DETERMINATION OF THE MAXIMUM PENETRATION LEVEL OF AUXILIARY SERVICE VOLTAGE SUB-STATIONS ON 132kV TRANSMISSION NETWORK

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Determination of the maximum penetration level of Auxiliary Service Voltage Transformer Sub-stations on 132kV Transmission Network

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DECLARATION

This thesis is my original work, and has not been presented for a degree in any other university.

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This MSc thesis is dedicated to my Mum, though illiterate, her love for education made me realize my dreams. . . .

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ABBREVIATIONS

ASVT	Auxilliary Service Voltage Transformer
C	Capacitance
CB	Circuit Breaker
HV	High Voltage
kVA	Kilo Volt-Ampere
L	inductance
LV	Low Voltage
MVA	Mega Volt-Ampere
P	Active power
PF	Power Factor
P_{max}	maximum active power
P.U	per unit
Q	Reactive power
R	Resistance
RE	Rural Electrification
SIL	Surge Impedance Loading
SSVT	Station Service Voltage Transformer
SSA	Sub-Sahara Africa
V_l	Line voltage
V_R	Receiving end voltage
V_S	Sending end voltage
X	Reactance

Z_in	Input impedance
Z_l	Load impedance
Z_O	Output impedance

ABSTRACT

The overall electricity access rate is still very low in most sub-Saharan African (SSA) countries. The rate is even lower in rural areas where most of the population in these countries live. One of the main obstacles to rural electrification (RE) is the high cost of laying the distribution infrastructure owing to the dispersed nature of loads and low demand. Thus, electrifying the rural areas needs to be considered holistically and not just on the financial viability. To reduce cost, it is important that auxiliary service voltage transformer (ASVT), which are cheaper than the conventional substation be explored. ASVT have been tried successfully in some parts of the world like Congo and Mexico. However the literature review showed that no work had so far been done with regard to determination of the penetration point and maximum penetration level of these technologies on power transmission networks. These ASVT sub-stations have the ability to tap power directly from high voltage transmission lines of either 132kV or 220kV and step it down to 240V for single phase distribution.

This research investigated the penetration point and maximum penetration level of ASVT sub-stations in power transmission networks with regard to transmission line voltage profile.

The research was done by simulating ASVT sub-station models terminated in High Voltage transmission lines using SIMULINK software. The realized voltage levels were compared with the expected H.V transmission line voltage levels to determine whether the voltage profile had been violated. The ASVT loadability curves and the constructed Surge Impedance Loading (SIL) curves were used to ascertain voltage stability of the system. The research revealed that the first ASVT sub-station can be terminated at any point on the H.V transmission line without violating voltage profile.

The simulation further revealed that a maximum of nine ASVT sub-stations can be terminated on a 440km, 132kV transmission line without violating the voltage profile of the transmission network.

CHAPTER ONE

INTRODUCTION

1.1 Background information

In most rural areas of the developing countries, the concentration of electricity users is low and the cost of deploying a conventional sub-station is very high. As a result, a power utility company cannot generate an adequate return on investment necessary to bring a conventional distribution sub-station on line [20],[9]. On the other hand, there are large numbers of rural communities in these areas living around or in close proximity to high voltage transmission lines (132kV) but are not supplied with electricity. The main obstacle is that, these transmission lines are operating at very high voltages that cannot be directly and cheaply be used for electrification [23],[19]. To address the high costs incurred with the use of conventional sub-stations, the application of non-conventional sub-station namely; Auxiliary Service Voltage Transformer (ASVT) sub-station has been explored in this research.

The ASVT also known as Station Service Voltage Transformer (SSVT) combines the characteristics of instrument transformer with power distribution capability. In this transformer, the high voltage side is connected directly to the overhead transmission line of either 220kV or 132kV, while the secondary side may be of typical voltage ratings of 240V, 480V, 600V or any other voltage level supplies designed on order. One step down principle is applied to achieve the low voltages just like in instrument transformers [1].

The ASVT can either be used to step down high voltage from transmission line to low voltage output then supply loads directly or simply step down 132kV to 11kV then use a conventional step down distribution transformer to supply the consumer loads. The use of conventional distribution transformers will only be preferable where this power is to be supplied to consumers far away from the high voltage transmission lines. In this case step up and step down of voltages is essential. Use of conventional transformer after ASVT substation will lead to additional cost which will finally be transferred to electricity consumers.

In developing countries where transmission line infrastructure is already in place but a wide spread distribution infrastructure is lacking, the non-conventional distribution sub-station technologies can be used to greatly reduce the electrification costs for small villages [6].

A distribution transformer is a transformer that provides the final voltage tranformation in the electric power distribution system, stepping down the voltage used in the distrisbution lines to the level used by the final consumers. These transformers only transform voltage from distribution lines unlike the Auxiliary service voltage transformers which steps down high voltages from transmission lines to level required by final consumers.

1.2 Problem statement

In Kenya about 8% of rural communities lives at close proximity to High voltage transmission lines, yet they are not connected to power network [27]. The absence of nearby conventional sub-station diminishes the hopes of ever being supplied with electricity, since the cost of setting up one is extremely high. On the other hand, it is the responsibility of every Government to ensure that all citizens are electrified. Due to this backdrop that this research explores an innovative, adoptable and cheaper approach to supply electricity to these communities.

The introduction of the ASVT sub-station in the existing transmission network, though may easily solve the existing problem facing the villages living at close proximity to the transmission lines, it may also pose stress to the system by possibly violating the voltage profile of the network. This may cause voltage instability.

The research investigates and presents the optimum penetration level of ASVT sub-station on high voltage transmission network.

1.3 Justification

Rural electrification, a key ingredient in improving modern life with regard to health, education, communication and lightING, remains largely elusive for most rural communities. The overall electrification rates in sub-Sahara Africa (SSA) stand at 14.2% in the urban and rural area figures standing at 59.9% and 30.5% respectively [2]. One way of tackling this problem is the use of ASVT. Literature shows that sub-Sahara Africa has the lowest percentage rural and urban electrification access, consequently, there arises a need to consider the use of ASVT sub-stations especially the cost reduction apparently offered by these systems. The maximum percentage penetration level of ASVT substation with regard to voltage quality, stability, and capacity constraints has been addressed to help policy makers and network utility companies in their planning and operations.

1.4 Objectives

1.4.1 General objectives

Determine the economic viability and maximum penetration level of ASVT sub-stations on 132kv transmission network, without voltage profile violation.

1.4.2 Specfic objectives

(1) Determine the maximum penetration level of ASVT sub-stations on a 132kV transmission line without voltage profile violation.

(2) Analyze voltage quality and stability of the system at different penetration levels of ASVT sub-stations on the 132kV transmission line.

(3) Carry out techno-economic comparative assessment of conventional versus non-conventional (ASVT) sub-stations

1.5 Scope

This thesis investigated the most economical sub-station which can be used to supply electricity to sparsely populated villages living within a 400metres radius to 132kv transmission line. The study was limited to the determination of the optimum penetration level of non-conventional (ASVT)sub-station on the H.V line to supply villages with electricity without voltage profile violation. The study further analyzed the voltage stability of the system at different ASVT sub-station penetration levels. A case study of Maungu village was also considered to analyze the economic viability of the ASVT sub-station in comparison to conventional sub-station and the maximum number of ASVT sub-stations that can be terminated in the system beyond which conventional sub-station will be more preferable. The study first considered a typical unloaded 132kV transmission line, then Nairobi-Rabai 132kV transmission line.

CHAPTER TWO

LITERATURE REVIEW

2.1 Background information

In many countries of sub-Sahara Africa, there are many rural regions where the distribution network is not developed mainly because of the dispersed nature and low load level compared to the investment needed to supply them. In some of these locations, its remarkable to notice that high voltage trunk line transverse through these regions but cannot feed any of these small villages living close to such lines (220, 400 and 735kV). Such lines carry power from large power stations to large towns some hundreds of kilometers away. This situation is also common in Canada, Russia and China [22]

2.2 Auxiliary Service Voltage Transformer.

The Auxiliary Service Voltage Transformer, sometimes known as a Station Service Voltage Transformer is insulated in sulfur hexafluoride (SF6) gas and combines the characteristics of instrument transformer with power distribution capability [23],[22]. All the dielectric characteristic of the conventional instrument transformer are applicable to ASVT even though these are hybrid apparatus which are between an instrument transformer and a distribution transformer. This inductive transformer has a very high thermal power in comparison with conventional instrument transformer, in general f rom 20 up to 60 times more than the design of new generation transformer, without reaching the capacity of a power transformer. [4]

A conventional power transformer and ASVT have one thing in common, they can all step down voltage to low levels for distribution purposes. Several conventional power transformers have to be employed to step down voltage from 132/66kV, 66/33kV, 33/11kV for distribution purposes whereas ASVT is capable of stepping 132/11kV or even lower in one step. This is made possible by the high range of the transformation ratio employed in ASVTs as compared to the coventional power transformers. The high range voltage step down capability of ASVTs demands that high provisions for better insulation be used compared to that of conventional power transformers and hence the use of SF6 gas for insulation unlike conventional power transformers which use oil.

According to Gray Vessel [12], the SSVT is constructed around the premises of an enlarged core and coil of an instrument transformer. This voltage transformer with a larger core and coil is then used to supply suitable thermal burden output for station service control power application or community electrification projects. These transformers have power rating of between 10kVA to 333kVA. [12]. The SSVT can be installed as a mini-substation.

ASVT with gas insulation are made with a magnetic core inside a metallic tank with its primary and secondary windings around it. These windings are made of heat resistant electric wires coated in synthetic resin and a layer of plastic with a high dielectric resistance and excellent thermal and mechanical performance[1]. The sulfur hexafluoride (SF6) gas and the plastic layer form the electrical insulation. An input gas for SF6 gas is provided on a side of tank together with manometer for monitoring leakages and gas pressure.

