from multiple pareto optimal solutions generated, which would effectively satisfy all the optimization goals.

Ziari et al [17] presented an integrated planning method for optimally regulating the power injected by DGs and capacitors in order to reduce power losses, enhance voltage stability and increase system reliability using Hybrid Discrete Particle Swarm optimization (HDPSO) Algorithm. This technique used two GA operators whereby cross over and mutation were applied to half of the population to increase the diversity of the optimizing variable and reduce the risk of confinement of the solution to a local minimum. This algorithm was tested in the IEEE 18 Bus

System and it was the lowest cost planning technique. The shortcoming of this method is that it may not give accurate results due to the risk of entrapment of solutions into a local minimum.

K. Varesi [18] applied a PSO based technique to determine the optimal DG allocation for reduction of line losses and voltage profile enhancement of a distribution system. The method was tested on the IEEE 30 Bus and 33 Bus radial distribution systems. The shortcoming of this method is that solutions may get confined into a local minima.

F. Boulaire et al [19] proposed a simulation framework using Agent-Based Modeling (ABM) and PSO to determine the effect of RDGs on a distribution network for effective economical and sustainable distribution network planning through visualization of the dynamic system and determination of RDGs optimal placement. ABM is a predictive technique which can be applied in complex systems where agents interact with each other and with the environment over a short time period while PSO was applied to determine optimal DG configuration for a long period of time. The ABM and PSO hybrid reduced convergence time.

S. Ram et al [20] applied GA and GSA to determine the optimal location and rating of a Unified Power Flow Controller (UPFC). GA was first used to determine the optimal siting and GSA was later used to optimize the UPFC's ratings to achieve an improvement of the voltage profile. This hybrid was tested on the IEEE-30 Bus test system. This method achieved fast convergence.

Sandeep et al [21] applied a hybrid of optimal power flow (OPF) and Improved Harmony Search (IHS) algorithm to achieve optimal DG placement. The potential locations were obtained by heuristic technique because of their non-monotonic solution surface. The optimal capacity in terms of real and reactive power was obtained using OPF. This method was tested on the IEEE 33-Bus System and the results were compared with Improved Analytical and PSO methods. This method gave quick convergence. The limitation of this hybrid technique is that it could result in premature convergence.

Kanth et al [22] used Sensitivity Analysis to determine optimal DG sites. Further, PSO was used to optimally size the DGs in order to reduce real power losses, THD and improve the system's voltage profile. The proposed hybrid approach was tested on the IEEE 15-Bus System. This method can be used to solve complex multi-objective problems but it has slow convergence and results can be confined into a local minimum. The limitation of this research work is that it did not consider reactive power losses.

Ganguly et al [23] proposed an optimal DG allocation approach using AGA for radial distribution networks while subjected to load and generation uncertainties. The uncertainties were modeled using fuzzy-based technique and optimal DG sites and sizes were determined by reducing power loss and node voltage deviation in the system. Since GA is a meta-heuristic algorithm, the results of multiple runs were taken. The algorithm was tested on the IEEE 33-Bus Test Network and 52-Node Indian Practical Distribution Network. AGA gives improved convergence than basic GA especially in determining solutions of dynamic multi-objective problems and it also finds the global optimum.

Watanabe et al [24] presented an optimal RES assignment approach to enhance voltage stability of a system with the penetration of the renewable energy sources. Energy storage installations in the power system were to mitigate against fluctuations and enhance voltage stability. This research work involved disrupting the power supply from the interconnected RDGs to one node while the other sources supplied the rated power. The problem was formulated to maximize the voltage stability at all the nodes against any RDG supply disruption in the system. Tabu Search (TS) and Differential Evolution (DE) methods were used to solve problem and the method was tested using IEEJ EAST 10-Machine System Model. The limitation of this research work is that it considered power supply disruption at only one node.

The advantage of this method is that TS has an adaptive memory which results to a flexible search pattern and this enables the solutions to escape entrapment in to a local minima. Therefore, it is suitable for solving large complex problems. The limitation of this technique is that the best solution obtained may not be the optimal solution.

Rajendar et al [25] presented a method of optimally placing capacitors using L-Index Sensitivity Matrix so as to improve voltage stability of a radial distribution system. This method was tested on the IEEE 15-Bus System. This work only considered the radial distribution system’s characteristics.

S. Rehma et al [26] used Bat Algorithm to determine optimal siting and sizing of DGs in radial distribution Systems in order to reduce power loss and enhance voltage stability. Total active Power Loss Index was used in the optimization and tested on the IEEE 33-Bus System and IEEE 69-Bus System. This work did not consider reactive power losses.

Z. Xiaozhao et al [27] located and sized dispersed wind generation (DWG) to reduce loss index and enhance voltage stability index on a distribution System. Sensitivity analysis was used to determine the locations and Modern Interior Point Method was applied in DWG sizing. This method was tested on PG & E69 Node System.

S. Hadavi et al [28] developed a new VSI to determine the weak bus that was proximate to voltage collapse in the radial distribution system for optimal DG allocation in order to enhance the network's voltage stability margin. Genetic Algorithm optimization technique was used and tested on the IEEE 33-Bus system and the IEEE 19-Bus System.

S. Hyoung et al [29] presented a method of optimally sizing multiple DGs to reduce power loss by using Reduced Multivariate Polynomial Model and Lagrange Multiplier Method. The method was tested on IEEE 31 Bus System.

S. Katamble et al [30] used the Fuzzy Logic technique to determine the optimal DG location in the IEEE 14-Bus System while Analytical Approach was used to determine the DG size. This work involved locating and sizing a single DG unit.

2.3.2 Summary of reviewed works

Table 2.1 gives a summary of the reviewed works, the techniques used and the research gaps identified.

Table 2.1 Summary of the Reviewed Works

Research work	Objectives	Technique/Method used	Gaps
H. Mantway et al [15]	Use of DGs as an alternative for distribution system planning and satisfy both the operational and economical requirements of the distribution system	Binary Particle Swarm Optimization (BPSO)	This work did not consider real and reactive power losses
Parizad et al [16]	Improvement of Voltage Profile and minimization of power loss	Distribution Power Flow Solution Algorithm	Considered active power losses only.
N. Jain et al [11]	Minimization of DG Size, reduction of real and reactive Line Loss Index (SLIP and SLIQ), improvement of System Voltage Performance Index (SVPI) and reduction of System Gas Emission Index (SGEI)	Multi Objective Particle Swarm Optimization (MOPSO)	Gave multiple Pareto-optimal solutions.
Ziari et al [17]	Minimization of line losses, maximization of System reliability and improvement of the voltage profile	Hybrid Discrete Particle Swarm Optimization (HDPSO)	Solutions may get confined into a local minima
K. Varesi et al [18]	Determination of optimal type, location and size of DGs to enhance voltage profile and minimise power loss in a distribution system	Particle Swarm optimization (PSO)	Solutions may get confined into a local minima
F. Boulaire et al [19]	Determination of the most economical DG configuration in a distribution system over a long time period	Agent Based Modelling (ABM) and Particle Swarm Optimization (PSO)	Required long computational time
S. Ram et al [20]	Improvement of transmission system's voltage stability by determining optimal locations of the UPFC	Genetic Algorithm (GA) and Gravitational search Algorithm (GSA)	Did not consider all DG types at distribution system level

Research work	Objectives	Technique/Method used	Gaps
Sandeep et al [21]	Minimization of power losses	Optimal Power Flow (OPF) Algorithm and Improved Harmony Search (IHS).	Premature convergence could occur
Kanth et al [22]	Minimization of real power loss, THD and voltage profile improvement	Particle swarm Optimization and Sensitivity Analysis	Did not consider reactive power losses.
Ganguly et al [23]	Reduction of power loss and node voltage deviation in the network	Adaptive Genetic Algorithm (AGA)	Faster convergence and able to get the global optimum
Watanabe et al [24]	Improvement of voltage stability	Tabu Search (TS) and Differential Evolution (DE)	Fast convergence but may give non-optimal results
Rajendar et al [25]	Voltage stability improvement	L-Index Sensitivity Matric	Considered the radial distribution system's characteristics
S. Rehma et al [26]	Reduction of power loss and enhancement of voltage stability	Bat Algorithm	Solutions may get stuck in a local optimum
Z. Xiaozhao et al [27]	Loss Index Reduction and Voltage Stability Index enhancement	Sensitivity Analysis and Modern Interior Point Method	Considered wind powered DGs only
S. Hadavi et al [28]	Active power loss reduction and improvement of the System's voltage stability margin	Genetic algorithm	Did not consider reactive power loss, DG investment and operational costs
S. Hyoung et al [29]	Minimization of power loss	Reduced Multivariate Polynomial Model RPM) and Lagrange Multiplier Method (LMM)	Did not consider reactive power loss
S. Katamble et al [30]	Total power loss reduction and enhancement of system's voltage profile	Fuzzy logic method and Analytical Approach	Only considered locating and sizing only one DG unit

Research work	Objectives	Technique/Method used	Gaps
This work	Reduction of total line losses and total voltage deviation	Index Based Planning, Adaptive Genetic Algorithm and Simulated Annealing	Considered both real and reactive power losses, effective in locating and sizing two RDGs and RES.

2.3.3 Research Gap

From the literature reviewed, most researchers solved the problem of improving power system's voltage stability through reactive power compensation devices such as optimally placed of FACTS, SVCs and static capacitors. Other researchers had applied Under Frequency Load Shedding (UFLS) and optimal sizing and siting of DG units.

Use of RDGs is an emerging trend mainly because of the increased advocacy for clean energy so as to minimize carbon emissions from thermal power plants. Furthermore, they can generate both active and reactive power. RDGs power output varies with time and hence optimal allocation of RES devices should be incorporated to enhance stability and also cater for both generation and load variations in the system.

This thesis considered grid interconnected PV solar and wind RDGs. Based on the reviewed literature, no published work had solved the problem of optimal RDG placement and sizing while considering integration of both wind and PV solar sources and incorporating RES assignment in the distribution system simultaneously so as to achieve voltage improvement. Both wind and solar sources and their impacts on the system's real and reactive powers were considered in this research work. Previously, most researchers solved the optimization problem while considering only real power losses. This thesis considered both real and reactive power losses.

To obtain more practical results the problem of RDG placement and sizing was tied to the problem of optimal RES assignment during the optimization process.

2.4 Problem Formulation

With the trend of increasing electrical load as a result of increased industrialization in Kenya, the Power System should expand proportionately based on the new demand rates and future forecast. Based on reviewed literature, RDGs can be interconnected at/near the load centers to improve the power quality in areas where voltage support by grid is a challenge.

This work involved analyzing the existing network with regards to determine the most volatile nodes using Index based planning. With the injection of RDGs, the voltage profile improved and there was a reduction of the total line losses. RDGs and RES also created a reserve capacity in the system.

The formulation considered two objective functions; Total Voltage Deviation and Total Line Losses. This thesis solved the multi-objective problem of improving the system's voltage stability and reducing the total line losses through optimally sizing and siting of the RDG units while incorporating optimal RES allocation in a radial distribution system.

Sections 2.41 and 2.42 describe the details of the problem formulation:

2.4.1 Voltage Stability Index (VSI)

In this thesis, VSI was used to determine the nodes that were more sensitive to voltage collapse [13] using equation (2.21).

$$VSI(j) = V_i^4 - 4V_i^2\left(P_{Lj}R_{ij} + Q_{Lj}X_{ij}\right) - 4\left(P_{Lj}X_{ij} - Q_{Lj}R_{ij}\right)^2 \tag{2.21}$$

Where, $VSI(j)$ is the voltage stability index of the receiving end bus, V_i is the magnitude of the sending-end voltage, R_{ij} and X_{ij} represent the line resistance and line reactance respectively. P_{Lj} and Q_{Lj} are the total real load power and total reactive load power fed through node j.

2.4.2 Renewable Energy Storage sizing.

Lead-acid batteries were considered in this research work based on the following rationale:

(i) They can withstand high discharge rates.

(ii) Have a longer lifecycle when properly maintained.
(iii) The lead can be recycled and used in new batteries.
(iv) Low investment cost.
(v) Performance is not affected by temperature.
(vi) They have the lowest self-discharge as compared to other rechargeable batteries.
(vii) They are easy to maintain due to the increased experience with these batteries over time.

They however, have the following short comings;

(i) They should not be stored in a discharged state.
(ii) They are heavy and bulk.
(iii) A lead acid battery gets destroyed fast when discharged below 50 % of its capacity.

Therefore, a factor of 1.5 is used for lead-acid batteries because all the power stored in a battery cannot be drawn at once.

RES was allocated based on the relation.

$$J_{BS} = 1.5 \times \sum_{i=1}^{N} (P_D \times T) \tag{2.22}$$

Where, J_{BS} is the RES size in KWh, P_D *is* the total load or demand on the i^{th} branch, T is the charging time in hours.

2.4.3 Objective Functions

The following two objective functions were combined to formulate the multi-objective function used in the optimization process. These include:

(i) Total voltage deviation (J_{TVD})

$$J_{TVD} = \sum_{i=1}^{N} |1 - V_i| \tag{2.23}$$

Where, i=1, 2, 3….N are the node/bus numbers and V_i is the per unit voltage at the nodes.

(ii) Total line losses (J_{TLL}) [31]

$$J_{TLL} = \sum_{i=1}^{B} (R_k + jX_k)|I_l|^2 \tag{2.24}$$

The magnitude of total line losses can be obtained from equation (2.20)

$$J_{TLL} = \sum_{i=1}^{B} \sqrt{{R_k}^2 + {X_k}^2} * \frac{{P_k}^2 + {Q_k}^2}{|V_k|^2} \tag{2.24 a}$$

Where, $\mathrm{R_k}$ and $\mathrm{X_k}$ are the resistance and reactance of the $\mathrm{k^{th}}$ branch and B is the total number of branches in the system,P_k and $\mathrm{Q_k}$ are the real and reactive powers at the sending end of the k^{th} branch and $\mathrm{V_k}$ is the voltage at the sending end of the $\mathrm{k^{th}}$ branch.

For a node with a DG unit integrated the total line loss equation can be written as shown in equation (2.24 b).

$$J_{TLL} = \sum_{i=1}^{N} \sqrt{{R_k}^2 + {X_k}^2} * \frac{(P_k + P_{kDG})^2 + (Q_k + Q_{kDG})^2}{|V_k|^2} \quad (2.24\ \mathrm{b})$$

Where, P_{kDG} and Q_{kDG} are the real and reactive powers of the DG at the sending end of the k^{th} branch and V_k is the voltage at the sending end of the k^{th} branch.

The following constraints were considered;

(i) Bus voltage limits shall be maintained within the standard levels

$$0.95\, p.u \leq V_i \ \leq 1.05\, p.u \quad (2.25)$$

(ii) Real and reactive power output capacity constraints

$$P_{DG\,min} \leq P_{DG} \leq P_{DG\,max} \quad (2.26)$$

$$Q_{DG\,min} \leq \ Q_{DG} \leq Q_{DG\,max} \quad (2.27)$$

Where, $P_{DG\,min}$ and $P_{DG\,max}$ are the minimum and maximum active power limits and $Q_{DG\,min}$ and $Q_{DG\,max}$ are the minimum and maximum reactive power limits respectively.

(iii)Power flow constraints

$$P_{Gi} - P_{Di} = \sum_{k=1}^{N} V_i\, V_k \{G_{ik} \cos(\delta_i - \delta_k) + B_{ik} \sin(\delta_i - \delta_k)\} \quad (2.28)$$

$$\mathrm{Q_{Gi} - Q_{Di} = \sum_{k=1}^{N} V_i\, V_k \{G_{ik} \sin(\delta_i - \delta_k) - B_{ik} \cos(\delta_i - \delta_k)\}} \quad (2.29)$$

Where, P_{Gi}-P_{Di} is the active power injected and Q_{Gi}-Q_{Di} is the reactive power injected at a bus, G_{ik} and B_{ik} represent the conductance and susceptance of the line between buses i and k.

(iv)Renewable Energy Storage constraints;

This was determined based on wind and PV solar capacity factors. According to the U. S. Energy Information Administration the capacity factor (C.F) for wind and PV Solar was 34.6% and 25.1%

respectively in 2018 [32]. This was used to determine charging time (T) for both wind and PV Solar Generators.

$$T \leq 24\ Hrs * C.F \tag{2.30}$$

For Wind Generators: $T \leq 8.304\ Hrs$ (2.30 a)

And for PV Solar Generators: $T \leq 6.024\ Hrs$ (2.30 b)

The Multi-objective function was formulated by assigning weights using the weighted sum approach to the two single objective functions as shown in equation (2.30). The weights represent the PV Solar and Wind RDGs penetration levels.

$$F = W_1 JTLL + W_2 JTVD \tag{2.31}$$

Where $0 \leq \mathrm{W}_1 \leq 1$ and $\mathrm{W}_1 + \mathrm{W}_2 = 1$

2.5 Chapter Conclusion

For the first time, a constrained two-objective function was formulated to solve the problem of voltage stability with RDG penetration with optimal RES allocation while taking into consideration both the real and reactive line losses. The following chapter describes the methodology and a detailed review of the three method hybrid used in this thesis.