The ASVT allows directly connection from high voltage line and transforms voltage from 220kV to 240V as shown in fig 2.1, with a thermal power of 50kVA up to 330kVA per phase [20],[23],[6]. This is unlike distribution transformers used for lower voltage distribution network as a means of end user connectivity (11kV, 6.6kV, 3.3kV, 440V, 230V) and are generally rated below 200MVA.

ASVTs were originally designed to suit supply for auxiliary services within the substation such as lighting loads, motor loads and instrument purposes [19],[4].

Tapping the high voltage transmission line and connecting an ASVT with a small footprint substation will provide affordable, readily available electricity to many rural communities in close proximity to high voltage lines and presently without power [23],[19].

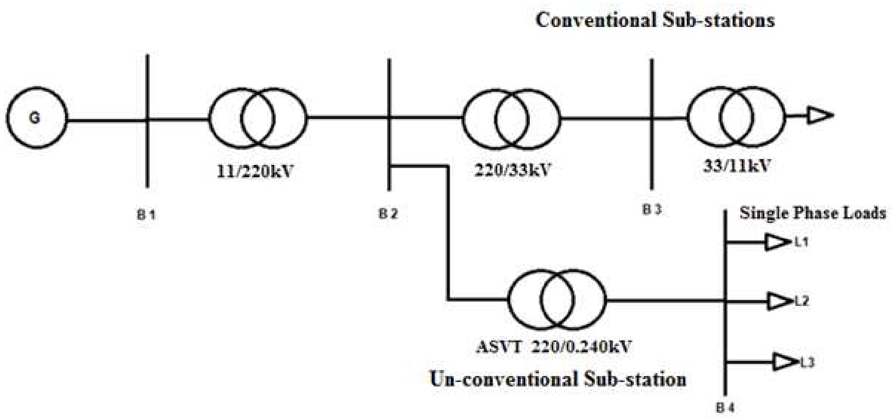

Figure 2.1: Single line diagram of ASVT VS conventional sub-station

A pilot project was successfully carried out in the rural town of Tubares in Mexico, where ASVT were used to supply the rural areas. The ASVT tapped power from a line of 123kV and transformed it to 230V for distribution purposes. According to Gomez [4], the system involves very simple station engineering and presented a successful and economically viable alternative for electrification of rural communities with a load requirement of 50kVA single phase up to 1MVA at three phase arrangement, supplying enough power for applications like refrigeration, water pumping, lighting and other low voltage applications.
The following protection measures were observed in ASVT sub-station. [4].

(1) Power fuses for the protection of high voltage line

(2) Surge arrester for substation protection

(3) Thermo magnetic low voltage circuit breaker for the transformer protection

(4) Current transformer at low voltage for metering applications

(5) Voltage riser transformer

(6) Recloser, as medium voltage interruptive device

(7) Voltage regulator

Another pilot project was successfully carried out in 2002 in a village located in Congo Brazzavile, which continues to function correctly up to date. In this project an Auxiliary Service Voltage Transformer with its primary side connected to high line voltage 220kV to produce a low voltage of single phase 230V directly to be used by the rural population. It has a power rating of 50kVA [22]
The ASVT substation was chosen in this research to supply the villages with electricity because of the following reasons:

(1) Use of ASVT as an isolator transformer for protection of the personnel, equipment and the electricity users

(2) ASVT being an instrument transformer is capable of providing dual services of power supply and instrumentation activities

Challenges of AVST systems:

(1) Determination of the penetration point of ASVT sub-station, that does not lead to voltage profile violation.

(2) ASVT insulation level - with the high tension experienced during step down of EHV to low voltages the insulation of transformer windings becomes a challenge since heavy currents will flow in the secondary windings.

2.2.1 Modeling of a Transformer

This transformer model introduces the sequence of operations necessary to evaluate the parameters of the transformer equivalent circuit by means of the numerically simulated open-circuit and short-circuit tests. The equivalent circuit for the transformer is shown in Figure 2.2. In this circuit, R_1 and R_2 represent the resistance of the primary and secondary windings, respectively. The leakage reactances of the primary and secondary windings are represented by X_1 and X_2, respectively. The magnetizing reactance is represented by X_m, and appears in the circuits vertical branch. The resistance R_c accounts for the losses in the magnetic core. In this drawing, N_1 and N_2 denote the number of turns of the primary and secondary windings, respectively. [24]

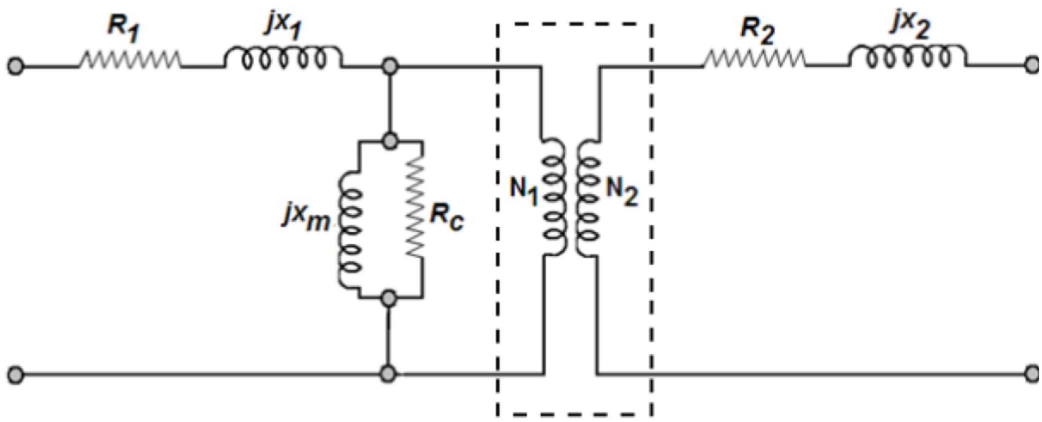

Figure 2.2: Transformer model

If the turns ratio of the transformer is assumed equal to one, the analysis task is facilitated by the use of the T-shaped, simplified equivalent circuit shown in Figure 2.3. Although study of power transformer performance is usually based on analysis of sinusoidal steady-state operation at 50 Hertz, only two magnetostatic field solutions are required for the numerically simulated open-circuit and short-circuit tests. The calculations of the various parameters indicated in Figure 4.3 are based on static solutions, hence the iron loss due to eddy currents cannot be computed. This represents a minor limitation for most power systems analysis tasks, because no-load losses in a transformer are a very small part of the transformer power rating, usually less than 1%. Based on the simplifying assumption of a lossless magnetic core, only the ohmic loss in the two conductive windings will be taken into account. The ohmic loss of each winding is computed from the known wire resistance. The test problem considered in the present study concerns the equivalent circuit of the idealized single-phase shell-type transformer.

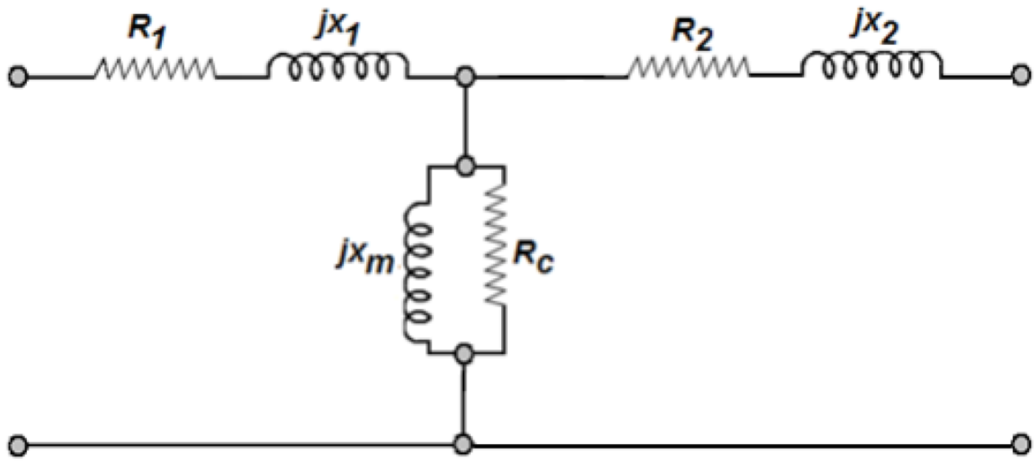

Figure 2.3: Simplified Transformer model

2.2.2 ASVT design and construction

The modeling programs have allowed designers to develop Auxiliary service voltage transformer capable of transforming extra high voltage like 132kV to low voltages like 600volts in one step which can be used in applications like control system, pump motors, instrumentation and illumination. [23]

An ASVT model is based on the knowledge of the magnetic circuit theory and finite analysis of a conventional transformers.

In the design of Auxiliary service voltage transformer, the terminal voltages, VA rating and frequency are specified. In the reverse design approach the physical characteristics and dimensions of the windings and core are specified.

Transformer performance depends on the manipulation of the amount of construction material used and its type.[3]

This method of transformer design allows for tailor made transformers customized to the required application. This creats room for a considerable flexibility in meeting the performance required for a particular application. This type of design is suitable for ASVT models since they are meant for customized application [3].

In the reverse design method, the transformer is built up from the core outwards. The core cross section dimensions (diameter for a circular core and side lengths for a rectangular core) are selected from catalogues of available materials. A core length is chosen. Laminations that are availabe can be specified in thickness. A core stacking factor can be estimated from the ratio of iron to total volume.

Given the core length l_c and diameter,(or b_{core} and w_{core} for a rectangular core), the inside winding usually low voltage winding is wound on layer by layer. The wire size is determined by considering the magnitude of the primary current. Insulation thickness is depends on the available space and cooling method used. The designer can then specify how many layers of each winding are wound.

Insulation is placed between core and the inside winding (former) and between each layer for high voltage applications. The outer winding usually the HV windings is wound over the inside winding,with the insulation between layers according to the voltage between them.

Windings current densities and volt per turn become a consequence of the design, rather than a design specification. The only rating requirements are the primary voltage and frequency.

The secondary voltage and transformer VA rating are a consequence of the construction of a transformer. The number of turns are estimated to be [3];

$$N_1 = \frac{l_c L_1}{t_1} \tag{2.1}$$

$$N_2 = \frac{l_c L_2}{t_2} \tag{2.2}$$

Where,

l_c = length of the core

L_1, L_2 = number of primary and secondary winding layers

t_1, t_2 = axial thickness of primary and secondary wire

This calculation assumes that the winding length is equal to the core length. The actual winding lengths may be used if the primary and the secondary winding lengths are different and do not fully occupy the winding window height.

2.2.3 Flowchart for ASVT reverse design method

In the reverse design approach the transformer is built up from the core outwards. The core crossectional dimensions are selected from catalogue of available materials. A core length is chosen, available lamination are specified in thickness. A core stacking factor can be estimated from the ration of iron to total volume. This type of design is suitable for ASVT models since they are meant for customized application. Fig 2.4 shows the proposed design procedure in a flow chart form.

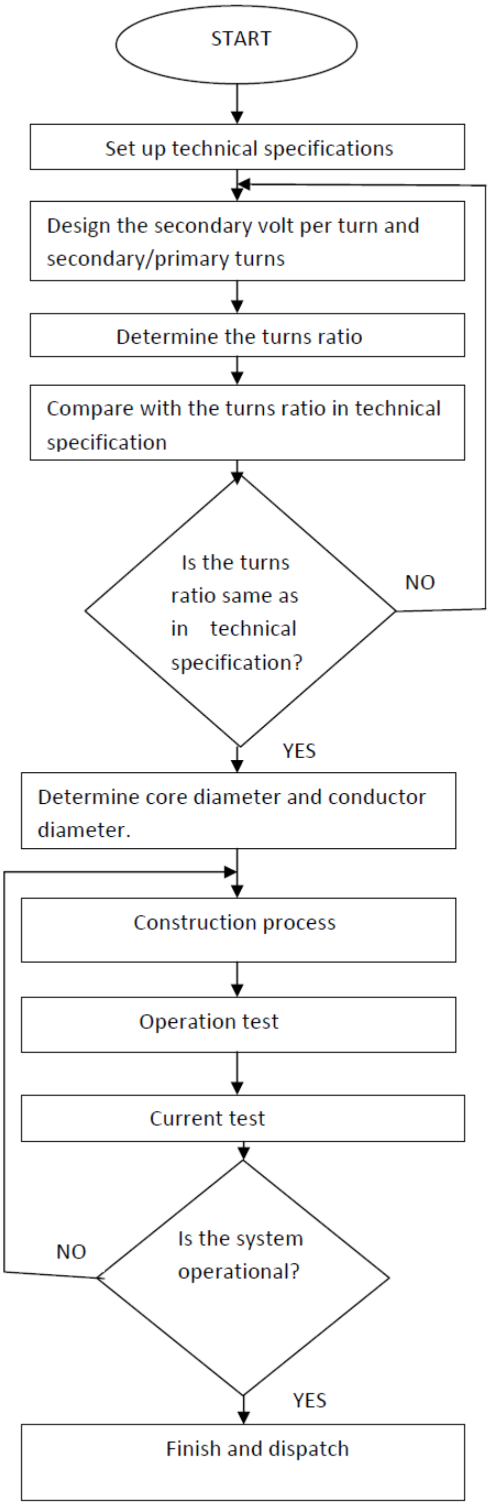

Figure 2.4: Flow chart for ASVT reverse design method

2.3 Parameters of transformer model

2.3.1 Winding Capacitance

Figure 2.5 shows the inner and outer sides of the transformer winding connected as the parallel plates of a capacitor with oil and paper as the dielectric. The equation for parallel plate capacitance is generally valid for calculation of the various capacitances.

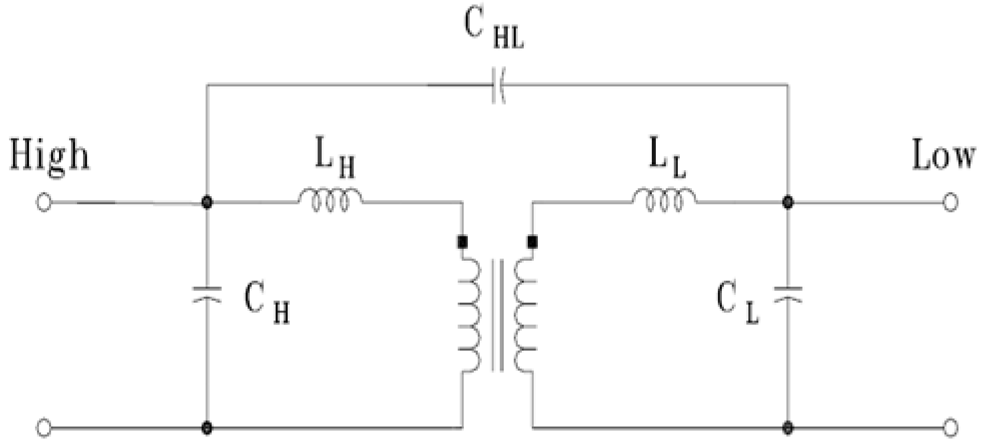

Figure 2.5: Equivalent circuit for winding capacitance

$$\mathrm{C} = \frac{A.\epsilon_0.\epsilon_r}{d} \tag{2.3}$$

where,

A = Area of one of the plates forming capacitance

d = Distance between the two parallel plates

ϵ_0 = permittivity of free space

ϵ_r = relative permittivity of the dielectric

Substituting the values of winding surface areas and gaps between windings in Equation (4.9), the winding capacitance can be calculated. For core-type transformers, the winding capacitances can in this way be approximated by parallel plate capacitance formulas in which the capacitance is proportional to the area of the plates and inversely proportional to the separation between the plates. The size of the plates can be approximated as being proportional to the square root of the MVA, while their separation can be approximated as being proportional to the basic insulation level for the higher of the two windings involved. For a two winding transformer, the capacitance of the HV winding to ground is generally less than the capacitance of the LV winding to ground because of the increased clearance needed for the HV winding. [28]

For a shell-type transformer, the parallel plate model for the transformer winding to ground capacitance calculations is not as accurate or as applicable. This is because of the clearance needed in the HV winding and the type of the insulation used. For the HV to LV capacitance, the parallel plate representation is quite reasonable and accurate. The HV to LV capacitance is proportional to the number of HV to LV gaps.

2.3.2 Inductance

The self- and mutual inductances of the two windings were calculated using the flux linkage approach. These calculations were based on a practical study of transformer parameters on open circuit condition, as shown in table 2.1.[24]

Table 2.1: Transformer parameters on open circuit condition

TRANSFORMER PARAMETER	VALUE
Flux linkage with the primary winding	211.936 wb
Terminal current of the primary winding	2.0 A
Flux linkage with the secondary winding	211.686 wb
Self-inductance	105.968 H
Mutual inductance M	105.843 H
Leakage inductance	0.125 H

The self-inductance L_1 of the primary winding is given by,

$$L_1 = \frac{\lambda_{11}}{i_{t1}} \tag{2.4}$$

where

λ_{11} =flux linkage with the primary winding

i_{t1} =terminal current of the primary winding

For a primary ;flux linkage of 211.936 webers and a terminal current of 2.0 A, the calculation yields;

$$L_1 = \frac{211.936}{2.0} = 105.968\ H \tag{2.5}$$

The mutual inductance M is calculated as;

$$M = \frac{\lambda_{21}}{i_{t1}} \tag{2.6}$$

where;

λ_{21} = flux linkage with secondary winding

For a secondary flux linkage of 211.686 webers and a primary terminal current of 2.0 A, the calculation gives;

$$M = \frac{211.686}{2.0} = 105.843\ H \tag{2.7}$$

Once both windings have equal number of turns, the leakage inductance of the primary is defined as;

$$l_1 = L_1 - M \tag{2.8}$$

2.3.3 Frequency dependancy core resistance

Coil resistances vary widely depending on the frequency of the current flowing. The variation is due to skin effect and proximity effect. Skin effect is caused by the nonuniform distribution of current in the conductor. As the frequency of the current is increased, more current flows near the surface of the conductor. Thus, the effective resistance increases. The effective resistance typically varies as the square root of frequency. [28]

$$R_{ac}(f) = R_{50}[f/50]^k \tag{2.9}$$

where,

k = 0.5

R_{50} = 50 HZ resistance

However, a higher number of layers in the coil lead to a great resistance variation due to proximity effect. The frequency dependency of coil resistance is:

$$R_{ac}(f) = real[R_{DC}.u.\coth(u) - 2/3\tanh(u) + 2/3.nl^2.\tanh(u)] \tag{2.10}$$

where,

a = coil diameter in metres

δ = skin depth in metres

$\mu_0 = 4\pi \times 10^{-7}$

θ = conductance(0.5×10^8)

nl = the number of layers

and

$$\delta = \sqrt{\frac{1}{\pi.f.\sigma.\mu_0}} \tag{2.11}$$

$$u = (1+j).\frac{a}{\delta} \tag{2.12}$$

2.4 Penetration level of ASVT sub-stations on power network

The term penetration point with regard to this thesis refers to the termination point of the first reactive system on a high voltage transmission network without voltage profile violation of the line. The penetration level refers to the maximum number of Auxiliary service voltage transformer sub-stations that can be terminated on a high voltage transmission line without violating the voltage profile of the network or causing voltage instability which may result to voltage collapse.