CHAPTER 3

3 RESEARCH METHODOLOGY

This chapter gives a detailed description of the methods used in solving the multi objective function aimed at reducing total line losses and total voltage deviation simultaneously. The methods used was a three method hybrid of Index Based Planning, Adaptive Genetic Algorithm and Simulated Annealing (IBP-AGA-SA).

3.1 Previous Methods

Table 3.1 gives the methods that have been used from previous reviewed literature:

Table 3.1 A Review of Previous Methods

Research work	Technique/Method used
H. Mantway et al [15]	Binary Particle Swarm Optimization (BPSO)
Parizad et al [16]	Distribution Power Flow Solution Algorithm
N. Jain et al [11]	Multi Objective Particle Swarm Optimization (MOPSO)
Ziari et al [17]	Hybrid Discrete Particle Swarm Optimization (HDPSO)
K. Varesi et al [18]	Particle Swarm optimization (PSO)
F. Boulaire et al [19]	Agent Based Modelling (ABM) and Particle Swarm Optimization (PSO)
S. Ram et al [20]	Genetic Algorithm (GA) and Gravitational search Algorithm (GSA)
Sandeep et al [21]	Optimal Power Flow (OPF) Algorithm and Improved Harmony Search (IHS).
Kanth et al [22]	Particle swarm Optimization and Sensitivity Analysis
Ganguly et al [23]	Adaptive Genetic Algorithm (AGA)
Watanabe et al [24]	Tabu Search (TS) and Differential Evolution (DE)
Rajendar et al [25]	L-Index Sensitivity Matric
S. Rehma et al [26]	Bat Algorithm
Z. Xiaozhao et al [27]	Sensitivity Analysis and Modern Interior Point Method
S. Hadavi et al [28]	Genetic algorithm
S. Hyoung et al [29]	Reduced Multivariate Polynomial Model RPM) and Lagrange Multiplier Method (LMM)
S. Katamble et al [30]	Fuzzy logic method and Analytical Approach

From reviewed literature, no previous work has used the three method hybrid of Index Based Planning, Adaptive Genetic Algorithm and Simulated Annealing in solving the problem of improving the Distribution System's voltage stability with RDGs.

3.2 Three Method Hybrid

Sections 3.2.1-3.2.3 give a clear description of the Three Method Hybrid used in this thesis.

3.2.1 Index Based Planning (IBP)

Index based planning involves the use of various indices so as to solve a system problem. In this research work Voltage Stability Index (VSI) was applied to determine the weak buses. Equation (2.13) was applied to determine the weakest buses which were included as the candidate buses in AGA.

3.2.2 Genetic Algorithm (GA)

Genetic Algorithm uses biologically inspired techniques which involve natural selection, genetic inheritance, mutation, and crossover in determining an optimal solution.

(i) Natural selection involves obtaining suitable individuals from a given population which will be involved in reproduction by applying the fitness criteria.
(ii) Mutation involves transformation of the chromosomes.
(iii)Crossover is the swapping of genetic material.

The initial population of GA comprises of individuals that are generated randomly based on some probability distribution. This population is subsequently updated in a stepwise approach referred to as generations. Natural selection is applied on the various individuals obtained from the generations depending on a fitness criterion. These individuals then crossover and mutate to create a new population set. Figure 3.1 shows a basic GA flow chart.

3.2.2.1 Steps of GA implementation

(i) Initial Population

In GA it is important to determine the optimal size of initial population and the criteria of selecting the suitable individuals. Selecting a small initial population size, would not give sufficient room for exploration of the search space and selection of a very large initial population reduces the efficiency of obtaining the optimal solution. In order to enhance efficiency, population seeding can be adopted. Seeding comprises of the addition of some good solutions to the initial population or adding a better quality solution from another optimization technique. Population seeding could however result to premature convergence if not carefully done [34].

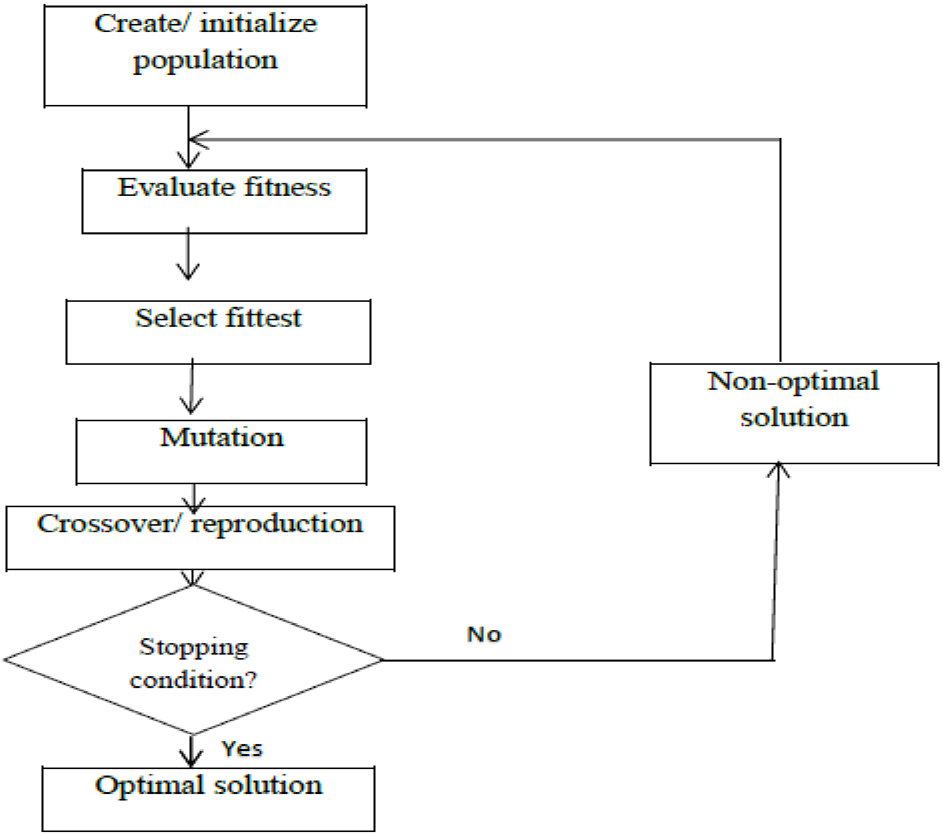

Figure 3.1 Genetic Algorithm Flow Chart [33]

(ii) Selection

Selection was originally done using roulette-wheel method which uses probability distribution to determine a suitable measure of fitness for all the individuals in the population.

(iii) Crossover

Crossover involves replacing some of the genes of one parent by the corresponding genes of the other parent.

(iv) Mutation

This is performed before any cross over to help in preserving diversity of the population. Mutation helps in reducing entrapment in to sub-optimal regions of the solution space. Adaptive mutation can be adopted in relation to mutation rates and population size to enhance efficiency.

(v) New population

The particle selection, mutation and crossover are repeatedly performed on the population until a new generation is obtained which is then taken as the new population. An elitist strategy can be applied so as to ensure only survival of the best individuals. These individuals are preserved while the rest of the individuals get to be replaced with new ones. The overlapping populations replace only a small fraction of the population (*generation gap*) during each generation.

The advantages of GA include the following:

(i) The solutions are resistant to being trapped into a local optima.
(ii) It can scan a vast solution set quickly.
(iii) Bad proposals are discarded and hence do not negatively affect the end solution.
(iv) It works by its own internal rules and hence it is not dependent on the program rules.

At first, voltage sensitivity index (VSI) was used to determine the sensitive buses for locating RDGs and RES, AGA was further used to size the RDGs and RES allocations, then simulated annealing was later used in the optimization process for exploitation. In this thesis the GA was made AGA through achieving adaptive mutation probability. Table 3.2 shows the mapping of parameters in Adaptive Genetic Algorithm.

Simulated annealing was used to further optimize the results from AGA.

Table 3.2 Mapping of AGA parameters

Parameter	**Meaning**	**Value**
Initial population	Refers to the initial number of chromosomes	50
Chromosome	A possible solution	50
Gene	Information contained in a chromosome.	Included: RDG and RES location and size.
Iteration	Movement to the next generation that will give rise to a possible solution.	Maximum iterations, I=10
Mutation probability (M)	0 < M < 1	$M_0 = 0.01$ To achieve adaptive mutation this value shall be varied as follows; $M = M_0 + \propto M_o$ Where; $\propto = \frac{k}{I}$ Where k is the bus number and I, is the maximum number of iterations
Crossover	Replacing some of the genes of a chromosome by the corresponding genes of the other chromosome	
Crossover probability (C)	0 < C < 1	0.85

3.2.3 Simulated Annealing (SA)

Simulated Annealing is a meta-heuristic algorithm that is capable of escaping entrapment in to a local optima using hill-climbing moves. It can be used to solve either discrete or continuous problems, multi-objective complex problems [34].

Annealing involves naturally cooling a molten liquid to form perfect crystals under a thermal equilibrium state. Annealing principle was applied 1980s to solve optimization problem with the Metropolis Algorithm being taken as the basis of SA algorithm. Any material is made of up of several particles with different energy levels, based on a probability distribution and depending on their temperature (T). The algorithm generates a new state from the initial state with energy, E by a mechanism involving a small change in the initial state. Various state transitions are performed before reaching at the optimal state. SA consists of two basic main steps;

(i) Specifying generation of states.
(ii) Determining the acceptance probability functions and the cooling schedule.

The main demerit of SA is that it requires high computation time.

Figure 3.2 shows Simulated Annealing (SA) flow chart.

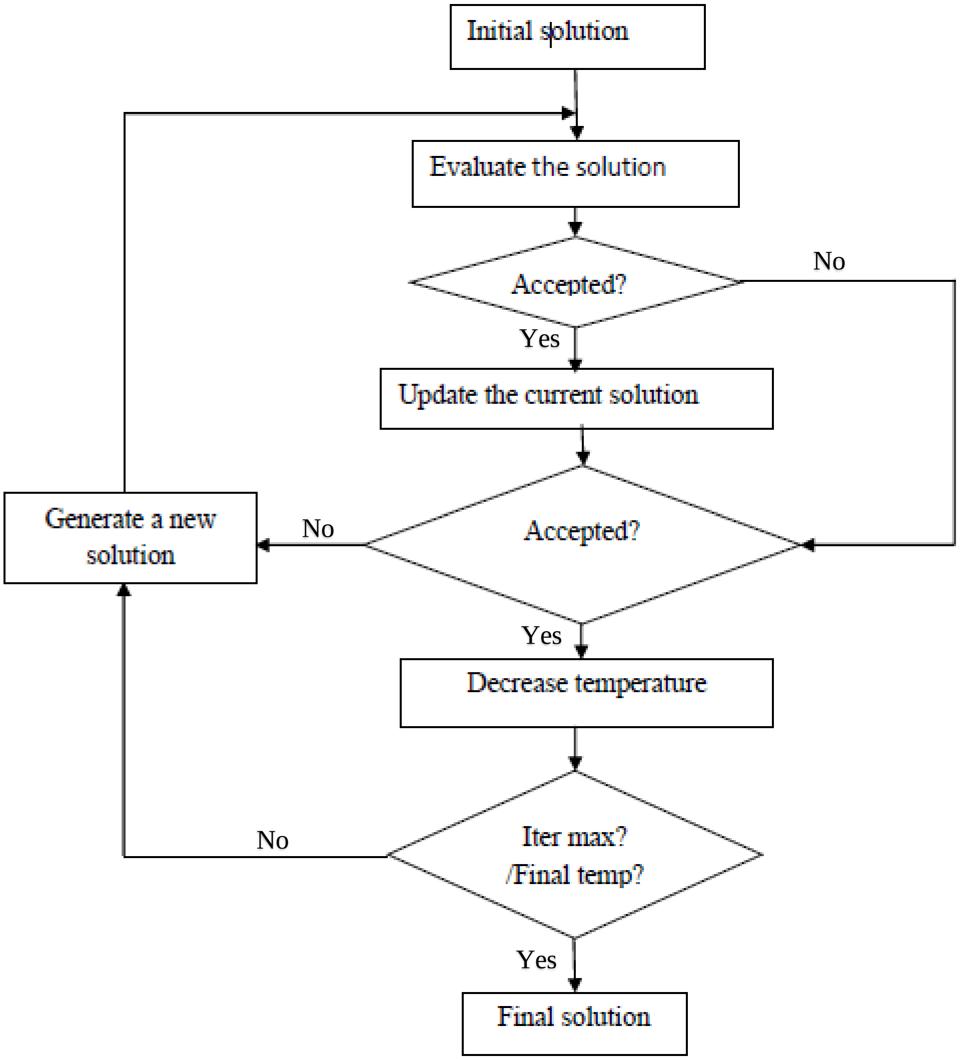

Figure 3.2 Simulated Annealing (SA) Algorithm Flow Chart [33]

SA parameter mapping is shown in Table 3.3.

Table 3.3 Mapping of SA parameters

Parameter	Meaning	Value
Initial population	Initial particle size (the result from AGA).	50
Particle	A possible solution	50
Temperature	RDG size (varied to achieve an optimal solution).	Initial temp=0.95 Final temp=0.025
Probability (P)	$0 < \alpha < 1$	Cooling coefficient=0.95
Cooling process or schedule	The iterative process.	Iterations=50
Cooling rate (r)	Rate of change of the solution (0<r<1)	r=0.9

Figure 3.3 shows a combined flow chart for the three method hybrid:

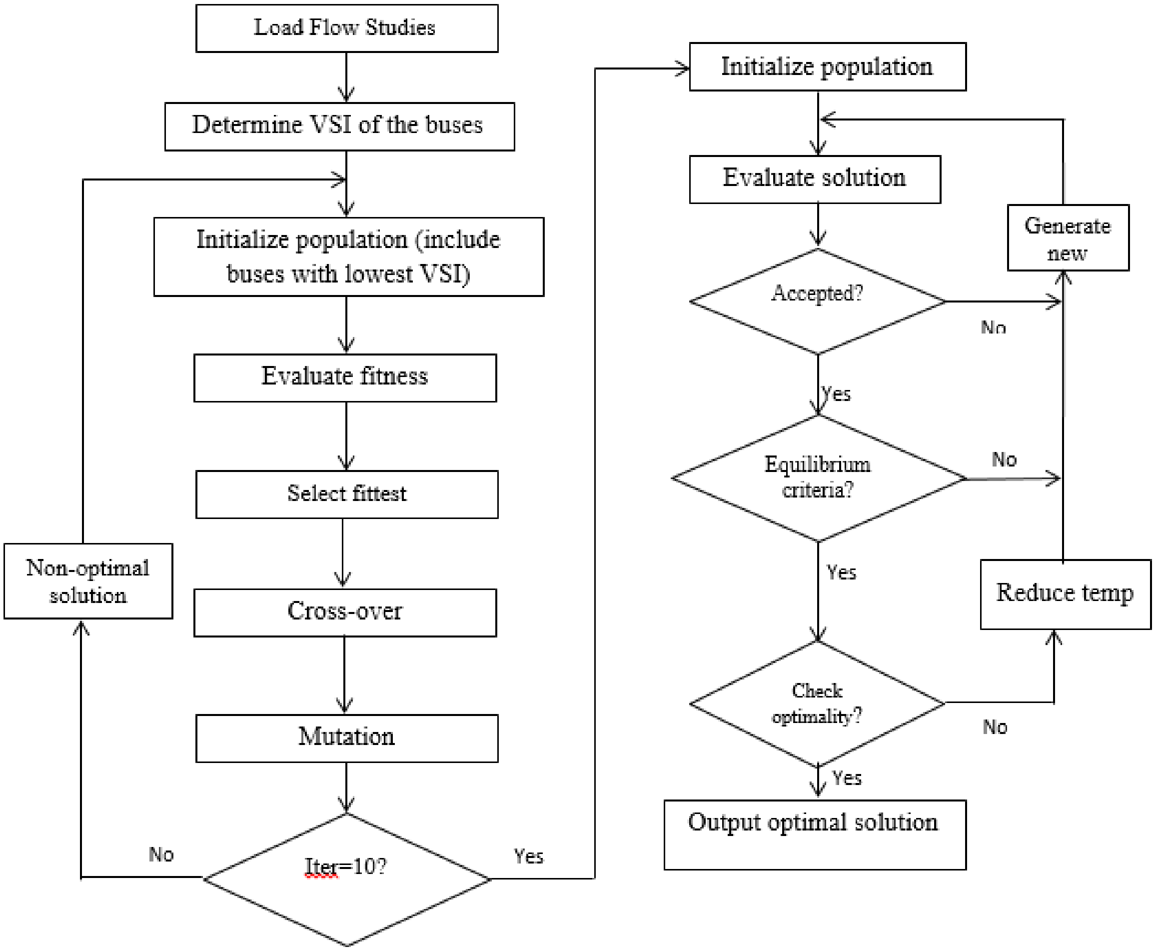

Figure 3.3 IBP-AGA-SA Algorithm

Newton Raphson Load flow method was applied to perform load flow studies of the IEEE 33-Bus system in order to determine the system's total line losses and total voltage deviation base values. Then Index based planning was used to determine the volatile buses that were susceptible to voltage collapse. The buses were selected as the possible locations for RDGs and RES. AGA and SA were further used to determine the optimal sizes of the RDGs and RES.

3.3 Chapter Conclusion

A three method approach has been presented for solving the two objective functions formulated in Chapter 2. The three method hybrid was considered because no reviewed literature had used the Algorithm and it was suitable for intermittent sources of generation, and was able to work well with both discrete and continuous parameters and avoid entrapment of solutions in a local optima. Based on the strengths of this method, the IBP-AGA-SA Algorithm is more superior to the reviewed methods and was therefore able to produce high quality and reliable results with fast convergence. The following chapter contains, results and analysis together with the validation of the developed algorithm.

CHAPTER 4

4 RESULTS AND ANALYSIS

This chapter contains the analysis of optimization (simulation) results obtained from the three method hybrid and the validation in the IEEE 33 Bus system using MATLAB.

4.1 Results and Analysis

The results of this research work were obtained and analyzed as follows:

(i) The base voltage profile and line losses at the buses in the system without integrating any RDGs.
(ii) The voltage profile and line losses at the buses in the system after incorporation of one, two and three PV Solar or Wind RDGs was obtained from the three method approach with W1=W2 (this denotes equal penetration of both PV solar RDGs and wind RDGs)
(iii)The results obtained were compared to those published by other researchers.

4.2 IEEE 33 Bus System Test Results

The base values of JTLL and JTVD were obtained as 0.2192MW and 0.1593 p.u approximately. The VSI for both the IEEE 33 Bus system is shown in Appendix A. The five critical buses in the IEEE 33-Bus system were found to be; 18, 17, 16 33 and 32 respectively and were therefore considered for RDG and RES placement. Optimal RDG sizing was done using AGA and SA and analyzed in the following cases;

(i) Incorporating Wind DGs only: Generating both active and reactive power.
(ii) Incorporating PV solar DGs only: Capable of generating active power only.
(iii) Incorporating STATCOMs: Capable of generating reactive power only.

The results for these cases were obtained with W1=W2. The weights represents the RDG penetration with W1 and W2 being equal, then there is equal penetration of both PV solar RDGs and wind RDGs.

The results from these were tabulated in Appendix B.

4.2.1 Results with one RDG placed at the most volatile Bus.

To solve the multi-objective function with both JTLL and JTVD being achieved simultaneously the weights were set at 0.5 each. The weakest Bus was found to be Bus 18 with a VSI of 0.6864 and hence the RDG was placed there. AGA and SA methods were used on the IEEE 33-Bus distribution system using MATLAB in order to determine the optimal RDG size for the three cases stated above when, W1=W2 to ensure that both objectives were achieved simultaneously and the results obtained were as shown in table 4.1.Variation of weights would affect the RDG penetration levels for both PV solar RDGs and wind RDGs.

Table 4.1 Optimal DG size, JTLL and JTVD with one RDG at Bus 18

Type	Bus	RES (KWh)	P (MW)	Q (MVAR)	JTLL	JTVD	%∆JTLL	%∆JTVD
Wind	18	1,121	1.5611	0.9366	0.0895	0.0782	59%	51%
PV solar	18	812	2.0414	-	0.099	0.071	55%	55%
STATCOM	18	-	0	2.3173	0.2196	0.0781	17%	50%

The results indicated that a wind RDG was most suitable where only one RDG is to be incorporated into the network. This is because it enhanced the system performance by reducing the JTLL by 59% and the JTVD by 51%. Incorporating a PV solar RDG reduced the JTLL by 55% while the JTVD would be improved by 55% whereas, if a STATCOM DG was incorporated at Bus 18 then the reduction in JTLL would be 17% and the improvement in JTVD would be 50%. Therefore installation a wind RDG at bus 18 would give superior results compared to a PV Solar RDG and a STATCOM installed at the same bus.

4.2.2 Results with two RDGs placed at the two most volatile Buses.

The two weakest buses that were considered for RDG placement were Bus 18 and Bus 17. From the results. The first RDG was a wind RDG located at Bus 18. A wind RDG, PV Solar RDG and a STATCOM RDG were each integrated at Bus 17 and the most effective RDG type was selected as the optimal type. Table 4.2 shows the results of having 2 wind RDGs placed at the two most volatile buses.

Table 4.2 Optimal DG sizes for a system with two wind RDGs.

Type	Bus	RES (KWh)	P (MW)	Q (MVAR)	JTLL	JTVD	%ΔJTLL	%ΔJTVD
Wind	18	1,121	1.5611	0.9366	0.0866	0.0806	60%	49%
Wind	17	746	0.08	0.048				

When two optimally sized wind RDGs were incorporated into the IEEE 33 Bus system, one at Bus 18 and the other at Bus 17 the TLL and TVD were reduced by 60 % and 49% respectively from the base values. Table 4.3 shows the results of having two types of RDGs, a wind, placed at the bus with the lowest VSI and a solar PV RDG placed at the bus with the second lowest value of VSI.

Table 4.3 Optimal DG sizes for a system with two RDGs, wind and PV Solar

Type	Bus	RES (KWh)	P (MW)	Q (MVAR)	JTLL	JTVD	%ΔJTLL	%ΔJTVD
Wind	18	1,121	2.0376	1.0769	0.0861	0.0812	61%	49%
PV solar	17	542	0.1456	0				

Installation of a PV Solar RDG at Bus 17 after the installation of a wind RDG at Bus 18 resulted in a slight increase in the reduction of TLL while the TVD remained unchanged.

4.2.3 Results with three RDGs.

The first two types of RDGs shown in table 4.3 were installed and the third RDG size was obtained using the algorithm. The third RDG was placed at Bus 16 which is the third weakest Bus after buses 18 and 17.

Table 4.4 shows the results of having three types of RDGs, two wind RDGs and one PV Solar RDG.

Table 4.4 Optimal DG sizes for the system with 3 RDGs, two wind and one PV Solar RDG

Type	Bus	RES (KWh)	P (MW)	Q (MVAR)	JTLL	JTVD	%ΔJTLL	%ΔJTVD
Wind	18	1,121	2.0376	1.0769	0.861	0.812	61%	49%
PV Solar	17	542	0.1456	0				
Wind	16	746	0.0	0.0				

Tables 4.5 shows the results of having three RDGs, one wind RDG and two PV Solar RDGs.

Table 4.5 Optimal DG sizes for the system with three RDGs, one wind and two PV Solar RDGS

Type	Bus	RES (KWh)	P (MW)	Q (MVAR)	JTLL	JTVD	%ΔJTLL	%ΔJTVD
Wind	18	1,121	2.0376	1.0769	0.861	0.812	61%	49%
PV solar	17	542	0.1456	0				
PV solar	16	542	0.0	0				

The results from tables 4.4-4.5 shows that it would not be necessary to incorporating a third RDG at Bus 16 because the solution had been fully optimized.

System performance was optimized by having two RDGs, a wind RDG at Bus 18 and a PV Solar RDGs at Bus 17. There was no further reduction in JTLL and JTVD.

The main hindrance to adoption of RES together with DGs is their cost. From previous research works, Lead Acid Batteries have been shown to have lower costs compared to other types of energy storage devices at $150/KWh while Lithium ion batteries have a cost of $200/KWh [35].

4.3 Comparison of the results with other research works.

The results obtained from the three method hybrid Algorithm was compared to the results obtained using Particle Swarm Optimization technique presented by K. Varesi [18] and also to results from a two method hybrid of Optimal Power flow and Improved Harmony Search (OPF and IHS) presented by Sandeep Kaur [21].

4.4 Validation Method

The methodology was tested on the IEEE 33 Bus radial distribution systems at the system loading. Intermittency nature of the renewable DGs was solved by the using optimally sized RES located at the same points as the RDGs. Results obtained were compared with the results from K Varesi's work [18] and Sandeep Kaur's work [21] were found to be superior. The algorithm was written using MATLAB software.

4.4.1 Results with only PV Solar RDGs integrated.

Tables 4.6-4.9 show the results from the three method hybrid tested in this research work compared with other research works. Table 4.6 gives optimal RDG sizes for all the five candidate buses with PV Solar RDGs only.

Table 4.6 Optimal RDG sizes for all candidate Buses with PV Solar RDGs

Bus No.	DG SIZE		JTLL (MW)	%ΔJTLL	JTVD	%ΔJTVD
	P (MW)	Q (MVAR)				
16	0.7813	-	0.174	-21%	0.11	-31%
17	1.0744	-	0.1697	-23%	0.09	-44%
18	2.0414	-	0.099	-55%	0.071	-55%
32	1.6311	-	0.1495	-32%	0.0879	-45%
33	3.5635	-	0.0824	-62%	0.0608	-62%

Results showed that installing a PV Solar RDG at Bus 33 enhanced system performance the most by reducing total line losses and total voltage deviation by 62 % and 62% respectively. Therefore Bus 33 was considered to be the most suitable site for the placement of the first PV Solar RDG.

Table 4.7 shows the results obtained with one PV Solar RDG integrated compared with other research works.

Table 4.7 JTLL and JTVD after placement of one PV Solar RDG

Method	Bus No.	RES (KWh)	DG SIZE (MW)	JTLL (KW)	%ΔJTLL	JTVD	%ΔJTVD
PSO [18]	6	-	2.59	112	47%	-	-
OPF and IHS [21]	6	-	2.59	111.1	47%	-	-
VSI, AGA and SA (This method)	33	542	3.5635	82.4	62%	0.0608	62%

The three method hybrid gave more superior results compared to PSO and a two method hybrid of OPF and IHS. The total line losses were reduced by 62% compared 47% reduction using PSO and a two method hybrid of OPF and IHS. The system’s total voltage deviation was also reduced by 62%.

Table 4.8 shows the results obtained with two PV Solar RDGs integrated with other research works.

This method gave a higher reduction in JTVD with incorporation of two PV Solar RDGs compared to having only one PV solar RDG incorporated. When two PV Solar RDGs were integrated into the system the total voltage deviation was reduced by 73% compared to the 62% reduction that was achieved with the incorporation of one PV Solar RDG.

Table 4.8 Placement of two PV Solar RDGs

Method	Bus No.	RES (KWh)	DG SIZE (MW)	JTLL(KW)	%∆JTLL	JTVD	%∆JTVD
PSO [18]	6	-	2.59	96.1	54%	-	-
	15	-	0.473				
OPF and IHS [21]	13	-	0.85	87.16	59%	-	-
	30	-	1.15				
VSI, AGA and SA (This method)	33	542	3.5635	82.9	62%	0.0427	73%
	18	813	0.5434				

Table 4.9 shows the comparison of the results obtained with three PV Solar RDGs integrated with other research works.

Table 4.9 Placement of three PV Solar RDGs

Method	Bus No.	RES (KWh)	DG SIZE (MW)	JTLL (KW)	%∆JTLL	JTVD	%∆JTVD
PSO [18]	6	-	2.59	88.6	58%	-	-
	15	-	0.473				
	25	-	0.637				
OPF and IHS [21]	13	-	0.8	72.8	66%	-	-
	24	-	1.09				
	30	-	1.05				
VSI, AGA and SA (This method)	33	542	3.5635	82.9	62%	0.0427	73%
	18	813	0.5434				
	16	542	0.0012				

VSI-AGA-SA gave a higher reduction in total line losses in comparison with PSO method only. The total line losses were reduced by 62% which is lower compared to 66% reduction using OPF and IHS hybrid. There total line losses and the total voltage deviation was not improved by the incorporation of a third PV Solar RDG compared to that of the system with two PV Solar RDGs integrated. Therefore the proposed method can be used to effectively site and size only two PV Solar RDGs and achieve the same system performance that would be achieved with incorporation of three PV Solar RDGs located using PSO only or a two method hybrid of OPF and IHS leading to reduced investment costs.

4.4.2 Results with only wind RDGs integrated.

Tables 4.10-4.12 shows a comparison of the results obtained with incorporation of one, two and three wind RDGs to other research works.

Table 4.10 Placement of one wind RDG

Method	**Bus**	**RES (KWh)**	**DG SIZE**		**JTLL(KW)**	**%∆JTLL**	**JTVD**	**%∆JTVD**
			P (MW)	**Q (MVAR)**				
PSO [18]	6	-	2.551	1.755	68	68%		
OPF and IHS [21]	6	-	2.554	1.761	67.854	68%		
VSI, AGA and SA (This method)	33	747	2.4515	1.7568	62.2	72%	0.0652	59%

The proposed three method hybrid gave a 72% reduction in JTLL and a 59% reduction in JTVD compared to 68% line loss reduction obtained from both PSO and two method hybrid of OPF and IHS algorithms.

Table 4.11 Placement of two wind RDGs

Method	**Bus**	**RES (KWh)**	**DG SIZE**		**JTLL(KW)**	**%∆JTLL**	**JTVD**	**%∆JTVD**
			P (MW)	**Q (MVAR)**				
PSO [18]	6	-	2.551	1.755	52	75%	-	-
	15	-	0.463	0.272				
OPF and IHS [21]	12	-	0.91	0.49	29.48	86%	-	-
	30	-	1.2	0.9				
VSI, AGA and SA (This method)	33	747	2.4515	1.7568	53.1	76%	0.0477	70%
	18	1,121	0.3912	0.2347				

When the three method hybrid was used to locate and size two wind RDGs JTLL was reduced by 76% while JTVD was reduced by 70%. The system performance was improved by having two wind RDGs installed as compared to having one wind RDG. Integration of only one wind RDG reduced JTLL by 72% and JTVD by 59%. The method gave superior results compared to PSO which gave a 75% reduction in total line losses.

Table 4.12 Placement of three wind RDGs

Method	Bus	RES (KWh)	DG SIZE		JTLL(KW)	%∆JTLL	JTVD	%∆JTVD
			P (MW)	Q (MVAR)				
PSO [18]	6	-	2.551	1.755	43	80%	-	-
	15	-	0.463	0.272				
	25	-	0.685	0.31				
OPF and IHS [21]	13	-	0.78	0.42	13.47	94%	-	-
	25	-	0.83	0.43				
	30	-	1.15	0.86				
VSI, AGA and SA (This method)	33	747	2.4515	1.7568	53	76%	0.0479	70%
	18	1,121	0.3912	0.2347				
	32	2,615	0	0.0092				

Incorporation of a third wind RDG did not improve the system performance compared to the system integrated with two wind RDGs. Results indicate that optimal system performance was achieved with only two RDGs incorporated. Installation of a third wind RDG would result to increased investment cost without any further system performance improvement.

The results would have been further validated by comparing them with those from similar schemes individually or in hybrid, however, no reviewed work had been tested using either IBP, AGA or SA algorithm on the IEEE 33 Bus system to either minimize JTLL or JTVD.

The results would have been authenticated further by comparing them with a practical scenario in Kenya, however, the Kenyan distribution system has not been automated and obtaining data from the manual records kept at various depots would be incomplete and inaccurate and the comparison would not be realistic.

4.5 Chapter Conclusion

The results obtained in Tables 4.1-4.12 indicates that the optimal RDG siting should not necessarily prioritize the buses with the least VSI. Having one wind RDG at bus 18 reduced the JTLL and JTVD by 59% and 51% compared to the reduction in JTLL and JTVB of 62% each which was achieved by having one wind RDG at Bus 33. Incorporation of wind RDGs gave better results compared to PV Solar RDGs located at the same locations. One optimally sized wind RDG placed at Bus 33 reduced JTLL and JTVD by 72% and 59% respectively. One optimally sized PV Solar RDG placed at the same bus reduced both JTLL and JTVD by 62%.

Two optimally sized wind RDGs placed at Bus 33 and Bus 18 reduced the total line losses and total voltage deviation by 76% and 70% respectively. Integration of two wind RDGs gave a better System performance Compared to incorporation of either one wind or PV Solar RDG

The incorporation of two PV Solar RDGs at Bus 33 and Bus 18 reduced the total line losses and total voltage deviation by 62% and 73% respectively. This gave a better system voltage profile compared to having one PV RDG installed at Bus 33 which reduced the total voltage deviation by 62%. These results indicate that the three method algorithm is suitable for sizing and siting either two wind or PV Solar RDGs effectively. Lead Acid Batteries were considered in this thesis because they are cheap compared to other types of energy storage devices with a cost of $150/KWh.

CHAPTER 5

5 CONCLUSION AND FUTURE RESEARCH WORK

This chapter gives a summary of the thesis conclusions, contribution and recommendations for further work.

5.1 Conclusion

A two-objective function was formulated in Chapter 2 of this thesis to achieve total line loss reduction and total voltage deviation improvement in a radial distribution system with PV Solar and wind sources penetration and optimal RES allocation. In Chapter three a three method hybrid of Index Based Planning, Adaptive Genetic Algorithm and Simulated Annealing was applied in solving the multi-objective function. The method was tested in IEEE 33 Bus System using MATLAB.

In Chapter 4, the results obtained were analyzed and the following conclusions drawn: Results from Tables 4.8 and 4.12 indicated that incorporation of two wind RDGs gave a better system performance by reducing total line losses by 76% and total voltage deviation by 70% compared to incorporating two PV Solar RDGs which reduced total line losses by 62% and the total voltage deviation by 73%. This is because the wind generators can generate both active and reactive power that are necessary for optimal system performance.