The penetration level of ASVT sub-station on transmission network is affected by the following parameters

(1) Transmission line voltage levels: parameters of transmission line conductors changes with the change in voltage levels being transmitted. The conductor sizes of transmission lines used 132kV lines is different to those of 400kV. The change in line parameters leads to corresponding change in capacitance and inductance of the line hence a change in surge impedance loading. A change in surge impedance loading of a line will lead to a change in the penetration level of the line.

(2) Transmission line length: changes in the length of a transmission line leads to a corresponding change of the capacitance and inductance of the line. Changes in capacitance and inductance of a line leads to corresponding change in the characteristic impedance of the line hence a change in surge impedance loading of the line. This affects the penetration level of a transmission network.

(3) The spacing of conductors as they are mounted on the supporting struture: changes of the spacing of conductors leads to a corresponding change in the capacitance and inductance of the line which affects the surge impedance loading of the line hence penetration level of the ASVT sub-stations on the network.

2.4.1 ABCD parameters

The transmission line parameters i.e. capacitance, resistance and inductance for the model has been determined using the following formulars;

$$L = 2 \times 10^{-7} \ln{(D/GMR)}\ H/m \tag{2.13}$$

$$C = \frac{2\pi\epsilon}{ln(D/r')}\ mF/m \tag{2.14}$$

$$R = \frac{\rho l}{A}\ \Omega \tag{2.15}$$

where;
L is the inductance of the transmission line
D is the space between conductors
GMR is the Geometric mean radius of the conductor bundle
$r' = 0.7788r$
C is the capacitance of the transmission conductor
ϵ is the permittivity of the conductor

ρ is the resistivity of the transmission conductor

l is the length of the transmission line

A is the crossectional area of the conductor

R is the resistance of the conductor

Before surge impedance loading (SIL) curves can be constructed it is important to determine the transmission line ABCD parameters. The method used is based on synchronised phasor measurements. This method uses the two-port ABCD parameters. [8]. The ABCD parameters give the relationship between the voltages and currents at two points. For a transmission line this means that the ABCD parameters represents the influence that the capacitance, inductance and resistance of the line has on the voltage and current values measured at the sending and receiving end sides. The relationship is given by the following equations [11],[30]

$$\begin{bmatrix} V_s \\ I_s \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_r \\ I_r \end{bmatrix} \tag{2.16}$$

$$A = cosh\gamma l \tag{2.17}$$

and B are defined by the equations

$$B = Z_c \ sinh\gamma l \tag{2.18}$$

where,

$$Z_O = \sqrt{\frac{(j\omega L + R)}{(j\omega C + G)}} \tag{2.19}$$

Where;

Z_O = characteristic impedance of a lossy line

ωL = inductive reactance of the line

ωC = capacitive reactance of the line

R = resistance of the line

G = conductance of the line

$$\gamma = \sqrt{yz} \tag{2.20}$$

From the preceding equation it is seen that once A and B are known, z and y can be calculated. Therefore, z and y have been defined as the series impedance and shunt admittance per unit length. To evaluate A and B, the sending and receiving ends of the complete model were driven by current or voltage sources at one end while the opposite end being open circuited or short circuited. A matrix was then constructed for the measurements of the two cases.

$$\begin{bmatrix} V_{s1} \\ I_{s1} \end{bmatrix} = \begin{bmatrix} V_{r1} & I_{r1} \\ V_{r2} & I_{r2} \end{bmatrix} \begin{bmatrix} A \\ B \end{bmatrix} \tag{2.21}$$

Using Cramers Rule A and B can be calculated.

$$A = \frac{det \begin{bmatrix} V_{s1} & I_{r1} \\ V_{s2} & I_{r2} \end{bmatrix}}{det \begin{bmatrix} V_{r1} & I_{r1} \\ V_{r2} & I_{r2} \end{bmatrix}} \tag{2.22}$$

$$B = \frac{det \begin{bmatrix} V_{r1} & V_{s1} \\ V_{r2} & V_{s2} \end{bmatrix}}{det \begin{bmatrix} V_{r1} & I_{r1} \\ V_{r2} & I_{r2} \end{bmatrix}} \tag{2.23}$$

To calculate y and z the results from (2.22) and (2.23) are substituted into (2.17) and (2.18).

This will provide two equations with two unknowns to solve. The method is very useful since the impedance is given as a value with a phase angle. This means that

the resistance and inductance are given as separate values. This is also the only method that gives the shunt admittance (y) from where the capacitance can be calculated.
The determination of ABCD parameters played a great role in the analysis of the changes of capacitance, inductance and resistance of the transmission line, when ASVT sub-stations were terminated on a 132kV line. These changes in capacitance and inductance of the transmission line led to corresponding change of the transmission line voltages. The imbalance of inductive reactance and capacitive reactance of the transmission line displays the point of voltage profile violation. In this instance the optimum penetration level of ASVT sub-stations on 132kV transmission line can be determined.

The study of penetration level of ASVTs in a power transmission network is essential, since the integration of the system into the transmission network results to reactive power imbalance which may cause change in the voltage profile of the line. There are two possible methods of determining the optimum penetration level of ASVTs in a power transmission line without steady state voltage violation. [18] namely:

(1) surge impedance loading (SIL) level of the transmission line

(2) use of X/R ratio and comparing it with voltage level on the receiving end

2.4.2 Surge Impedance Loading (SIL)

Surge Impedance Loading (SIL) is defined as the amount of active power that is transfered to a load at unity power factor.This make the line appear purely resistive[25]. In this case the line capacitance provides all the reactive power that is absorbed by the inductance of the line. This implies that, depending on the system load, the line can be either absorbing or providing reactive power.
Balance of both consumption and production of reactive power may result to a flat voltage profile along the transmission line hence keep voltage stable.

For reactive power balance to be realized, the pi-section of the transmission line must be purely resistive. Although, this is practically impossible since its not possible to realize capacitive reactance being equal to inductive reactance. Therefore, a resonable balance has to be determined, so as to have a good voltage profile (not neccessarily flat). The SIL value can be determined by using the capacitance and inductance of the total line shown in equation (2.24)

$$\text{SIL} = \frac{(V_l)^2}{\sqrt{L/C}} \tag{2.24}$$

where;

L is the inductance of the transmission line

and

C is the capacitance of the transmission line

The voltage V_l is the line to line sending end voltage of the three phase transmission line. The SIL value in the equation is given in watts. When a line is loaded below SIL value the line is providing reactive power. The inverse also applies that when the line is loaded above the surge impedance value it absorbs reactive power. When a transmission line absorbs reactive power, additional sources of reactive power has to be supplied for the line. This is done by means of capacitor banks that support power transfer over lines under heavy loading conditions [25],[17].

By changing the amount of power that is being supplied to the load , and recording the resultant change in reactive power, a SIL curve can be constructed. The SIL value for a transmission line can be read on the SIL curve. The SIL value will be the active power on the graph that results to zero net reactive power on the line

SIL is defined by V, L and C as already indicated in equation 2.24, but L and C are defined by conductor size and arrangement. SIL is not affected by length directly, but the reactive power developed in the line is affected by length when the load is not at SIL. A SIL curve has been used to determine the following;

(1) Stability limit of the transmission line.

(2) The current loading on the line and determine whether it would be possible to increase the power transfer across the line.

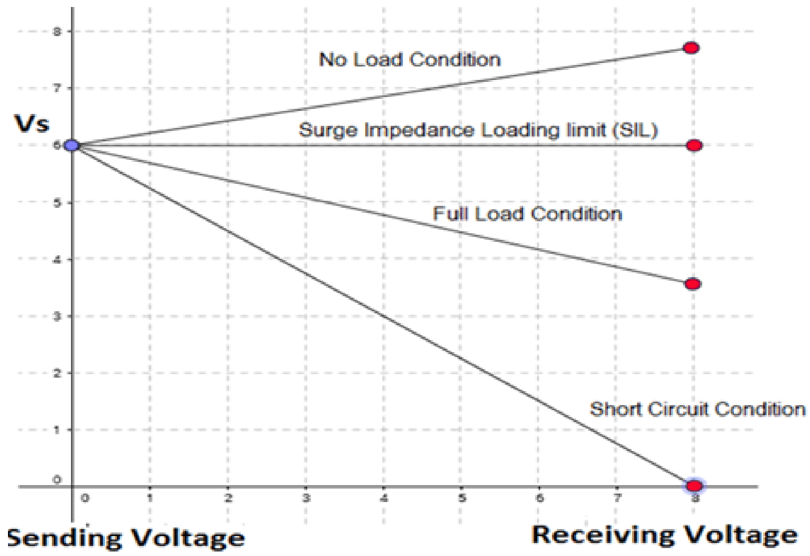

Figure 2.6: Typical SIL curve

It should be noted that the surge impedance and hence the SIL of a transmission line is independent of the length of the line. The value of surge impedance is the same at all points on the line and hence the voltage.
When the line is terminated by surge impedance, the receving end voltage is the same as the sending end voltage. This case is know as flat voltage profile. Figure 2.6 shows the voltage profile of a transmission line under different loading cases.

2.4.3 X/R Transmission line ratio

Voltage instability is mostly analyzed by considering the characteristics of transmission systems and then examining how the phenomenon is influenced by characteristics of generators, load and reactive power compensation devices[25],[10].
The maximum power that can be delivered to loads and relationship between load power and network voltage are the two basic properties that require analysis.
According to Shukla and Sekar [5], In their case study, where the line lengths were varied keeping X/R ratio and power factor constant. The following conclusions were

drawn;

(1) High X/R ratio decreases the maximum power transfered and affects the voltage stability adversely. Maximum power transfer takes place only if the sending end input impedance is equal to receiving end output impedance. The changes in transmission line impedance affects the maximum power transfer. Increase in reactance of the transmission line decreases the maximum powe transfer.