Incorporation of a third PV Solar or wind RDG did not have any considerable system performance improvement compared to the system interconnected with two RDGs. Results in Tables 4.9 and 4.12 indicate that the three method hybrid approach used gave optimal solutions with integration of two RDGs in to the system and that optimal system performance enhancement was achieved with only two RDGs. The integration of any other RDGs would not be necessary as it would result in increased investment cost without any improvement to the system performance. Hence this three method hybrid can be used to optimally size and site two PV Solar or wind RDGs in the IEEE 33-Bus radial distribution system.

5.2 Contribution of the Research Work

Results in this thesis are superior to those of either Index Based Planning, AGA or SA when applied independently and are therefore deemed to be more accurate and reliable for recent applications aimed at the voltage profile enhancement and reduction of system line losses of a radial distribution system where two RDGs have to be incorporated. Optimally allocated RES systems would further increase network reliability. The modified distribution systems would have the following benefits; minimized environmental pollution, increased system efficiency due to reduced losses, reliable and better quality of power supplied at a lower cost.

5.3 Recommendations for Further Research Work

In this thesis, it was assumed that all the buses were viable sites for either wind or PV solar RDGs, however, it would be necessary to design a decision making tool for determining the suitability of the candidate buses for either PV solar RDG or wind RDG placement in future work.

The three method hybrid presented was tested in a radial system and it can be tested further in a meshed network.

This thesis has considered total line losses only, however, a robust assessment of losses incorporating the switchgear losses can be done in the future.

The cost benefit analysis of the RES devices can be carried out and the return on investment calculated in future so as to aid in determining the viability of the project.

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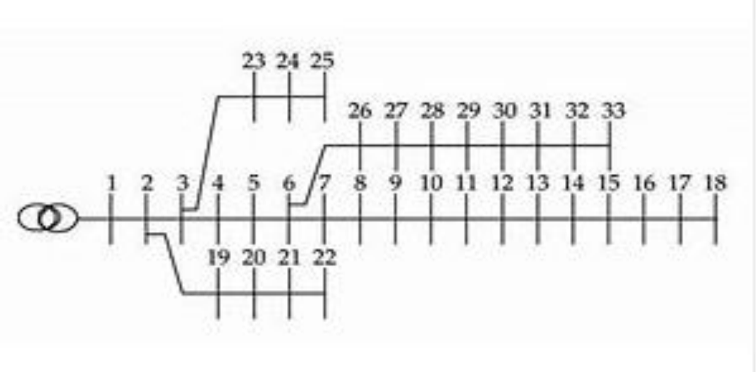
APPENDICES

Appendix A: IEEE 33 Bus system results

Appendix A.1 IEEE 33 Bus Radial Distribution System

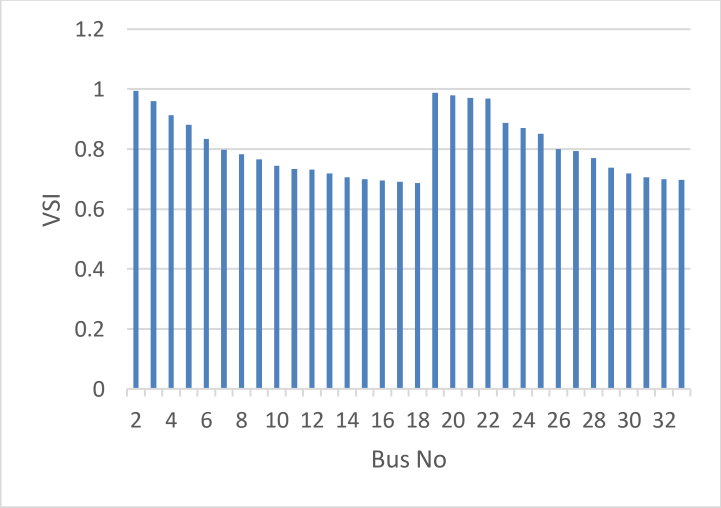


Appendix A.2 VSI for IEEE 33 Bus System

Bus No	**33 bus**
2	0.990
3	0.9599
4	0.9135
5	0.8808
6	0.8347
7	0.7972
8	0.7831
9	0.7646
10	0.7452
11	0.7347
12	0.7306
13	0.7185
14	0.7053
15	0.7004
16	0.6958
17	0.6905
18	0.6864
19	0.9870
20	0.977

Bus No	33 bus
21	0.9704
22	0.9678
23	0.8882
24	0.8691
25	0.8515
26	0.800
27	0.7922
28	0.7691
29	0.7370
30	0.7183
31	0.7064
32	0.6986
33	0.6971

Appendix A.3 Graphical Representation of VSI for IEEE 33 Bus System



Appendix B: Code Listing

Appendix B.1 Main code

```
clc;
Np=50;
Nd=2;
Nt=10;
num = 33;
PDG_min = 0;
PDG_max = 5;
```

```
QDG_min = 0;
QDG_max = 3;
busd = busdatas(num);
V = busd(:,3);
CandidateBus = [16,17,18,32,33]; % candidate buses

for z=1:5
Bus = CandidateBus(z)
xMin=[PDG_min, QDG_min];
xMax=[PDG_max, QDG_max];

    % Initializing the population
      R = zeros(Np, Nd);
        for p=1:Np
           for i =1:Nd
               R(p,i) =  xMin(1,i) + (xMax(1,i)-xMin(1,i)) * rand;
           end
        end
    p=0;
    k=0;
    M = Fitness(Np, Nd, Nt, xMin, xMax, R, k, Bus, p, V);
    for p =1:Np
        pBestfit(p) = M(p);  %best fitness for each chromosome
        for i =1:Nd
            pBestRDGSize(p,i)= R(p,i);   %best DG size
        end
    end

        gBestfit = min(M);  % best fitness in all chromosome fitness values
        index=find(M==min(M));
        gBestRDGSize = R(index,:);  % best DG size among all DG sizes

for k=1:Nt % For each iteration
    Pnew = [];
    for u=1:Np/2
    X = CrossMut(Np, Nd, Nt, xMin, xMax, R, k, Bus, p, V);
    Pnew = [Pnew; X];
    R=Pnew;
       % Updating population size constraints (minimum & Maximum DG sizes)
            for p=1:Np
            for i=1:Nd

       % Correct any errors
    if R(p,i) > xMax(1,i)
       R(p,i) = xMax(1,i);
    elseif  R(p,i) < xMin(1,i)
            R(p,i) = xMin(1,i);
              end

            end
        end

        % Evaluating Fitness
        M = Fitness(Np, Nd, Nt, xMin, xMax, R, k, Bus, p, V);
        for p=1:Np
```

```
            if M(p) < pBestfit(p)
                pBestfit(p) = M(p);
                for i=1:Nd
                    pBestRDGSize(p,i) = R(p,i);
                end
            end

            if M(p) < gBestfit
                gBestfit = M(p);
                for i=1:Nd
                    gBestRDGSize(i) = R(p,i);
                end
            end

        end

        bestFitnessHistory(k) = gBestfit;

        k=k+1;
end

    z=z+1;

    %SA STARTS HERE
    SA_Population = pBestRDGSize;

    T0=0.95;       % Initial Temp.
    Tf=0.025;      % Final Temp.
    alpha=0.95;    % Temp. Reduction Rate/cooling co-efficient
    MaxIt=50;      % Maximum Number of Iterations
    T=T0;
    R = SA_Population;
    M = Fitness(Np, Nd, Nt, xMin, xMax, R, k, Bus, p, V);
    R;
    for p =1:Np
        pBestfit(p) = M(p);
        pBestRDGSize(p,:)= R(p,:);

    end

        gBestfit = min(M);
        index=find(M==min(M));
        gBestRDGSize = R(index,:);

    while T>Tf
        for i=1:MaxIt
            for p=1:Np
             R(p,:) = R(p,:) + rand*(gBestRDGSize()-pBestRDGSize(p,:));
                  for i=1:Nd
                    % Correct any errors
                         if R(p,i) > xMax(1,i)
                             R(p,i) = xMax(1,i);
                         elseif  R(p,i) < xMin(1,i)
                                 R(p,i) = xMin(1,i);
```

```
                         end

                   end
            M = Fitness(Np, Nd, Nt, xMin, xMax, R, k, Bus, p, V);

            if M(p) < pBestfit(p)
               pBestfit(p) = M(p);
               pBestRDGSize(p,:) = R(p,:);
            else if exp(-(M(p)-pBestfit(p))/T)>rand
                    pBestfit(p) = M(p);
                    pBestRDGSize(p,:) = R(p,:);
                end

            end

            if M(p) < gBestfit
                gBestfit = M(p);
                for i=1:Nd
                    gBestRDGSize(i) = R(p,i);

                end
            end

            end
        R=pBestRDGSize;

       end
        T = alpha*T;
    end

        pBestfit;
        gBestfit;
        pBestRDGSize;
        R;
        gBestRDGSize;
        Optimal_DG_Size = gBestRDGSize;

        DG = Optimal_DG_Size;

        [JTLL, JTVD] = NewtonRaphson_OptimalDG_Size(Np, Nd, Nt, xMin, xMax,
R, k, Bus, p, V, DG);

End
```

Appendix B.2 Newton Rhapson code

```
function [JTLL, JTVD] = NewtonRaphson_OptimalDG_Size(Np, Nd, Nt, xMin, xMax,
R, k, Bus, p, V, DG)
nbus = 33;
Y = ybusppg(nbus);
busd = busdatas(nbus);
lined = linedatas(nbus);
BMva = 100;
```

```
bus = busd(:,1);
type = busd(:,2);
V = busd(:,3);
del = busd(:,4);
Ubusdt = UpdatedBusdatas_OptimalDG_Size(Np, Nd, Nt, xMin, xMax, R, k, Bus, p,
V, DG);
Pg = Ubusdt(:,5)/BMva;
Qg = Ubusdt(:,6)/BMva;
Pl = busd(:,7)/BMva;
Ql = busd(:,8)/BMva;
Qmin = busd(:,9)/BMva;
Qmax = busd(:,10)/BMva;
P = Pg - Pl;                % Pi = PGi - PLi
Q = Qg - Ql;                % Qi = QGi - QLi
Psp = P;
Qsp = Q;
G = real(Y);
B = imag(Y);

pv = find(type == 2 | type == 1);
pq = find(type == 3);
npv = length(pv);
npq = length(pq);

Iter = 0;
Iter_max=10;
while Iter<Iter_max
    Iter=Iter+1;
    P = zeros(nbus,1);
    Q = zeros(nbus,1);
% Calculate P and Q
    for i = 1:nbus
        for k = 1:nbus
            P(i) = P(i) + V(i)* V(k)*(G(i,k)*cos(del(i)-del(k)) +
B(i,k)*sin(del(i)-del(k)));
            Q(i) = Q(i) + V(i)* V(k)*(G(i,k)*sin(del(i)-del(k)) -
B(i,k)*cos(del(i)-del(k)));
        end
    end

% Checking for Q-limit violations
    if Iter <= 10 && Iter > 2     % checked up to 10th iteration
        for n = 2:nbus
            if type(n) == 2
                QG = Q(n)+Ql(n);
                if QG < Qmin(n)
                    V(n) = V(n) + 0.01;
                elseif QG > Qmax(n)
                    V(n) = V(n) - 0.01;
                end
            end
         end
    end

    % Calculating the change from Psp and Qsp
    dPa = Psp-P;
```

```
    dQa = Qsp-Q;
    k = 1;
    dQ = zeros(npq,1);
    for i = 1:nbus
        if type(i) == 3
            dQ(k,1) = dQa(i);
            k = k+1;
        end
    end
    dP = dPa(2:nbus);
    M = [dP; dQ];       % Mismatch Vector

   % Jacobian matrix
   % J1 - Derivative of Real Power Injections with Angles
    J1 = zeros(nbus-1,nbus-1);
    for i = 1:(nbus-1)
        m = i+1;
        for k = 1:(nbus-1)
            n = k+1;
            if n == m
                for n = 1:nbus
                    J1(i,k) = J1(i,k) + V(m)* V(n)*(-G(m,n)*sin(del(m)-
del(n)) + B(m,n)*cos(del(m)-del(n)));
                end
                J1(i,k) = J1(i,k) - V(m)^2*B(m,m);
            else
                J1(i,k) = V(m)* V(n)*(G(m,n)*sin(del(m)-del(n)) -
B(m,n)*cos(del(m)-del(n)));
            end
        end
    end

   % J2 - Derivative of Real Power Injections with V
    J2 = zeros(nbus-1,npq);
    for i = 1:(nbus-1)
        m = i+1;
        for k = 1:npq
            n = pq(k);
            if n == m
                for n = 1:nbus
                    J2(i,k) = J2(i,k) + V(n)*(G(m,n)*cos(del(m)-del(n)) +
B(m,n)*sin(del(m)-del(n)));
                end
                J2(i,k) = J2(i,k) + V(m)*G(m,m);
            else
                J2(i,k) = V(m)*(G(m,n)*cos(del(m)-del(n)) +
B(m,n)*sin(del(m)-del(n)));
            end
        end
    end

  % J3 - Derivative of Reactive Power Injections with Angles
    J3 = zeros(npq,nbus-1);
    for i = 1:npq
        m = pq(i);
        for k = 1:(nbus-1)
```

```
            n = k+1;
            if n == m
                for n = 1:nbus
                    J3(i,k) = J3(i,k) + V(m)* V(n)*(G(m,n)*cos(del(m)-del(n))
+ B(m,n)*sin(del(m)-del(n)));
                end
                J3(i,k) = J3(i,k) - V(m)^2*G(m,m);
            else
                J3(i,k) = V(m)* V(n)*(-G(m,n)*cos(del(m)-del(n)) -
B(m,n)*sin(del(m)-del(n)));
            end
        end
    end

  % J4 - Derivative of Reactive Power Injections with V
    J4 = zeros(npq,npq);
    for i = 1:npq
        m = pq(i);
        for k = 1:npq
            n = pq(k);
            if n == m
                for n = 1:nbus
                    J4(i,k) = J4(i,k) + V(n)*(G(m,n)*sin(del(m)-del(n)) -
B(m,n)*cos(del(m)-del(n)));
                end
                J4(i,k) = J4(i,k) - V(m)*B(m,m);
            else
                J4(i,k) = V(m)*(G(m,n)*sin(del(m)-del(n)) -
B(m,n)*cos(del(m)-del(n)));
            end
        end
    end

    J = [J1 J2; J3 J4];     % Jacobian Matrix

    X = inv(J)*M;           % Correction Vector
    dTh = X(1:nbus-1);      % Change in the voltage angel
    dV = X(nbus:end);       % Change in the magnitude of the voltage

 % Updating State Vectors
    del(2:nbus) = dTh + del(2:nbus);    % for change in Voltage Angle
    k = 1;
    for i = 2:nbus
        if type(i) == 3
            V(i) = dV(k) + V(i);        % for change in Voltage Magnitude..
            k = k+1;
        end
    end

    Iter = Iter + 1;
    Tol = max(abs(M));                  % Tolerance..

end

Vm = pol2rect(V,del);
```

```
Del = 180/pi*del;
fb = lined(:,1);
tb = lined(:,2);
nl = length(fb);
Pl = busd(:,7);                  % PLi..
Ql = busd(:,8);                  % QLi..
Iij = zeros(nbus,nbus);
Sij = zeros(nbus,nbus);
Si = zeros(nbus,1);

% Bus Current Injections
 I = Y*Vm;
 Im = abs(I);
 Ia = angle(I);

%Line Current Flows
for m = 1:nl
    p = fb(m); q = tb(m);
    Iij(p,q) = -(Vm(p) - Vm(q))*Y(p,q); % Y(m,n) = -y(m,n)..
    Iij(q,p) = -Iij(p,q);
end
Iij = sparse(Iij);
Iijm = abs(Iij);
Iija = angle(Iij);

% Line Power Flows
for m = 1:nbus
    for n = 1:nbus
        if m ~= n
            Sij(m,n) = Vm(m)*conj(Iij(m,n))*BMva;

        end
    end
end
Sij = sparse(Sij);
Pij = real(Sij);
Qij = imag(Sij);

% Line Losses
Lij = zeros(nl,1);
for m = 1:nl
    p = fb(m); q = tb(m);
    Lij(m) = Sij(p,q) + Sij(q,p);
end
Lpij = real(Lij);
Lqij = imag(Lij);

% Bus Power Injections
for i = 1:nbus
    for k = 1:nbus
        Si(i) = Si(i) + conj(Vm(i))* Vm(k)*Y(i,k)*BMva;
    end
end
Pi = real(Si);
Qi = -imag(Si);
Pg = Pi+Pl;
```

```
Qg = Qi+Ql;

%Calculating total voltage deviation
JTVD=zeros;                         %Initializing the total voltage deviation
    for i = 1:nbus
      a = real (Vm (i));
       b = imag (Vm (i));
       Vi = sqrt((a^2)+(b^2));       %Calculating bus Voltage Magnitude
       Vn = sqrt((1-Vi)^2);          %Calculating Voltage deviation Magnitude
       JTVD = JTVD + Vn;             %Summation of voltage deviations
    end

%Calculating total line losses
JTLL=zeros;                          %Initializing the line losses
    for k = 1:nl                     %For all network branches
        %k
        Rk = lined(k,3);             %Resistance for kth branch
        Xk = lined(k,4);             %reactance for kth branch
        c = lined(k,1);
        Pk = Pi(c);                  %pu real Power injected at kth branch
        Qk = Qi(c);                  %pu Reactive power injected at kth
branch
%picking the bus at sending end
        a = real (Vm (c));
        b = imag (Vm (c));
        Vk = sqrt((a^2)+(b^2));              %Calculating Voltage Magnitude

        LL=(sqrt((Rk^2)+(Xk^2)))*((Pk^2)+(Qk^2))/(Vk^2);
        JTLL= JTLL +(sqrt((Rk^2)+(Xk^2)))*((Pk^2)+(Qk^2))/(Vk^2);

    end

PLQL = [sum(Lpij) sum(Lqij)];

SL = PLQL;

RES Allocation
for z=1:5
Bus = CandidateBus(z)
PDi=busd(z,7)

     T=8.304  % for wind
     T=6.024   % for PV Solar
     JB=1.5 *PDi*T

     JB=1.5 *PDi*T
end

end
```