(2) Low power factors have detrimental effect on voltage stability characteristics:

(3) Line capacitance tends to improve the voltage characteristics

In a typical power transmission line, the SIL is of concern but is not a maximum power condition though it can be used as an indicator to gauge penetration level of ASVT unit(s)

On the other hand, typical R/X ratio for a power transmission line is small and the resistance has very little to do with the line impedance of the line. Therefore, it is plausible to use SIL as opposed to X/R ratio for penetration level measurement of ASVTs and especially for long transmission lines, since from research SIL curve has proved capable of estimating reactance needed to support a load on a line. The SIL curves can be used to determine the loadabilty of a transmission line. [18]

The literature review has addressed surge impedance loading and X/R transmission ratio as the parameters to be considered when evaluating the penetration level of any reactive system in a transmission line but has not addressed the maximum penetration level of the ASVT sub-stations that can be terminated on a transmission line beyond which the voltage profile of the line will be violated.

A research was carried out by Michael Juma Saulo to investigate the penetration level of unconventional sub-stations used to supply electricity along Kiambere-Rabai transmission line. In his study he considered two unconventional sub-stations, namely ASVT and capacitor coupled sub-station. The two types of sub-stations were fisrt considered one at a time then considered interchangeably along the same transmission line.

In this study the researcher found out that several unconventional sub-stations could be terminated along 220kV, kiambere-Rabai transmission line without voltage profile violation. This research further pointed out that the maximum penetration level of ASVT sub-station on a power network is governed by surge impedance loading. The research however, did not point out the maximum number of ASVT sub-stations that could be terminated on a power network without voltage profile violation. The research further failed to address the penetration of ASVT sub-station on a power network with loads. Most of the transmission lines in sub-sahara Africa have conventional distribution sub-stations used to supply electricity to towns along the line. The earlier researches pointed out that ASVT sub-stations are cheap and reliable, but they do not point out the extend in which ASVT sub-stations are cheaper than conventional distribution sub-stations.

The earlier researches did not also address the penetration point of the ASVT sub-station on a transmission line, this research investigated whether the termination point of the first ASVT sub-station on a transmission line may lead to violation of the line voltage profile.

The research further investigated the maximum number of ASVT sub-stations that can be terminated on a transmission line without violating the voltage profile of the line.

2.5 Ferranti effect

Ferranti-effect is a phenomenon caused by the charging current of the line capacitances. When the power line is considerably long or it has a remarkable line capacitance value, the voltage rises towards the receiving end. This effect can also be as a result of light loads along the transmission line. The phenomenon can be explained in detail with long line equations but it is not relevant in the scope of this work.

Termination of ASVT sub-stations on 132kv transmission line may lead to imbalance between capacitive reactance and inductive reactance. This imbalance leads to effects on surge impedance loading of of the line hence violation of the voltage profile

of the line and voltage instability.The reactive power of the transmission line depends on the line loading whereas the capacitive reactive power is almost constant. If capacitance reactance of the line is higher than inductive reactance, the line is said to be more capacitive than inductive and this makes the line have a high receiving end voltage than sending end voltage. This state is known as ferranti effect.
This research investigated whether at optimum penetration point ferrent effect occured.

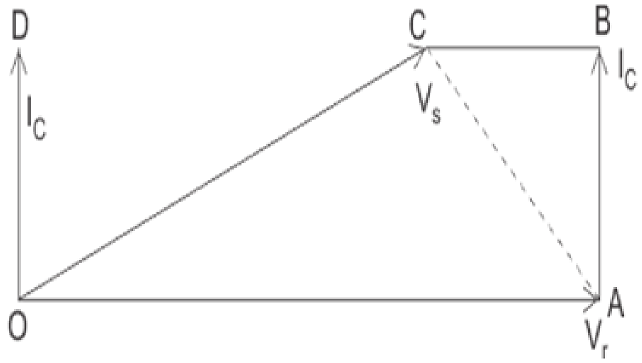

Figure 2.7: Ferranti effect phasor diagram

A simpler explaination is gained if the whole capacitive current is assumed to go to the capacitance in the receiving end in no-load situation. As the receiving end current is zero, the current going to the line capacitance is purely capacitive and causes a negative voltage drop across the series inductance. As a result, the voltage in the receiving end is greater compared to the sending end.[7],[26] The strength of Ferranti-effect depends on the values of line capacitances. Besides the line type, line capacitance is also proportional to the length of the power line so the phenomenon is stronger with longer lines. As mentioned earlier, cables have considerable higher values of capacitance over the inductance part of the series impedance. Therefore, Ferranti-effect is considerable stronger with cables.

2.6 Voltage stability limit

The voltage stability of a transmission line is maintained when the voltage profile of the line is flat or close to being flat. Termination of ASVT sub-stations on the transmission line which leads to voltage profile violation, may either lead to voltage instability or voltage collapse. This state can be avoided by maintaining the maximum penetration level of ASVT sub-stations on transmission line or employ reactance compensation method on the transmission line when ASVT sub-stations are terminated on the line.

Figure 2.8 shows a simple diagram used to illustrate factors that govern voltage stability limit.

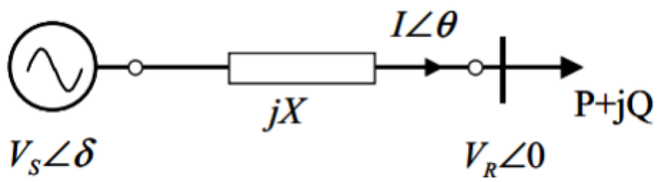

Figure 2.8: Single line diagram of voltage stability limit

Where,

$$\mathrm{P} = \frac{V_S V_R}{X} \sin\delta \tag{2.25}$$

$$\mathrm{Q} = \frac{V_S V_R}{X} \cos\delta - \frac{(V_R)^2}{X} \tag{2.26}$$

At the receiving end;

$$V_R I^* = P + jQ \tag{2.27}$$

So;

$$I = \frac{P - jQ}{V_R} \tag{2.28}$$

$$V_S = V_R + (\frac{P - jQ}{V_R})jX = (V_R + \frac{QX}{V_R}) + j(\frac{PX}{V_R}) \tag{2.29}$$

The corresponding magnitude equation is;

$$(V_S)^2 = (V_R + \frac{XQ_R}{V_R})^2 + (\frac{PX}{V_R})^2 \tag{2.30}$$

The power delivered to the load as a function of receiving end voltage when Q = 0 can be solved as follows;

$$\mathrm{P} = \sqrt{\frac{(V_S)^2 - (V_R)^2}{X}}\, V_R \tag{2.31}$$

where;
I is the receiving end current
and I* is the conjugate of I

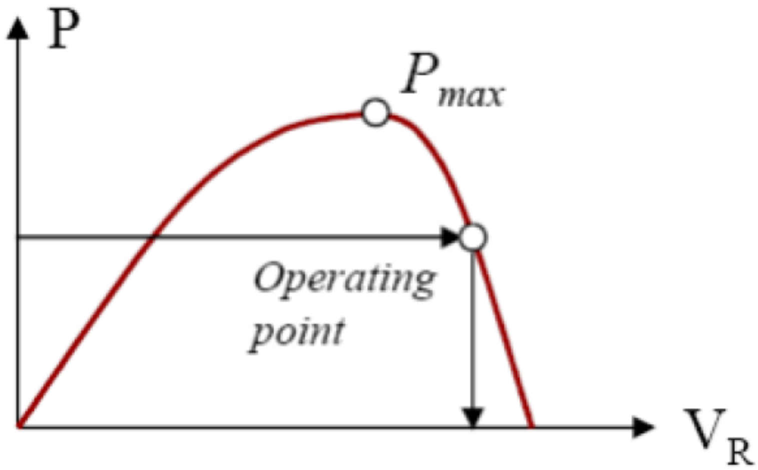

Figure 2.9: Power transfer capability curve

Since V_S is constant and close to 1 per unit, and X and V_R are only variables that can vary , then, when X is constant the power will vary with V_R as shown in Figure 2.9

The maximum power transmitted is attained when $\frac{dp}{d_{VR}} = 0$, which can be determined as,

$$P_{max} = \frac{(V_S)^2}{2X} \tag{2.32}$$

The voltage corresponding to the equation 2.9 is given by;

$$V_{nose} = \frac{V_S}{\sqrt{2}} \tag{2.33}$$

Where,

V_{nose} is the nose point voltage

Equation 2.9 is the voltage stability limit of the power transmission line. Considering nominal pi configuration, the transmission line and it's equivalent circuit can be represented as shown in Figure 2.10

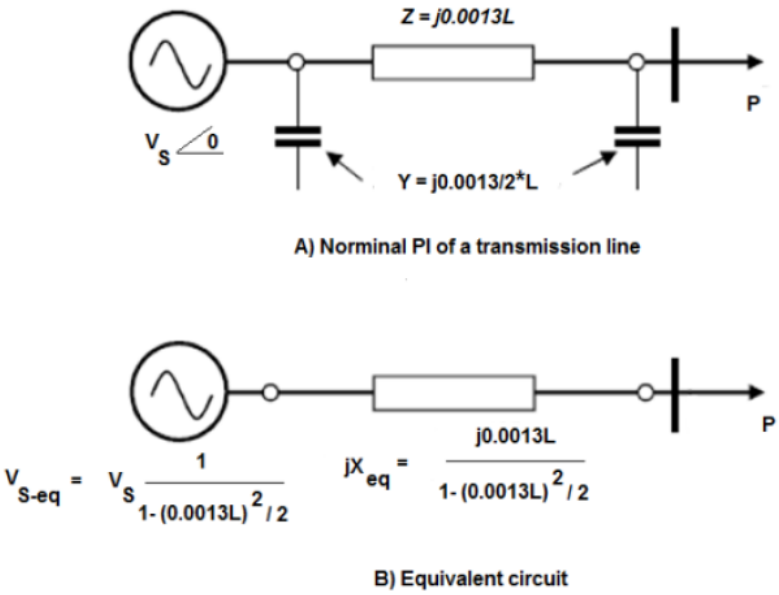

Figure 2.10: Transmission line and it's equivalent circuit

The transmission line impedance per given length is $Z = J0.0013L$ and its admittance is $\gamma = \frac{j0.0013L}{2}$

where L is the length of the transmission line in km.