Appendix B.3 Fitness code

```
function M = Fitness(Np, Nd, Nt, xMin, xMax, R, k, Bus, p, V)

    % Initialize Fitness Values
M = zeros(Np,1);


for p=1:Np

[JTLL, JTVD] = NewtonRaphson(Np, Nd, Nt, xMin, xMax, R, k, Bus, p, V);
    JTLL;
    JTVD;
%defination of weights for the MOF.

w1=0.5;
w2=(1-w1);

M(p)  = (w1*JTLL)+(w2*JTVD);

end
M;
end
```

Appendix B.4 Bus data

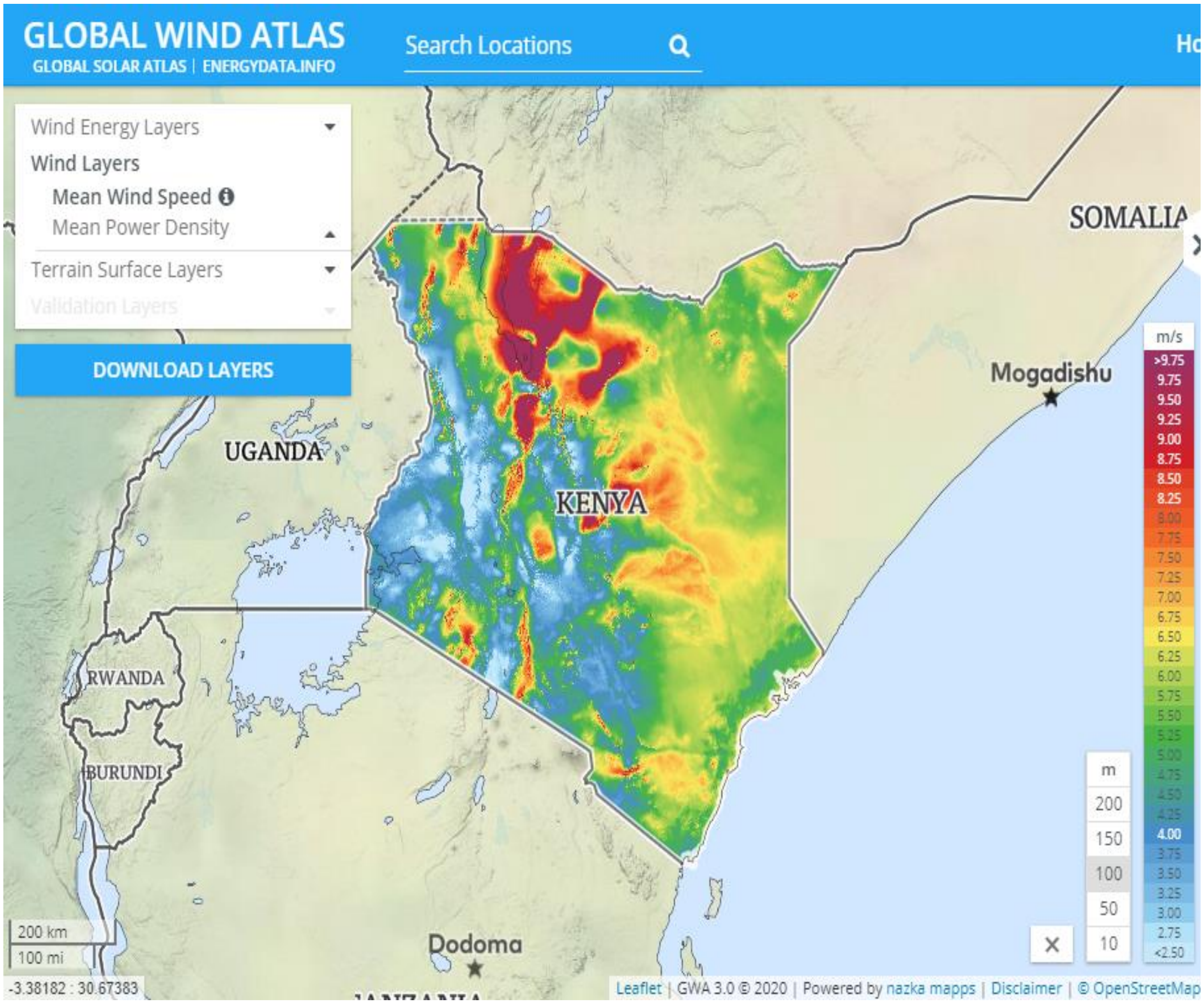
```
function busdt = busdatas(num)


%          |Bus | Type | Vsp | theta | PGi |  QGi | PLi |  QLi |  Qmin |  Qmax
|
busdat33 = [1      1      1.000     0      0.0      0.0    0.0      0.0      0.0
0.0;
             2      3      1.000     0      0.0      0.0    0.1      0.06     0.0
0.0;
             3      3      1.000     0      0.0      0.0    0.09     0.04     0.0
0.0;
             4      3      1.000     0      0.0      0.0    0.12     0.08     0.0
0.0;
             5      3      1.000     0      0.0      0.0    0.06     0.03     0.0
0.0;
             6      3      1.000     0      0.0      0.0    0.06     0.02     0.0
0.0;
             7      3      1.000     0      0.0      0.0    0.2      0.1      0.0
0.0;
             8      3      1.000     0      0.0      0.0    0.2      0.1      0.0
0.0;
             9      3      1.000     0      0.0      0.0    0.06     0.02     0.0
0.0;
            10      3      1.000     0      0.0      0.0    0.06     0.02     0.0
0.0;
```

```
           11      3      1.000     0      0.0      0.0     0.045    0.03     0.0
0.0;
           12      3      1.000     0      0.0      0.0     0.06     0.035    0.0
0.0;
           13      3      1.000     0      0.0      0.0     0.06     0.035    0.0
0.0;
           14      3      1.000     0      0.0      0.0     0.12     0.08     0.0
0.0;
           15      3      1.000     0      0.0      0.0     0.06     0.01     0.0
0.0;
           16      3      1.000     0      0.0      0.0     0.06     0.02     0.0
0.0;
           17      3      1.000     0      0.0      0.0     0.06     0.02     0.0
0.0;
           18      3      1.000     0      0.0      0.0     0.09     0.04     0.0
0.0;
           19      3      1.000     0      0.0      0.0     0.09     0.04     0.0
0.0;
           20      3      1.000     0      0.0      0.0     0.09     0.04     0.0
0.0;
           21      3      1.000     0      0.0      0.0     0.09     0.04     0.0
0.0;
           22      3      1.000     0      0.0      0.0     0.09     0.04     0.0
0.0;
           23      3      1.000     0      0.0      0.0     0.09     0.05     0.0
0.0;
           24      3      1.000     0      0.0      0.0     0.42     0.2      0.0
0.0;
           25      3      1.000     0      0.0      0.0     0.42     0.2      0.0
0.0;
           26      3      1.000     0      0.0      0.0     0.06     0.025    0.0
0.0;
           27      3      1.000     0      0.0      0.0     0.06     0.025    0.0
0.0;
           28      3      1.000     0      0.0      0.0     0.06     0.02     0.0
0.0;
           29      3      1.000     0      0.0      0.0     0.12     0.07     0.0
0.0;
           30      3      1.000     0      0.0      0.0     0.2      0.6      0.0
0.0;
           31      3      1.000     0      0.0      0.0     0.15     0.07     0.0
0.0;
           32      3      1.000     0      0.0      0.0     0.21     0.1      0.0
0.0;
           33      2      1.000     0      0.0      0.0     0.06     0.04     0.0
0.0];

% Type (1 - Slack Bus; 2 - PV Bus; 3 - PQ Bus)
switch num
       case 33
       busdt = busdat33;
  end
```

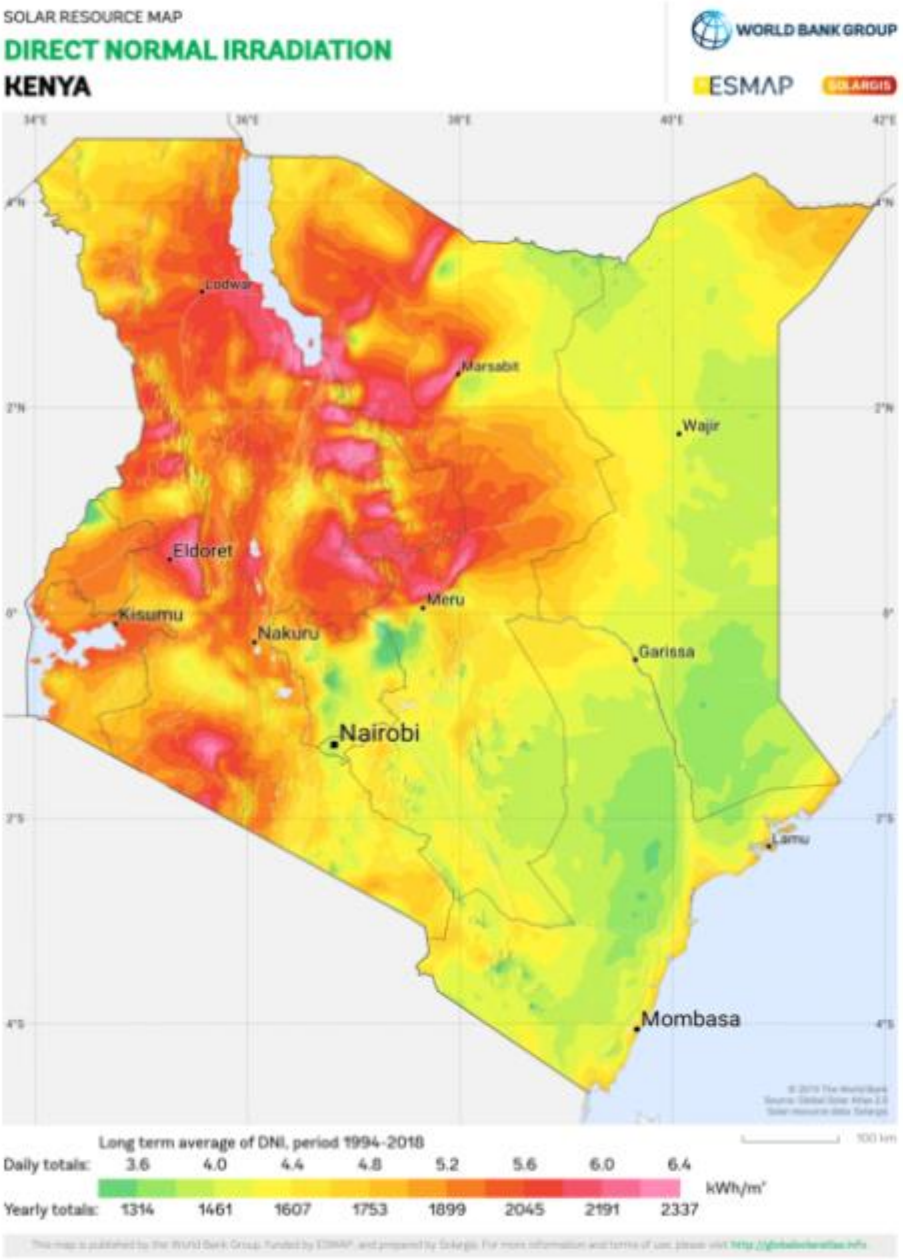
Appendix B.5 Line data

```
function linedt = linedatas(num)


%          |  From |  To   |   R      |   X      |     B/2  |  X'mer  |
%          |  Bus  | Bus   |  pu      |  pu      |     pu   | TAP (a) |
linedat33 = [   2    3    0.03076   0.01567     0         1
                3    4    0.02284   0.01163     0         1
                4    5    0.02378   0.01211     0         1
                5    6    0.0511    0.04411     0         1
                6    7    0.01168   0.03861     0         1
                7    8    0.04439   0.01467     0         1
                8    9    0.06426   0.04617     0         1
                9   10    0.06514   0.04617     0         1
               10   11    0.01227   0.00406     0         1
               11   12    0.02336   0.00772     0         1
               12   13    0.09159   0.07206     0         1
               13   14    0.03379   0.04448     0         1
               14   15    0.03687   0.03282     0         1
               15   16    0.04656   0.034       0         1
               16   17    0.08042  -0.89262     0         1
               17   18    0.04567   0.03581     0         1
                2   19    0.01023   0.00976     0         1
               19   20    0.09385   0.08457     0         1
               20   21    0.02555   0.02985     0         1
               21   22    0.04423   0.05848     0         1
                3   23    0.02815   0.01924     0         1
               23   24    0.05603   0.04424     0         1
               24   25    0.0559    0.04374     0         1
                6   26    0.01267   0.00645     0         1
               26   27    0.01773   0.00903     0         1
               27   28    0.06607   0.05826     0         1
               28   29    0.05018   0.04371     0         1
               29   30    0.03166   0.01613     0         1
               30   31    0.0608    0.06008     0         1
               31   32    0.01937   0.02258     0         1
               32   33    0.02128   0.03319     0         1
                1    2    0.00575   0.00293     0         1];

switch num
    case 33
    linedt = linedat33;

 end
```

Appendix C: Map showing mean wind speed in various parts of Kenya



Appendix D: Map showing the average Direct Normal Irradiation in various parts of Kenya



Appendix E: Published Works

Voltage Stability optimization with Renewable Distributed Generation (RDG) using Index Based planning (IBP) and Genetic Algorithm (GA)

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Abstract-Voltage stability is very important in a power system operation. This paper presents a detailed study on voltage stability and line losses of a radial distribution system incorporating Renewable Distributed Generation (RDG) using a two method approach of Index Based planning (IBP) and Genetic Algorithm (GA). RDGs have been largely adopted in most power systems due to their ability to meet increased electrical load faster and cheaply without expanding the transmission network, they have minimal environmental effects and they cannot be depleted. Formulation and solution of distribution voltage stability problem of a distribution network with RDG is very critical in the modern power system operation and control. Researchers have previously solved the voltage stability problem by obtaining optimal placement of Flexible AC Transmission Systems (FACTS), Static VAR Compensators (SVC) and static capacitors to provide reactive power to the system and improve the voltage profile. Other researchers have used Under Frequency Load Shedding (UFLS) and others have used optimal sizing and siting of DG units to improve the distribution network's voltage profile. This paper outlines a detailed research of the effect of interconnecting RDGs on the voltage stability and line loss of the IEEE 14 bus radial distribution system using Index Based planning and Genetic Algorithm. The results indicate the total voltage deviation and the total line loss for Photovoltaic DG, Wind DG and Static compensators (STATCOMS). In addition it gives a detailed formulation of the problem. The results obtained shows that appropriate sizing and location of RDGs improves the voltage profile and reduces the line losses of the radial distribution system.

Keywords—Renewable distributed generation (RDG), Index Based planning (IBP), Genetic Algorithm (GA), Flexible AC Transmission Systems (FACTS), and Static Compensator (STATCOM)

I. INTRODUCTION

Voltage stability is the ability of a power system to maintain acceptable voltages at all buses in the system under normal conditions and after being subjected to a disturbance [1]. It is important in a power system because all electrical equipment, appliances and loads have a specific rating and varying the voltage levels would affect them by either causing a permanent damage or reducing their useful lives. In addition a voltage collapse may occur due to voltage instability which would result to partial or full power blackout. Hence it is very important to maintain the voltage levels within acceptable limits [2][3]. Conventionally voltage stability was maintained by varying the generator excitation, load compensation, line compensation and Under Frequency Load Shedding. UFLS resulted to undesirable outages to power customers and hence it was important to consider generation expansion planning so as to match the generation capacity to the increased energy demand and reduce power outages. As a result RDGs were set up and subsequently connected to the grid at the load centers. Incorporation of RDGs in the distribution network has been on an increase over the last decade because they cause minimal environmental pollution and are infinitely available [4] [5] [6].

Contribution: The formulation of the voltage stability problem with RDGs and a hybrid optimization of this problem using IBP and GA results to more accurate and realistic results that can be reliably applied in the distribution network and achieve optimal performance.

Paper organization: This paper has five major sections; section II contains a review of previous related works, Section III has problem formulation, section IV has the results and analysis and section V consists of the conclusion.

II. LITERATURE REVIEW

A. DG Technologies

Traditionally Distribution expansion planning involved substation expansion, construction of new feeders or uprating of the existing feeders, load switching and use of capacitor banks which required increased investment in both transmission and generation networks. With the introduction of DGs this problem has been solved and network reconfiguration is only done at the distribution network. DG refers to small power generators which are interconnected to the distribution system so as to improve voltage profile, reduce power losses, eliminate the need for reserve margin for meeting peak loads and to increase the distribution network capacity [7]. DGs technologies have evolved overtime from conventional hydro and thermal power generators to wind power plants, Solar Photovoltaic power plants, Biomass power plants, geothermal power plants and tidal power plants.

DGs can be categorized into the following types; (i) Wind DGs: are capable of generating and absorbing both active power and reactive power(ii) Photovoltaic solar DGs:

capable of generating active power only and are interconnected to the grid via converters and (iii) STATCOM DGs: capable of generating and absorbing reactive power only.

B. *Impacts of interconnecting RDGs to the distribution network*

When RDGs are interconnected to the grid at the optimal locations and penetration they have several merits such as improvement of the distribution system voltage profile, improve the power quality through reduced transmission losses, increase of power transfer capability of the system and they also support the peak load growth if installed at strategic locations [8]. Generally RDGs can improve the system security and reduce power losses when optimally sized and located [2] [9] [10]. However, if not well sized and placed in the distribution network they pose a great challenge of ensuring system stability is maintained. This is because they cannot generate an instantaneous power at all times due to the intermittent sources which generate a variable power output. Renewable Energy storage systems can be incorporated to counter this effect. Small scale Photovoltaic Distributed Generation (PV-DGs) result to significant imbalances of both current and voltage. This could arise when one phase may experience significant reverse power flow while the other two phases may not be affected. This phenomenon affects overcurrent protection and the voltage regulators in the line. Reverse power flow also affect the transformer voltage and loading limit which in turn affects the operation of the transformer differential protection. PV-DGs introduce total harmonic distortion (THD) to the network because they require additional power electronics interface equipment at the converter stations such as Distributed Energy Storage (DES), rectifiers, inverters and voltage regulators so as to be interconnected to the distribution grid. The interaction of these equipment and the capacitor banks on the network may lead to resonance [11] [12] [13] [14] [15] [16]. With an increased trend of incorporating RDGs in the distribution networks, their effects to the existing system should be studied using effective techniques for future planning of the distribution system.

II. PROBLEM FORMULATION

For an electrical circuit with load at the end, we have the following:

$$V_s = V_r + \frac{PR}{V_r} + \frac{QX}{V_r} \qquad (1)$$

Where V_s is the sending end voltage, V_r is the receiving end voltage, P is the active power flowing in the line, Q is the reactive power flowing in the line, R and X are the line resistance and reactance respectively.

The voltage drop $(V_s - V_r)$ is therefore given by:

$$\text{Voltage drop} = \frac{PR}{V_r} + \frac{QX}{V_r} \qquad (2)$$

Since R<<X, then;

$$\text{Voltage drop} = \frac{QX}{V_r} \qquad (3)$$

From equation 11 it is evident that voltage stability in a power system is proportional to reactive power in the system.

Voltage stability with RDG problem has been formulated as a single Objective or a Multi-Objective problem with various constraints.

Some Objective Functions are as follows.

A. *Minimization of Total Voltage Deviation*

Total voltage deviation has been represented by equation (4) by Majid Nayeripour et al [20] and A.H. Mantway et al [25]}

$$J_{TVD} = \sum_{i=1}^{N} |1 - V_i| \qquad (4)$$

Where i =1, 2, 3….N are the bus numbers and V_i is the per unit voltage at the buses.

B. *Minimization of Tootal Line losses*

Total line loss has been formulated as follows [17]

$$J_{TLL} = \sum_{i=1}^{N} (R_k + X_k) \frac{P_k^2 + Q_k^2}{|V_k|^2} \qquad (5)$$

Where R_k and X_k are the resistance and reactance of the k^{th} branch, P_k and Q_k are the real and reactive powers at the sending end of the k^{th} branch and V_k is the voltage at the sending end of the k^{th} branch

C. *Constraints*

The objective functions for the Voltage stability with RDG problem have been solved while putting into consideration the following constraints:

(i) Bus voltage limits shall be maintained within the standard levels

$$0.95 \text{ p.u} \le V_i \le 1.05 \text{ p.u} \qquad (6)$$

(ii) Real and reactive power output capacity constraints

$$P_{DG\,min} \le P_{DG} \le P_{DG\,max} \qquad (7)$$

$$Q_{DG\,min} \le Q_{DG} \le Q_{DG\,max} \qquad (8)$$

Where $P_{DG\,min}$ and $P_{DG\,max}$ are the minimum and maximum active power limits and $Q_{DG\,min}$ and $Q_{DG\,max}$ are the minimum and maximum reactive power limits respectively.

(iii) Power flow constraints

$$P_{Gi} P_{Di} \sum_{k=1}^{N} V_i V_k G_{ik} \cos(\delta_i - \delta_k) B_{ik} \sin(\delta_i - \delta_k) \qquad (9)$$

$$Q_{Gi} Q_{Di} \Sigma_{k=1}^{N} V_i V_k G_{ik} \cos(\delta_i - \delta_k) B_{ik} \sin(\delta_i - \delta_k) \quad (10)$$

Where $P_{Gi} P_{Di}$ is the active power injected and $Q_{Gi} Q_{Di}$ is the reactive power injected at a bus, G_{ik} and B_{ik} represent the conductance and susceptance of the line between buses i and k.

D. Multi-objective formulation of the problem of voltage stability with RDGs.

So as to improve the distribution system's voltage profile and reduce line losses, total voltage deviation objective function together with total line loss objective function shall be combined together into one objective using weighted sums as follows;

$$F = W_1 J_{TLL} + W_1 J_{TVD} \quad (11)$$

III. RESULTS AND ANALYSIS

The Problem of voltage stability with RDGs was optimized using IBP and GA for the three types of RDGS (wind DGs, Photovoltaic solar DGs and STATCOMs) and the following Results were obtained for each category of DGs.

IBP was used to determine the 7 buses which were susceptible to voltage collapse as follows:
For the 14 bus system the buses obtained were; 6, 7, 8, 10, 12, 13 and 14

A. Results for wind RDGs only from IEEE 14 bus system

Table 1. Shows the base values of the total power loss (JTLL) and total voltage deviation (JTVD) before optimization.

Table I. Base values before optimization

Description	MW
JTLL	0.2649
JTVD	0.1593

Table 2. Shows the optimal DG size and the JTLL and JTVD after optimization of the Multi-objective function for case 1 where W1<W2.

Table 2. Optimal DG sizes

	Optimal DG Size			
Bus	P (MW)	Q (MVAR)	JTLL	JTVD
6	0.9677	0.105	0.2634	0.1266
7	0.9141	0.5484	0.232	0.1156
8	0.6928	0.4157	0.2409	0.1221
10	1.6491	0.9895	0.2059	0.0477
12	0.3421	0.2053	0.2526	0.1338
13	0.7759	0.4655	0.2568	0.0952
14	1.1087	0.6652	0.2705	0.0648

Table 3 shows the percentage reduction of the total line losses and total voltage deviation after optimization for case 1.

Table 3. Analysis of JTLL and JTVD for case 1

Bus	JTLL	JTVD	% reduction of JTLL	% reduction of JTVD
6	0.2634	0.1266	-1%	-21%
7	0.232	0.1156	-12%	-56%
8	0.2409	0.1221	-9%	-23%
10	0.2059	0.0477	-22%	-70%
12	0.2526	0.1338	-5%	-16%
13	0.2568	0.0952	-3%	-40%
14	0.2705	0.0648	2%	-59%

It was noted that from case 1, that the wind DGs at bus 14 increase the total line loss and has the greatest reduction of the total Voltage deviation. But for all other buses both line losses and total voltage deviation are improved by the wind DGs.
This indicates that the weights are related to DG penetration and if the DG penetration is exceeds a certain limit, then it may cause adverse effects to the power system such as increasing the line losses.

Table 3 shows optimal DG size and the JTLL and JTVD after optimization of the Multi-objective function for case 2 where *W1 =W2*.

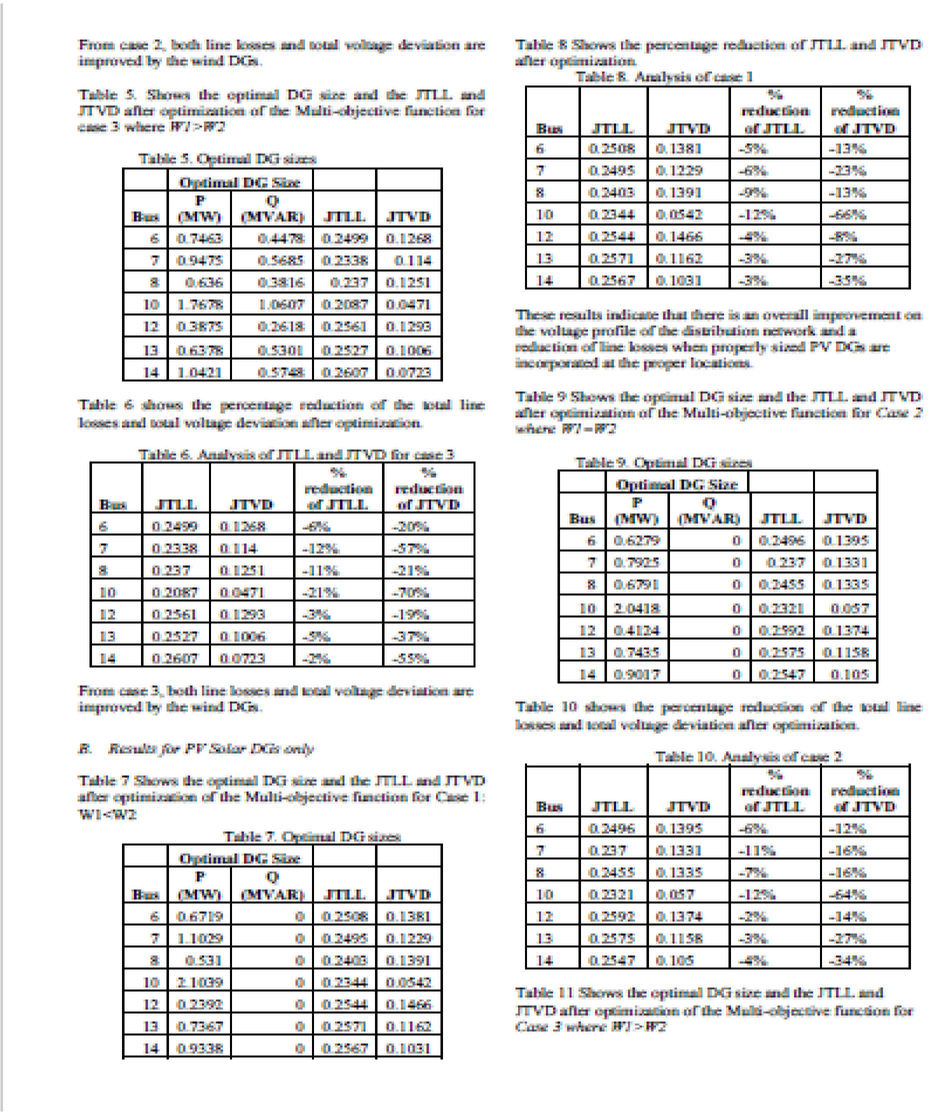
Table 3. Optimal DG sizes

	Optimal DG Size			
Bus	P (MW)	Q (MVAR)	JTLL	JTVD
6	0.7275	0.6423	0.2574	0.1235
7	0.8734	0.5241	0.2302	0.1176
8	0.6778	0.4067	0.2397	0.1229
10	1.7318	1.0381	0.2078	0.0469
12	0.4412	0.2647	0.2594	0.1264
13	0.7903	0.4742	0.258	0.094
14	0.8663	0.5198	0.2469	0.0851

Table 4 shows the percentage reduction of the total line losses and total voltage deviation after optimization.

Table 4. Analysis of JTLL and JTVD for case 2

Bus	JTLL	JTVD	% reduction of JTLL	% reduction of JTVD
6	0.2574	0.1235	-3%	-22%
7	0.2302	0.1176	-13%	-56%
8	0.2397	0.1229	-10%	-23%
10	0.2078	0.0469	-22%	-71%
12	0.2594	0.1264	-2%	-21%
13	0.258	0.094	-3%	-41%
14	0.2469	0.0851	-7%	-47%



From case 2, both line losses and total voltage deviation are improved by the wind DGs.

Table 5. Shows the optimal DG size and the JTLL and JTVD after optimization of the Multi-objective function for case 3 where *W1>W2*

Table 5. Optimal DG sizes

	Optimal DG Size			
Bus	P (MW)	Q (MVAR)	JTLL	JTVD
6	0.7463	0.4478	0.2499	0.1268
7	0.9475	0.5685	0.2338	0.114
8	0.636	0.3816	0.237	0.1251
10	1.7678	1.0607	0.2087	0.0471
12	0.3875	0.2618	0.2561	0.1293
13	0.6378	0.5301	0.2527	0.1006
14	1.0421	0.5748	0.2607	0.0723

Table 6 shows the percentage reduction of the total line losses and total voltage deviation after optimization.

Table 6. Analysis of JTLL and JTVD for case 3

Bus	JTLL	JTVD	% reduction of JTLL	% reduction of JTVD
6	0.2499	0.1268	-6%	-20%
7	0.2338	0.114	-12%	-57%
8	0.237	0.1251	-11%	-21%
10	0.2087	0.0471	-21%	-70%
12	0.2561	0.1293	-3%	-19%
13	0.2527	0.1006	-5%	-37%
14	0.2607	0.0723	-2%	-55%

From case 3, both line losses and total voltage deviation are improved by the wind DGs.

B. Results for PV Solar DGs only

Table 7 Shows the optimal DG size and the JTLL and JTVD after optimization of the Multi-objective function for Case 1: W1<W2

Table 7. Optimal DG sizes

	Optimal DG Size			
Bus	P (MW)	Q (MVAR)	JTLL	JTVD
6	0.6719	0	0.2508	0.1381
7	1.1029	0	0.2495	0.1229
8	0.531	0	0.2403	0.1391
10	2.1039	0	0.2344	0.0542
12	0.2392	0	0.2544	0.1466
13	0.7367	0	0.2571	0.1162
14	0.9338	0	0.2567	0.1031

Table 8 Shows the percentage reduction of JTLL and JTVD after optimization.

Table 8. Analysis of case 1

Bus	JTLL	JTVD	% reduction of JTLL	% reduction of JTVD
6	0.2508	0.1381	-5%	-13%
7	0.2495	0.1229	-6%	-23%
8	0.2403	0.1391	-9%	-13%
10	0.2344	0.0542	-12%	-66%
12	0.2544	0.1466	-4%	-8%
13	0.2571	0.1162	-3%	-27%
14	0.2567	0.1031	-3%	-35%

These results indicate that there is an overall improvement on the voltage profile of the distribution network and a reduction of line losses when properly sized PV DGs are incorporated at the proper locations.

Table 9 Shows the optimal DG size and the JTLL and JTVD after optimization of the Multi-objective function for Case 2 *where W1=W2*

Table 9. Optimal DG sizes

	Optimal DG Size			
Bus	P (MW)	Q (MVAR)	JTLL	JTVD
6	0.6279	0	0.2496	0.1395
7	0.7925	0	0.237	0.1331
8	0.6791	0	0.2455	0.1335
10	2.0418	0	0.2321	0.057
12	0.4124	0	0.2592	0.1374
13	0.7435	0	0.2575	0.1158
14	0.9017	0	0.2547	0.105

Table 10 shows the percentage reduction of the total line losses and total voltage deviation after optimization.

Table 10. Analysis of case 2

Bus	JTLL	JTVD	% reduction of JTLL	% reduction of JTVD
6	0.2496	0.1395	-6%	-12%
7	0.237	0.1331	-11%	-16%
8	0.2455	0.1335	-7%	-16%
10	0.2321	0.057	-12%	-64%
12	0.2592	0.1374	-2%	-14%
13	0.2575	0.1158	-3%	-27%
14	0.2547	0.105	-4%	-34%

Table 11 Shows the optimal DG size and the JTLL and JTVD after optimization of the Multi-objective function for *Case 3 where W1>W2*

Table 11. Optimal DG sizes

	Optimal DG Size			
Bus	P (MW)	Q (MVAR)	JTLL	JTVD
6	0.6721	0	0.2508	0.1381
7	0.8936	0	0.2396	0.1298
8	0.6476	0	0.244	0.1347
10	2.1498	0	0.2362	0.0526
12	0.3516	0	0.2564	0.1407
13	0.9303	0	0.2709	0.1049
14	0.9355	0	0.2569	0.103

Table 12 shows the percentage reduction of the total line losses and total voltage deviation after optimization for case 3.