The characteristic impedance of the line $Z_c = \sqrt{Z/\gamma}$

In this case the reactance $X_{eq} = \frac{j0.0013L}{1-(0.0013L)^2/2}$

$$Z_c = \frac{j0.0013L}{1-(0.0013L)^2/2} \times \frac{1}{j0.0013L} \tag{2.34}$$

$$Z_c = \frac{1}{1-(0.0013L)^2/2} \tag{2.35}$$

The open circuit voltage $V_{s-eq} = V_S \times Z_c$

$$V_{s-eq} = V_s \times \frac{1}{1-(0.0013L)^2/2} \tag{2.36}$$

From the expresion of the transmission line equivalent circuit, it's clear that when the line length increases, the open circuit voltage V_{S-eq} also increases due to line charge. This is known as Ferranti effect. The effect leads to increase of the noise point voltage.

It can further be deduced from Figure 2.8 that when the length increases to a specific value the nose point voltage will become higher than the sending end voltage. When this happens it becomes impossible to operate the system at any operating point with acceptable voltage level below the nose point voltage, which is unstable case. The line length at which the nose point will move above the sending end voltage can be determined using the following conditions;[18]

$$V_{nose} = V_S \tag{2.37}$$

Assuming that the receiving end Q load is equal to 0, then

$$V_{nose} = \frac{V_{S-eq}}{\sqrt{2}} = \frac{V_S}{\sqrt{2}} \frac{1}{1-\frac{(0.0013L)^2}{2}} = V_S \tag{2.38}$$

Solving the above equation yields;

$$L = \sqrt{\frac{2-\sqrt{2}}{(0.0013)^2}} = 588.7KM \tag{2.39}$$

This demonstrates that the power transfer capability is limited by voltage stability concern when the line length is greater than 588.7KM.

The quantum of power that a given high voltage transmission line can safely carry depends on various limits. These limits can be categorised into two types thermal and Stability/Surge Impedance Limit (SIL) limits. In case of long lines the capacity is limited by its SIL level only which is much below its thermal capacity due to large inductance. Decrease in line inductance and surge impedance shall increase the SIL and transmission capacity. Thermal capacity is the ultimate capacity of a line corresponding to its capability to withstand the heat generated due to line loss. It depends on the; [25]

(1) Type of the conductor

(2) Maximum permissible conductor temperature

(3) Other enviromental factors

In this research SIL curves have been used to determine the voltage stability limits of the 132kV transmission line beyond which voltage profile will be violated.

2.7 Distance from ASVT sub-station to Village house holds

A study was carried out to investigate the indepth analysis and evaluation of the amount of voltage drops in households along selected streets in Benin city, which was restricted to power Holding Company of Nigeria (PHCN). This study embraced the reading of the transformer supplied voltage, currents and power consumption in each household using clip on metre, while the distance of each household from the transformer supplying the streets was obtained using measuring tape[29]. The results showed that if consumers are to receive a reasonable supplied voltage for efficient operation of their appliances the distance of the consumer service cable at the farthest end from the transformer should not exceed 400 m.
The study was carried out using aluminium conductor of crossectional area of $50mm^2$ at a supply voltage of 220V.

Causes of the voltage drop are:

- Material used e.g copper is better than aluminium in terms of voltage drop.
- Cable size- large cable sizes (diameter) will have less voltage drop than smaller cable size of the same length.
- Cable length.
- Current being carried.

From the above research it was found out that[29]:

(1) The farther the distance the consumer was from the distribution transformer the lower the voltage the consumer received and hence the higher the voltage drop.

(2) Any distance exceeding 400m resulted to a voltage drop exceeding 5% of the supply value which is unreasonable since it can affect effective operation of electrical appliances. This was obtained regardless of the applied loads.

The electrical designs are done in accordance with the requirement of the National Electrical Code which states that a voltage drop of 5% of the supply voltage at the farthest receiptance in branch wiring circuit is acceptable for normal efficiency.
From Ohm's law:

$$V = IR \tag{2.40}$$

The voltage dropped V_D between two terminals (source VS and receipient VR) is given by:

$$V_D = V_S - V_R \tag{2.41}$$

Per unit voltage drops: this is the ratio of voltage drop to the supplied voltage:

$$P.U = \frac{V_S - V_R}{V_S} \tag{2.42}$$

When expressed as a percentage it becomes:

$$P.U = \frac{V_S - V_R}{V_S} \times 100 \tag{2.43}$$

The results are as captured in table 2.2.

Table 2.2: Distance from transformer and corresponding voltage drop

Injection substation	Approx Distance D (m)	consumer recieved voltage V_s (V)			Voltage drops V_s (V)			Percentage Unit voltage drops P.U (%)		
		T_1	T_2	T_3	T_1	T_2	T_3	T_1	T_2	T_3
Guiness	40	220.0	220.0	220.0	0.0	0.0	0.0	0.0	0.0	0.0
	100	217.0	218.0	219.0	3.0	2.0	1.0	1.4	0.9	0.5
	160	215.0	216.0	218.0	5.0	4.0	2.0	2.3	1.8	0.9
	220	214.0	215.0	217.0	6.0	5.0	3.0	2.7	2.3	1.4
	280	212.0	212.0	215.0	8.0	8.0	5.0	3.6	3.6	2.3
	340	210.0	209.7	210.0	10.0	10.3	10.0	4.5	4.7	4.5
	400	209.2	208.5	209.0	10.8	11.5	11.0	4.9	5.2	5.0
	460	202.0	204.0	200.0	18.0	16.0	20.0	8.2	7.3	9.1
	520	196.0	198.0	195.0	24.0	22.0	25.0	10.9	10.9	11.4
	580	186.0	180.0	188.0	34.0	40.0	32.0	15.5	18.2	14.5
	640	169.0	171.0	170.0	51.0	49.0	50.0	23.2	22.3	22.7
	700	154.0	156.0	155.0	66.0	64.0	65.0	30.0	29.1	29.5
	900	139.0	138.0	140.0	81.0	82.0	80.0	36.8	37.3	36.4
Ikpoba	40.0	215.0	216.0	217.6	0.0	0.0	0.4	0.0	0.0	0.2
	100	214.5	216.0	216.4	0.5	0.0	1.6	0.2	0.0	0.7
	160	213.0	215.0	215.0	2.0	1.0	3.0	0.9	0.3	1.4
	220	212.0	213.5	213.0	3.0	2.5	5.0	1.4	1.2	2.3
	280	210.0	211.0	210.9	5.0	5.0	7.1	2.3	2.3	3.3
	340	207.0	208.0	210.0	8.0	8.0	8.0	3.7	3.7	3.7
	400	204.5	205.6	206.8	10.5	10.4	11.2	4.9	4.8	5.1
	460	201.0	201.4	202.0	14.0	14.6	16.0	6.5	6.8	7.3
	520	197.0	197.1	192.0	18.0	18.9	26.0	8.4	8.8	11.9
	580	190.0	192.0	191.6	25.0	24.0	26.4	11.6	11.1	12.1

The cable sizes and ratings used to supply voltage from 220V transformer can also be used to supply voltage from a 240V, thus from table 2.2 it can be concluded that an ASVT sub-station with an output voltage of 240V can be used to supply households at a radius of 400m, without violating 5% voltage drop of the source voltage which is the recommended maximum voltage drop by the National Electrical code practice [29].

CHAPTER THREE

METHODOLOGY

3.1 Background information

This research aimed at establishing whether violation of voltage profile on the high voltage transmission lines could have led to low penetration level of Auxiliary Service voltage Transformer sub-stations on high voltage networks. The research considered a 132kV line running from Nairobi (Juja Road) to Rabai and a voltage profile to be maintained being in the range of ±6% . i.e. 132 ±8kV which is the voltage profile maintained by Kenya Power and Lighting Company. The surge impedance loading of a line can only be affected if there is a wide disparity on the reactive power being absorbed and reactive power being produced, this means it's only the reactive load-ing which affects the voltage profile of the network leading to voltage instability.