Table 12. Analysis of case 3

Bus	JTLL	JTVD	% reduction of JTLL	% reduction of JTVD
6	0.2508	0.1381	-5%	-13%
7	0.2396	0.1298	-10%	-19%
8	0.244	0.1347	-8%	-15%
10	0.2362	0.0526	-11%	-67%
12	0.2564	0.1407	-3%	-12%
13	0.2709	0.1049	2%	-34%
14	0.2569	0.103	-3%	-35%

From table 12, it was observed that a PV DG at bus 13 increases the total line losses by 2% and reduces the total voltage deviation by 34%. Thus the penetration is affected by the weights and this further affects the system parameters.

C. *Results for STATCOM DGs only*

Table 13 Shows the optimal DG size and the JTLL and JTVD after optimization of the Multi-objective function for Case 1 where W1<W2

Table 13. Optimal DG sizes

	Optimal DG Size			
Bus	P (MW)	Q (MVAR)	JTLL	JTVD
6	0	0.4194	0.2606	0.151
7	0	0.6213	0.2586	0.144
8	0	0.4245	0.2599	0.1482
10	0	1.5197	0.2606	0.1063
12	0	0.2755	0.2637	0.1494
13	0	0.5154	0.2645	0.1386
14	0	0.5979	0.2622	0.1339

Table 12 shows the percentage reduction of the total line losses and total voltage deviation after optimization for case

Table 14. Analysis of case 1

Bus	JTLL	JTVD	% reduction of JTLL	% reduction of JTVD
6	0.2606	0.151	-2%	-5%
7	0.2586	0.144	-2%	-10%
8	0.2599	0.1482	-2%	-7%
10	0.2606	0.1063	-2%	-33%
12	0.2637	0.1494	0%	-6%
13	0.2645	0.1386	0%	-13%
14	0.2622	0.1339	-1%	-16%

Table 15 shows the percentage reduction of the total line losses and total voltage deviation after optimization for case 2 where W1=W2.

Table 15. Optimal DG sizes

	Optimal DG Size			
Bus	P (MW)	Q (MVAR)	JTLL	JTVD
6	0	0.434	0.2609	0.1507
7	0	0.5562	0.2568	0.1456
8	0	0.3045	0.2569	0.1513
10	0	1.4682	0.2588	0.108
12	0	0.2775	0.2638	0.1493
13	0	0.4799	0.263	0.14
14	0	0.5899	0.2619	0.1343

Table 15 shows the percentage reduction of the total line losses and total voltage deviation after optimization.

Table 15. Analysis of case 2

Bus	JTLL	JTVD	% reduction of JTLL	% reduction of JTVD
6	0.2609	0.1507	-2%	-5%
7	0.2568	0.1456	-3%	-9%
8	0.2569	0.1513	-3%	-5%
10	0.2588	0.108	-2%	-32%
12	0.2638	0.1493	0%	-6%
13	0.263	0.14	-1%	-12%
14	0.2619	0.1343	-1%	-16%

Table 16 Shows the optimal DG size and the JTLL and JTVD after optimization of the Multi-objective function for Case 3 where W1>W2

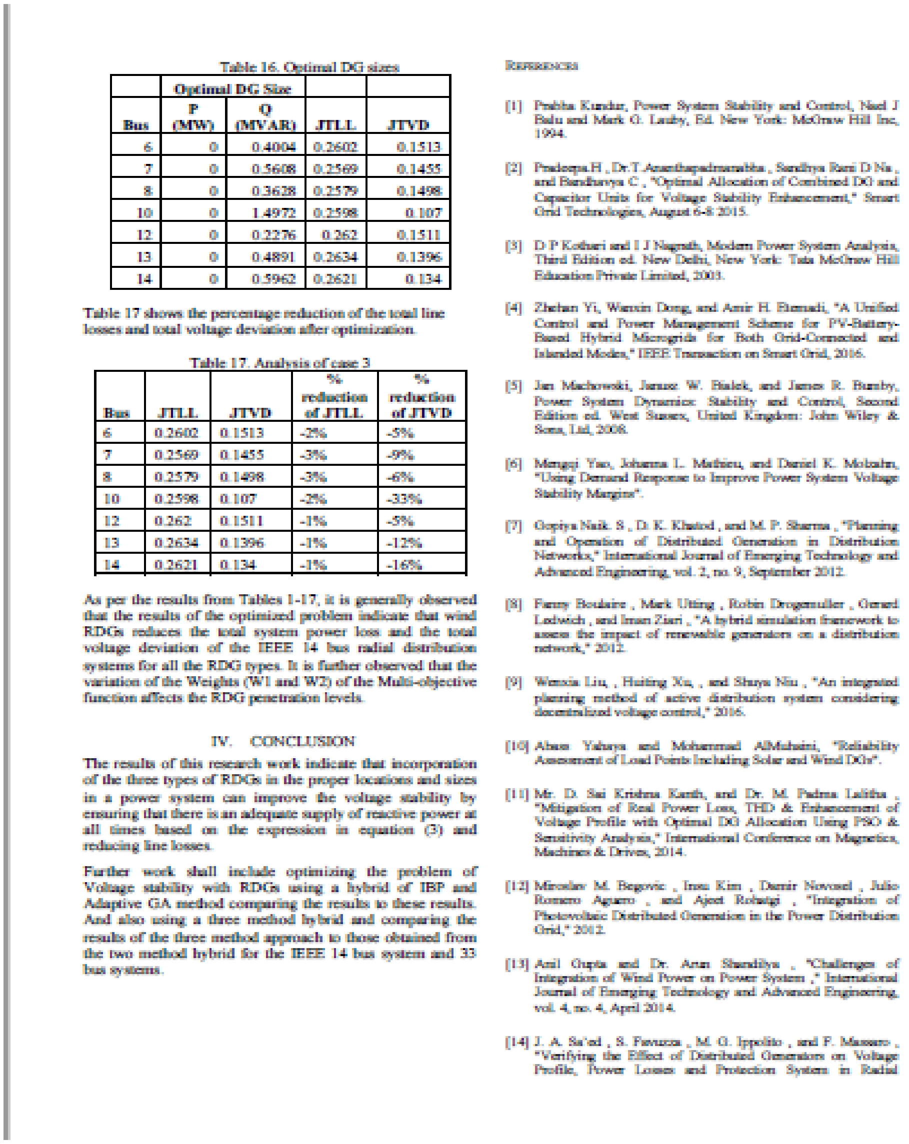


Table 16. Optimal DG sizes

	Optimal DG Size			
Bus	P (MW)	Q (MVAR)	JTLL	JTVD
6	0	0.4004	0.2602	0.1513
7	0	0.5608	0.2569	0.1455
8	0	0.3628	0.2579	0.1498
10	0	1.4972	0.2598	0.107
12	0	0.2276	0.262	0.1511
13	0	0.4891	0.2634	0.1396
14	0	0.5962	0.2621	0.134

Table 17 shows the percentage reduction of the total line losses and total voltage deviation after optimization.

Table 17. Analysis of case 3

Bus	JTLL	JTVD	% reduction of JTLL	% reduction of JTVD
6	0.2602	0.1513	-2%	-5%
7	0.2569	0.1455	-3%	-9%
8	0.2579	0.1498	-3%	-6%
10	0.2598	0.107	-2%	-33%
12	0.262	0.1511	-1%	-5%
13	0.2634	0.1396	-1%	-12%
14	0.2621	0.134	-1%	-16%

As per the results from Tables 1-17, it is generally observed that the results of the optimized problem indicate that wind RDGs reduces the total system power loss and the total voltage deviation of the IEEE 14 bus radial distribution systems for all the RDG types. It is further observed that the variation of the Weights (W1 and W2) of the Multi-objective function affects the RDG penetration levels.

IV. CONCLUSION

The results of this research work indicate that incorporation of the three types of RDGs in the proper locations and sizes in a power system can improve the voltage stability by ensuring that there is an adequate supply of reactive power at all times based on the expression in equation (3) and reducing line losses.

Further work shall include optimizing the problem of Voltage stability with RDGs using a hybrid of IBP and Adaptive GA method comparing the results to these results. And also using a three method hybrid and comparing the results of the three method approach to those obtained from the two method hybrid for the IEEE 14 bus system and 33 bus systems.

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Reduction of Line Losses and Enhancement of Voltage Stability in a Radial Distribution System with Renewable Distributed Generation

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***Abstract*— Reduction of line losses in a distribution system is very important and cannot be overlooked in the modern distribution systems which have been expanded to meet the increased load demand. This is because line losses have an undesirable effect on the voltage profile of the power system especially when electrical power has to be transmitted over long distances due to increased line resistance. Consequently this results to increased voltage drop along the lines and voltage compensation has to be employed to avoid voltage collapse. Introduction of Renewable Distributed Generation (RDG) in the distribution network has been deployed in addressing this problem in the recent past. However, interconnection of these RDGs to the grid has to be properly done to enhance the performance of the system by reducing line losses and improving the system's voltage profile. A formulation of the multi-objective problem of reducing line losses and enhancing voltage stability of the distribution system with RDGs is very important for proper system operation. This paper presents a three method approach of optimally locating and sizing RDGs using Voltage Stability Index (VSI), Adaptive Genetic Algorithm (AGA) and Simulated annealing (SA) to solve this problem. Researchers have solved this problem by; using under frequency load shedding, optimally locating Flexible AC Transmission systems (FACTS) and by use of capacitor banks to achieve reactive power compensation. Over the last decade optimal DG placement and sizing has been an emergent trend. This paper contains a review of the methods applied by other researchers in solving the problem, a detailed formulation of the multi-objective problem and an analysis of the solutions obtained from the standard IEEE 33 Bus test system using MATLAB. Results from the proposed method are compared with Particle Swarm Optimization (PSO) method and Optimal Power Flow and Improved Harmony Search (OPF and IHS) hybrid. Obtained results indicate that properly located and sized RDGs reduce line losses and increase voltage stability in a radial distribution network.**

Keywords:-Renewable Distributed Generation (RDG), Voltage Stability Index (VSI), Adaptive Genetic Algorithm (AGA), Simulated Annealing (SA).

I. INTRODUCTION

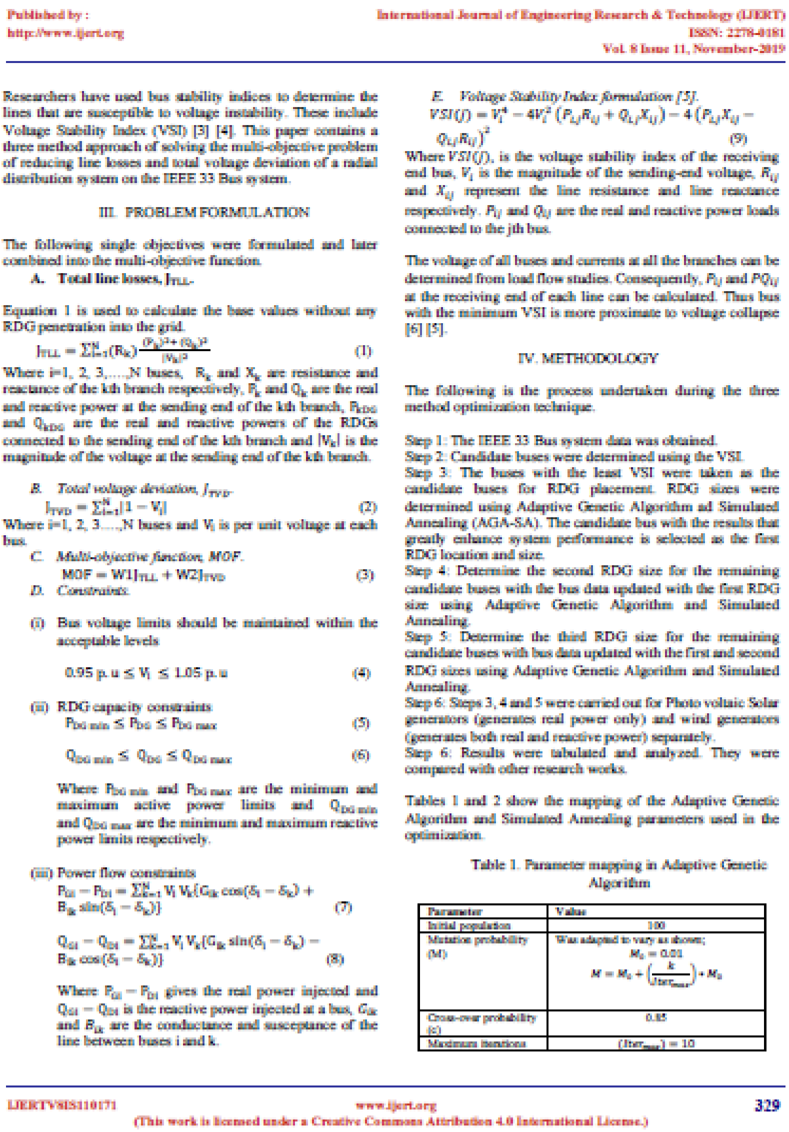
Owing to the increase in electrical load at the distribution level of a power system, distribution network expansion has proofed to be inevitable. It is therefore, critical to ensure that the system remains stable and reliable. Renewable Distributed Generation has been an emerging trend in curbing the problem of line losses and voltage stability in expansive distribution networks by having RDGs located near the consumer centers. This reduces transmission line losses and eliminates the cost of transmission network expansion that would be required to cater for the additional electrical load. RDGs have been adopted because they pose minimal environmental effects and cannot be depleted unlike fossil fuel Distributed Generators. Following the increased advocacy on environmental conservation worldwide, RDG has become an active emergent trend over the last decade.

Contribution:-This research paper gives a review of various methods used in placing and sizing grid interconnected DGs, a detailed formulation of the multi-objective problem aimed at reducing line losses and improving voltage stability of a radial distribution system with Renewable Distributed Generation and a two method hybrid optimization technique of solving this problem using a proper blend of wind and Photovoltaic solar sources.

Paper organization:-This paper has five major parts; part II contains literature review, Part III has the problem formulation, part IV consists of the methodology, part V contains the results and a detailed analysis and part VI is made up of the conclusion.

II. LITERATURE REVIEW

Renewable distributed Generation refers to renewable energy sources that are located at load centers either individually or with grid integration so as to meet increased electrical load. Grid Interconnected Renewable Distributed Generation is an emerging trend in modern power systems and it is therefore important to study their effects in the distribution system and also how to improve system performance. Previous research works have found out that incorporation of RDGs in to the grid may affect the system's power factor, line losses and voltage profile due to the fluctuation of power output from the sources. Consequently, system protection may be affected because RDGs may cause reverse active power flow in the feeders [1] [2]. Non-optimally sized and located RDGs results in increased losses, costs and system instability.



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Researchers have used bus stability indices to determine the lines that are susceptible to voltage instability. These include Voltage Stability Index (VSI) [3] [4]. This paper contains a three method approach of solving the multi-objective problem of reducing line losses and total voltage deviation of a radial distribution system on the IEEE 33 Bus system.

III. PROBLEM FORMULATION

The following single objectives were formulated and later combined into the multi-objective function.

A. Total line losses, J_{TLL}.

Equation 1 is used to calculate the base values without any RDG penetration into the grid.

$$J_{TLL} = \sum_{i=1}^{N} (R_k) \frac{(P_k)^2 + (Q_k)^2}{|V_k|^2} \quad (1)$$

Where i=1, 2, 3,….,N buses, R_k and X_k are resistance and reactance of the kth branch respectively, P_k and Q_k are the real and reactive power at the sending end of the kth branch, P_{kDG} and Q_{kDG} are the real and reactive powers of the RDGs connected to the sending end of the kth branch and $|V_k|$ is the magnitude of the voltage at the sending end of the kth branch.

B. Total voltage deviation, J_{TVD}.

$$J_{TVD} = \sum_{i=1}^{N} |1 - V_i| \quad (2)$$

Where i=1, 2, 3….,N buses and V_i is per unit voltage at each bus.

C. Multi-objective function, MOF.

$$MOF = W1 J_{TLL} + W2 J_{TVD} \quad (3)$$

D. Constraints.

(i) Bus voltage limits should be maintained within the acceptable levels

$$0.95 \text{ p.u} \le V_i \le 1.05 \text{ p.u} \quad (4)$$

(ii) RDG capacity constraints

$$P_{DG\,min} \le P_{DG} \le P_{DG\,max} \quad (5)$$

$$Q_{DG\,min} \le Q_{DG} \le Q_{DG\,max} \quad (6)$$

Where $P_{DG\,min}$ and $P_{DG\,max}$ are the minimum and maximum active power limits and $Q_{DG\,min}$ and $Q_{DG\,max}$ are the minimum and maximum reactive power limits respectively.

(iii) Power flow constraints

$$P_{Gi} - P_{Di} = \sum_{k=1}^{N} V_i V_k \{G_{ik} \cos(\delta_i - \delta_k) + B_{ik} \sin(\delta_i - \delta_k)\} \quad (7)$$

$$Q_{Gi} - Q_{Di} = \sum_{k=1}^{N} V_i V_k \{G_{ik} \sin(\delta_i - \delta_k) - B_{ik} \cos(\delta_i - \delta_k)\} \quad (8)$$

Where $P_{Gi} - P_{Di}$ gives the real power injected and $Q_{Gi} - Q_{Di}$ is the reactive power injected at a bus, G_{ik} and B_{ik} are the conductance and susceptance of the line between buses i and k.

E. Voltage Stability Index formulation [5].

$$VSI(j) = V_i^4 - 4V_i^2 \left(P_{L,j} R_{ij} + Q_{L,j} X_{ij}\right) - 4\left(P_{L,j} X_{ij} - Q_{L,j} R_{ij}\right)^2 \quad (9)$$

Where $VSI(j)$, is the voltage stability index of the receiving end bus, V_i is the magnitude of the sending-end voltage, R_{ij} and X_{ij} represent the line resistance and line reactance respectively. P_{ij} and Q_{ij} are the real and reactive power loads connected to the jth bus.

The voltage of all buses and currents at all the branches can be determined from load flow studies. Consequently, P_{ij} and PQ_{ij} at the receiving end of each line can be calculated. Thus bus with the minimum VSI is more proximate to voltage collapse [6] [5].

IV. METHODOLOGY

The following is the process undertaken during the three method optimization technique.

Step 1: The IEEE 33 Bus system data was obtained.
Step 2: Candidate buses were determined using the VSI.
Step 3: The buses with the least VSI were taken as the candidate buses for RDG placement. RDG sizes were determined using Adaptive Genetic Algorithm ad Simulated Annealing (AGA-SA). The candidate bus with the results that greatly enhance system performance is selected as the first RDG location and size.
Step 4: Determine the second RDG size for the remaining candidate buses with the bus data updated with the first RDG size using Adaptive Genetic Algorithm and Simulated Annealing.
Step 5: Determine the third RDG size for the remaining candidate buses with bus data updated with the first and second RDG sizes using Adaptive Genetic Algorithm and Simulated Annealing.
Step 6: Steps 3, 4 and 5 were carried out for Photo voltaic Solar generators (generates real power only) and wind generators (generates both real and reactive power) separately.
Step 6: Results were tabulated and analyzed. They were compared with other research works.

Tables 1 and 2 show the mapping of the Adaptive Genetic Algorithm and Simulated Annealing parameters used in the optimization.

Table 1. Parameter mapping in Adaptive Genetic Algorithm

Parameter	Value
Initial population	100
Mutation probability (M)	Was adapted to vary as shown; $M_0 = 0.01$ $M = M_0 + \left(\frac{k}{Iter_{max}}\right) * M_0$
Cross-over probability (c)	0.85
Maximum iterations	$(Iter_{max}) = 10$

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Table 2. Parameter mapping in Simulated Annealing Algorithm

Parameter	Meaning	Value
Initial population	Initial particle size after 10 iterations	5
Particle	Possible solution	5
Initial temperature	Initial DG size obtained from AGA	0.95
Cooling coefficient (α)	0 < α < 1	0.95
Maximum iterations ($Iter_{max}$)	Maximum iterations	50
Final temperature	Optimal DG size	

V. RESULTS AND ANALYSIS

The Proposed method was tested on IEEE 33 bus system with base active power load of 3.72MW and base reactive power load of 2.3 MVAR. W1 was set to be equal to W2 of the multi-objective function to ensure that the solution met both objectives simultaneously. The P.F was set at 0.83 based on the setting of the work to be compared with by K. Varesi [2]

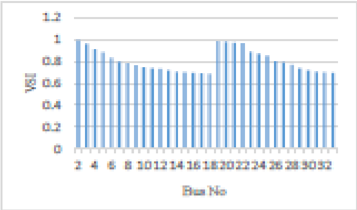
Table 3 shows the base values of JTLL and JTVD before RDG integration into the system.

Table 3. Base JTLL and JTVD

System	Real JTLL (KW)	Reactive JTLL (KVAR)	JTVD
IEEE 33 bus system	219.2	148.6	0.1593

Figure 1 shows Voltage stability indices for each bus based on equation 9 using Newton Raphson method.

Figure 1. Voltage stability index for IEEE 33 Bus system



The weakest buses with VSI of less than or equal to 0.7 were identified as buses 18, 17, 16, 32 and 33 with voltage stability indices of 0.6864, 0.6905, 0.6958, 0.6986 and 0.6971 respectively.

Table 4 shows the optimal RDG size, the total line losses and total voltage deviation after incorporating one real power generating RDG.

Table 4: Results with placement of one RDG generating real power only

Method	Bus No.	RDG SIZE P (MW)	JTLL (KW)	JTVD	% ΔJTLL	% ΔJTVD
PSO [2]	6	2.59	112	Not considered	47%	
OPF and IHS [12]	6	2.59	111.1	Not considered	47%	
VSI, AGA and SA	33	3.5635	82.4	0.0608	62.4%	61.8%

The proposed method gives a 62.4% reduction on the total line losses which is greater compared to the losses from the other comparative works. It also gives a 61.8% reduction in the total voltage deviation and the system performance is therefore, enhanced by having a 3.56 MW Photovoltaic Solar generator placed at bus 33.

Table 5 shows the optimal RDG sizes, the total line losses and total voltage deviation after incorporating two real power generating RDGs.

Table 5: Results with placement of two RDGs generating real power only

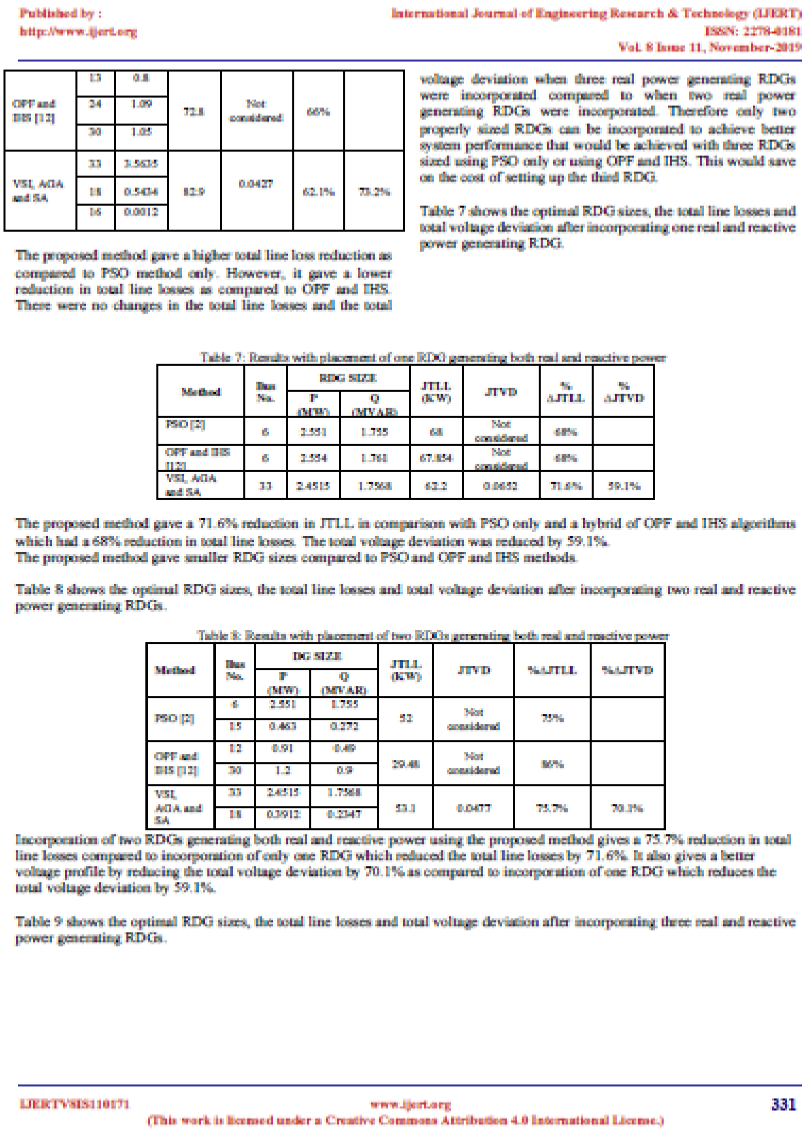
Method	Bus No.	RDG SIZE P (MW)	JTLL (KW)	JTVD	% ΔJTLL	% ΔJTVD
PSO [2]	6	2.59	96.1	Not considered	54%	
	15	0.473				
OPF and IHS [12]	13	0.85	87.16	Not considered	59%	
	30	1.15				
VSI, AGA and SA	33	3.5635	82.9	0.0427	62.1%	73.2%
	18	0.5434				

The proposed method gives a 62.1% reduction in total line losses with incorporation of two real power generating RDGs at buses 33 and 18. There was 73.2% improvement in the total voltage deviation from the base value with two real power generating RDGs incorporated as compared to the 61.8% improvement with only one real power generating RDG.

Table 6 shows the optimal RDG sizes, the total line losses and total voltage deviation after incorporating three real power generating RDGs.

Table 6: Results with placement of three RDGs generating real power only

Method	Bus No.	RDG SIZE P (MW)	JTLL (KW)	JTVD	% ΔJTLL	% ΔJTVD
PSO [2]	6	2.59	88.6	Not considered	58%	
	15	0.473				
	25	0.637				



OPF and IHS [12]	13	0.8	72.8	Not considered	66%	
	24	1.09				
	30	1.05				
VSI, AGA and SA	33	3.5635	82.9	0.0427	62.1%	73.2%
	18	0.5434				
	16	0.0012				

The proposed method gave a higher total line loss reduction as compared to PSO method only. However, it gave a lower reduction in total line losses as compared to OPF and IHS. There were no changes in the total line losses and the total voltage deviation when three real power generating RDGs were incorporated compared to when two real power generating RDGs were incorporated. Therefore only two properly sized RDGs can be incorporated to achieve better system performance that would be achieved with three RDGs sized using PSO only or using OPF and IHS. This would save on the cost of setting up the third RDG.

Table 7 shows the optimal RDG sizes, the total line losses and total voltage deviation after incorporating one real and reactive power generating RDG.

Table 7: Results with placement of one RDG generating both real and reactive power

Method	Bus No.	RDG SIZE		JTLL (KW)	JTVD	% ΔJTLL	% ΔJTVD
		P (MW)	Q (MVAR)				
PSO [2]	6	2.551	1.755	68	Not considered	68%	
OPF and IHS [12]	6	2.554	1.761	67.854	Not considered	68%	
VSI, AGA and SA	33	2.4515	1.7568	62.2	0.0652	71.6%	59.1%

The proposed method gave a 71.6% reduction in JTLL in comparison with PSO only and a hybrid of OPF and IHS algorithms which had a 68% reduction in total line losses. The total voltage deviation was reduced by 59.1%.
The proposed method gave smaller RDG sizes compared to PSO and OPF and IHS methods.

Table 8 shows the optimal RDG sizes, the total line losses and total voltage deviation after incorporating two real and reactive power generating RDGs.

Table 8: Results with placement of two RDGs generating both real and reactive power

Method	Bus No.	DG SIZE		JTLL (KW)	JTVD	%ΔJTLL	%ΔJTVD
		P (MW)	Q (MVAR)				
PSO [2]	6	2.551	1.755	52	Not considered	75%	
	15	0.463	0.272				
OPF and IHS [12]	12	0.91	0.49	29.48	Not considered	86%	
	30	1.2	0.9				
VSI, AGA and SA	33	2.4515	1.7568	53.1	0.0477	75.7%	70.1%
	18	0.3912	0.2347				

Incorporation of two RDGs generating both real and reactive power using the proposed method gives a 75.7% reduction in total line losses compared to incorporation of only one RDG which reduced the total line losses by 71.6%. It also gives a better voltage profile by reducing the total voltage deviation by 70.1% as compared to incorporation of one RDG which reduces the total voltage deviation by 59.1%.

Table 9 shows the optimal RDG sizes, the total line losses and total voltage deviation after incorporating three real and reactive power generating RDGs.

Table 9: Results with placement of three RDGs generating both real and reactive power

Method	Bus No.	DG SIZE		JTLL (KW)	JTVD	%ΔJTLL	%ΔJTVD
		P (MW)	Q (MVAR)				
PSO [2]	6	2.551	1.755	43	Not considered	80%	
	15	0.463	0.272				
	25	0.685	0.31				
OPF and HHS [12]	13	0.78	0.42	13.47	Not considered	94%	
	25	0.83	0.43				
	30	1.15	0.86				
VSI, AGA and SA	33	2.4515	1.7568	53	0.0652	75.8%	59.1%
	18	0.3912	0.2347				
	32	0	0.0092				

Incorporation of a third real and reactive power generating RDG did not have any considerable effect on the reduction of line losses compared to the system with two such RDGs integrated. However, the voltage profile deteriorated from a 70.1% reduction in total voltage deviation with two RDGs to 59.1% reduction with three RDGs. The results in table 7 and 8 indicate that the system achieves enhanced performance with only two RDGs incorporated. Integration of a third RDG would result to increased costs of setting up the third RDG unit which would cause a distortion of the system`s performance. Therefore the proposed method would be used in optimally siting ad sizing two RDG units.

VI. CONCLUSION

This paper has presented a three method approach of solving the multi-objective problem of reducing total line losses and total voltage deviation in IEEE 33 bus system. The optimal locations were obtained using Voltage Stability Index and a hybrid of Adaptive Genetic Algorithm and Simulated Annealing was used to achieve the optimal RDG sizes while solving both objectives simultaneously because it has the better convergence. Results show that having one and two optimally placed and sized RDGs would improve the system performance. A third RDG would not be required with the propose algorithm because it would distort the system performance. Further work can be done on applying this method on larger interconnected test systems and also tested on a network with a variable loading profile.

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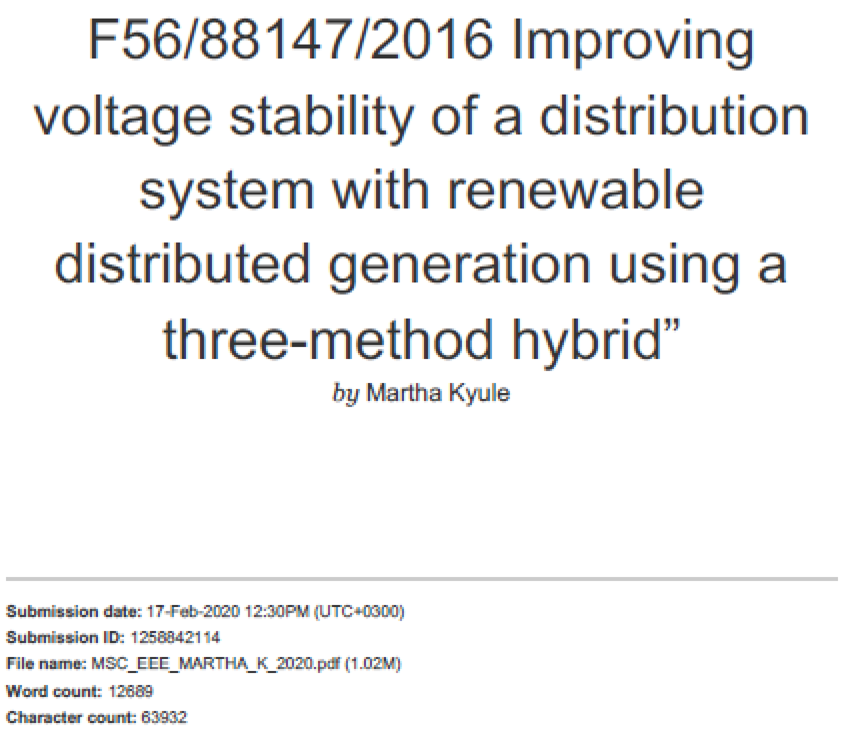

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by Martha Kyule

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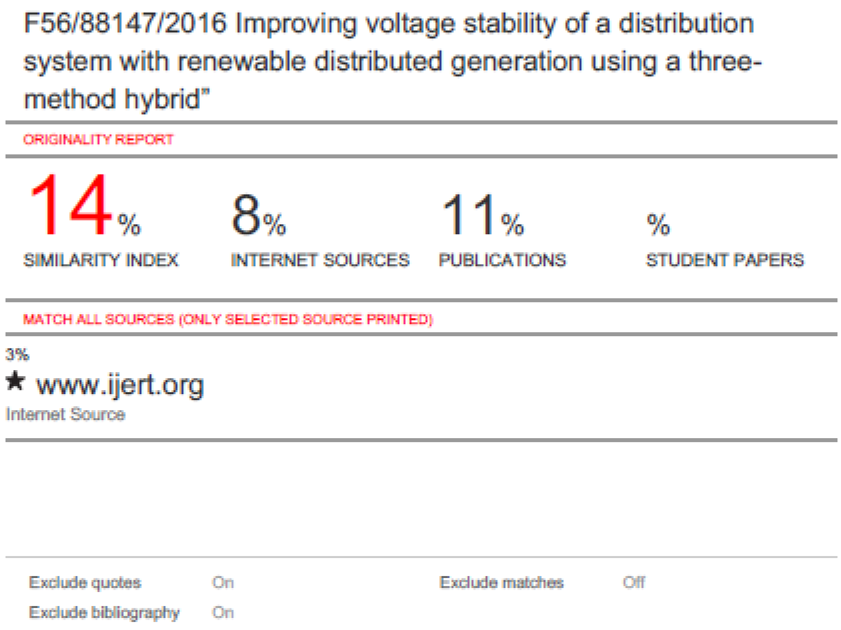

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