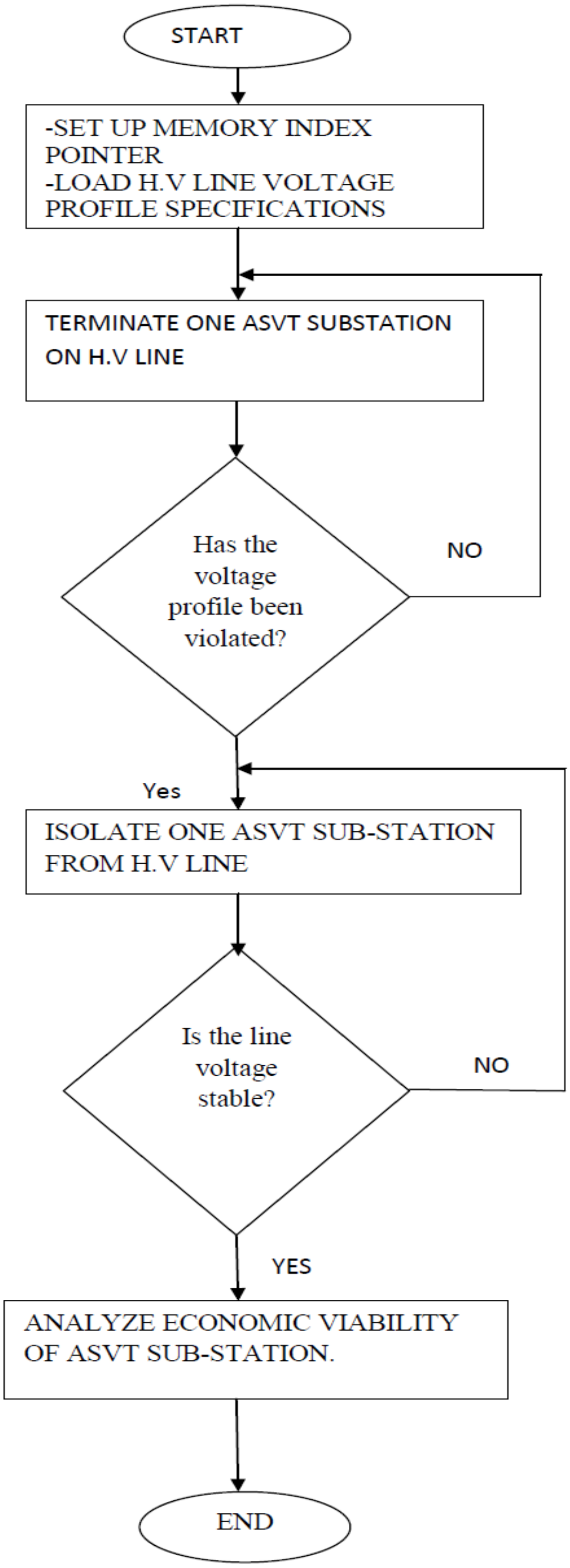

Figure 3.1: Methodology flow chart

Fig 3.1 above shows the steps followed to address the objectives of this research. The maximum penetration level of ASVT sub-stations on 132kv transmission line without voltage profile violation was determined by constructing a transmission line model using SIMULINK software in MATLAB, Where ASVT sub-stations were terminated. The simulation data was analysed using line graphs to clearly represent the number of ASVT sub-stations that can be terminated on 132kV transmission line without voltage profile violation.

The voltage stability of the system was analysed using the simulation data and SIL curves. This analysis was made to find out whether there was voltage stability, voltage instability or voltage collapse on the transmission line after penetration of ASVT sub-stations on the transmission network.

The termination of inductive machines on a high voltage transmission line affects the production, absorption and flow of the reactive power on the system. This may affect the voltage profile of the transmission line. Violation of a voltage profile of a transmission line at some point may lead to voltage instability.

The termination of inductive machines on a transmission line introduces harmonics. The increased value of total harmonics on a transmission line compromises the quality of the voltage being transmitted.

The research was further carried out to analyse the economic viability of ASVT sub-station when used to supply Maungu village with electricity. The study further determined the maximum number of ASVT sub-stations that can be terminated on the same transmission line to supply electricity to neighbouring villages beyond which it will be economically viable to set up a conventional sub-station to supply the villages.

The study was first carried out on a typical 132kV unloaded line then on 132kV Nairobi-Rabai transmission line.

3.2 Surge Impedance Loading (SIL)

The surge impedance loading was used to determine the maximum penetration level of the ASVTs; this is due to the fact that for a flat voltage profile, balance of consumption and production of reactive power by transmission line must be maintained. ASVT is a reactive device; its penetration on a transmission line is likely to affect the reactive power of the network. It is important to note that the point at which the ASVT is connected in the line becomes the receiving end point with respect to the sending end.

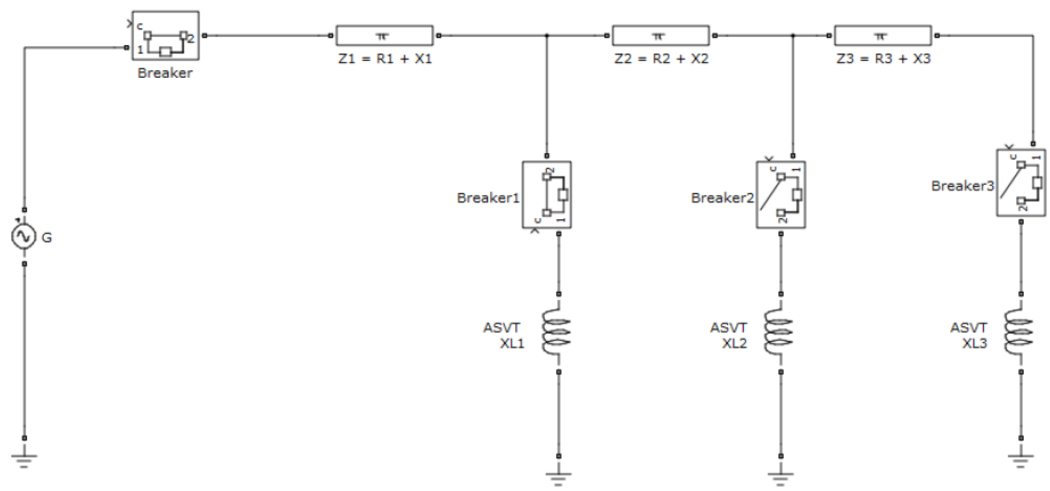

Figure 3.2: Termination of ASVT sub-stations on HV transmission lines

Figure 3.2 above is used to illustrate the effect of transmission line reactance when a reactive machine like ASVT is terminated on the high voltage transmission line. Considering breaker 3 alone to be closed, with 1 and 2 open, the impedance of the transmission line shall appear as follows: [13]

$$Z_l = R_l + X_l \tag{3.1}$$

where,

Z_l is the total impedance of the transmission line

$$R_l = R_1 + R_2 + R_3 \tag{3.2}$$

$$X_l = X_1 + X_2 + X_3 + X_{l3} \tag{3.3}$$

Considering breaker 3 and breaker 1 to be closed; The output reactance

$$X_O = X_1 + (X_2 + X_3 + X_{l3})//X_{l1} \tag{3.4}$$

hence expression 3.4 can be reduced to:

$$X_O = X_1 + X_{l1} \tag{3.5}$$

While the input reactance

$$X_i = X_1 \tag{3.6}$$

In a transmission conductor, the resistance of the line is supposed to be very small to reduce power losses *i.e.* $p = I^2R$ watts. Thus resistance can be considered negligible. This means in this case equivalent reactance of the line will be given by:

$$X_l = X_1 + X_{l1} \tag{3.7}$$

Comparing equation 3.3 and 3.7, it is clear that the reactance of the line has reduced by (X_2+X_3) by terminating a reactive machine (ASVT) on the line. This is likely to change the reactive power of the transmission network as well as the voltage profile of the line. If breaker 2 is closed implying termination of another ASVT on the line, the reactance of the line will further change implying a further change on the reactive power of the line and voltage profile of the entire system.

The SIL of the line can be determined by an equation involving capacitance and inductance, as shown in equation 3.8 and it's unit is KW [11] .

$$\mathrm{SIL} = \frac{V_l^2}{\sqrt{L/C}} \tag{3.8}$$

In this research, the SIL curve was drawn using the parameters of equation 3.8. The termination of the ASVT sub-station on a transmission line made the line either absorb or provide reactive power depending on the point of penetration. This is because of the coresponding change of the equivalent system reactance when an ASVT sub-station is terminated. Reactive power either provided or absorbed was plotted against the active power delivered to the load. The SIL value is the active power on the graph that results to zero reactive power on the line.

It is noted that SIL depends on V_L, L and C as shown in equation 3.8. L and C are defined by conductor size and arrangement. SIL is not affected by length directly but the reactive power developed in the line is affected by the length when the load is not SIL.

SIL curve was used to determine the following:

(1) The termination point of the ASVT that does not interfere with the SIL of the transmission line

(2) The maximum number of ASVTs that has been terminated on a transmission line to tap power for rural electrification without interfering with the SIL of the line.

(3) The voltage stability limits of the network on connecting ASVTs.

3.3 Termination point of ASVT sub-station on a Transmission line

The maximum power in a transmission line is transferred when the input impedance is equal to the load impedance.

The input impedanceZin is given by [11]:

$$Z_i n = Z_0 . \frac{Z_l + jZ_0 \tan \beta l}{Z_0 + jZ_l \tan \beta l} \tag{3.9}$$

where,

$$l = \frac{\lambda}{2} \tag{3.10}$$

and

$$\beta = \frac{2\pi}{\lambda} \tag{3.11}$$

$$Z_in = Z_0 . \frac{Z_l + jtan\frac{2\pi}{\lambda}.\frac{\lambda}{2}}{Z_0 + jZ_l \tan\frac{2\pi}{\lambda}.\frac{\lambda}{2}} \tag{3.12}$$

$$Z_in = Z_0 . \frac{Z_l}{Z_0} \tag{3.13}$$

$$Z_in = Z_l \tag{3.14}$$

The maximum power transfer of a transmission line is realized when the input impedance is equal to the load impedance. The termination of ASVT sub-station on a transmission line changes the line impedance and this may affect maximum power transfer phenomenon.

The penetration point of the ASVT sub-station was determined by terminating an ASVT sub-station from the voltage source to farthest end of a modelled transmission network using simulink software. The voltage levels of the network were monitored after every simulation to ascertain that the voltage profile of the network was maintained. The surge impedance loading of the transmission line is always constant.

The power grids and conventional sub-stations supplying high voltages of 132kV, 66kV and 33kV to transmission lines were used as sources of power to ASVT sub-stations. The ASVT sub-stations were only viable where there was no nearby conventional sub-station except incases where they are required to form an integral part of the conventional sub-station to supply single phase loads within a transmission

sub-station . Setting up an ASVT sub-station near a conventional distribution sub-station was considered un economical since the nearby villages can be supplied from conventional sub-station. This type of sub-station is only economical to supply low power demand consumers where utility power company will realise no returns on setting up a conventional sub-station to supply them.
The penetration point of the consequent ASVT sub-stations, i.e. the spacing of the ASVT sub-stations will depend on:

(1) The surge impedance loading of the transmission line which determines voltage profile.

(2) The next village which is at close proximity to the transmission line i.e. not more than 400 metres radius.

This means the spacing of the ASVT sub-stations is not necessarily governed by a specific formular but by the settlement of the villages.

3.4 Penetration point of ASVT sub-station.

Simulation was carried out to determine the penetration point of the ASVT sub-station on a H.V transmission line. This refers to the point of terminating the first ASVT sub-station without transmission line voltage profile violation. A transmission line model was constructed in SIMULINK software in MATLAB to be used to carry out the voltage profile analysis. [16]
A simulation model of an ASVT sub-station terminated on a 132kV transmission line was used in this research. Circuit breakers were used one at a time to vary the point of ASVT termination from the power generation station. Initially a 440KM, 132kV transmission line has been considered as captured in Appendix A, Figure 1_a. The first ASVT sub-station is terminated at 1KM, then 62.857KM then 377.142KM by switching ON circuit breaker 1, 2 and 4 intercheageably maintaining all the other

circuit breakers open.

The length of the transmission line was then increased to 600KM. This was aimed at investigating the effects of Ferranti effect on voltage profile of the transmission line on terminating the first ASVT sub-station and the results are as captured in table 4.1.

In this research, a constant sending end voltage of 132kV was used. The termination of the ASVT sub-station was not controlled by any mathematical formular. This was based on the fact that the location of the village to be supplied by this sub-stations was random along the transmision line and obeyed no mathematical pattern. The simulation results were presented using per unit values with a base voltage of 132kV. The research was aimed at investigating whether a voltage profile of $132000 \pm 6\%$ was maintained after terminating the first ASVT sub-station.

The ASVT sub-station used was to supply an average load of 50kw to the village. The 132kV transmission line considered was unloaded.

3.5 Penetration level of ASVT sub-stations on 132kV transmission line

This section was used to investigate the maximum number of ASVT substations that can be terminated on a 132kV transmission line without violating its voltage profile. The simulation model used in determining the penetration point of ASVT substation was used with several circuit breakers turned ON, then voltage level and corresponding distance noted. The simulation model is as shown in the Appendix A, Figure 1_a.

The penetration level of ASVT sub-stations were investigated by terminating ASVT sub-stations on high voltage transmission line then analysis of the resutant voltage levels were observed to establish whether the transmission line voltage profile was violated. The pi-section of the transmission line were set at 62.857KM and circuit breakers 1, 2 & 3 turned ON to terminate ASVT sub-stations to the high voltage transmission line. The resultant voltage levels and corresponding distances from the generation station were tabulated as shown in table 4.2. [14]

3.6 A loaded Nairobi - Rabai 132kV transmission line

This research has further investigated effects of varying consumer loads being supplied by ASVT sub-station to the maximum penetration level of the unloaded 132kV transmission line. The consumer loads were varied from 25kW to 50kW then from 50kW to 100kW then from 100kW to 250kW. The analysis of the voltage levels obtained from the above study were used to draw conclusions on whether changes on the consumer loads has a direct effect on the voltage profile of the line.
A Nairobi -Rabai transmission line was used to investigate the penetration level of ASVT sub-stations on the line. The capacity of the uncompensated transmission line was 50Mw while the existing loads were of 54MW. The line had to be com-pensated to a capacity of 60MW before conventional distribution sub-stations were terminated to avoid voltage profile violation.

$\frac{p'}{p} = \frac{60MW}{50MW} = 1.2$
This allowed for the capacity of the transmission line to be raised by 20% for the same apparent current. The power factor of the uncompensated line was 0.75. The compensation allowed the power factor of 0.90 to be used.
$\phi_1 = \cos^{-1}(0.75) = 41.41^0$
$\phi_2 = \cos^{-1}(0.90) = 25.84^0$
The KVAR taken by the reactive power compensator was given by the expression:
$KVAR = P(tan\phi_1 - tan\phi_2)$
$= 50MW(tan41.41^0 - tan25.84^0) = 19.88MVAR$
The total reactive power supplemented by the reactive power compensators to raise the capacity of the Nairobi-Rabai transmission line to 60Mw was 19.88MVAR.

The compensated transmission line was then terminated with conventional distribution sub-stations supplying loads of 54Mw. The termination of ASVT sub-stations was also carried out to investigate their penetration level on the power network. The ratings of conventional sub-stations, the distances from one sub-station to the other and the consumer loads are as shown in fig 3.3

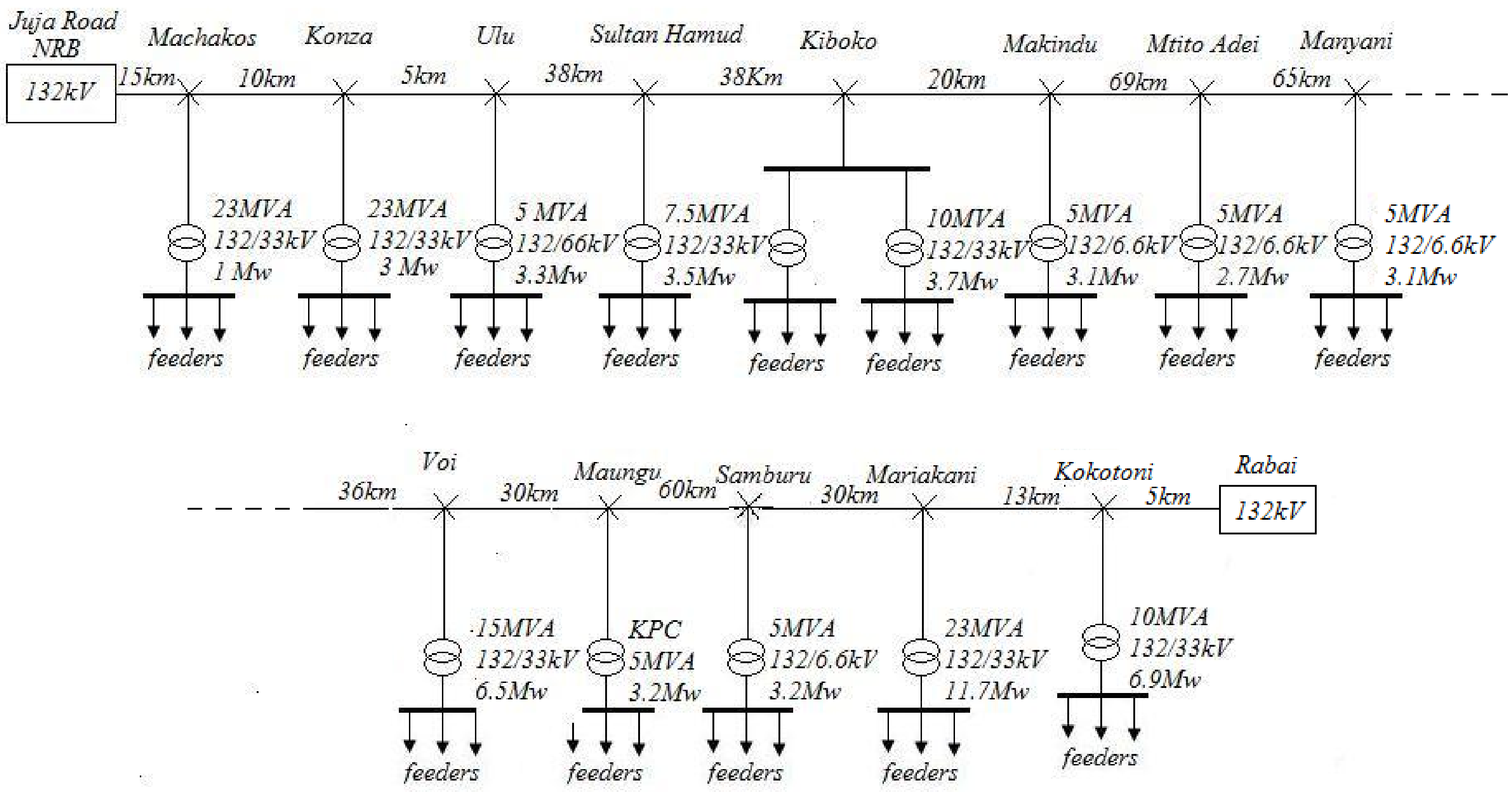

Figure 3.3:Nairobi - Rabai 132kV transimission line

3.7 Analysis of voltage quality and stability

MATLAB/SIMULINK was used for analyse the voltage profile of the system. An integration algorithm (Runge Kutta 2nd & 3rd Order) ensures fast convergence of the results. The steady state voltage and current values were obtained and used as an indicator of a decay or growth in simulation results.

The decay of either current or voltage was used as an indicator of voltage instability or voltage collapse, while growth in voltage has been used to indicate ferrent effect in the system of which eventually lead to voltage instability.

The transmission line waveforms and ASVT output waveforms were also displayed. These waveforms were used to monitor voltage stability of the transmission network. The surge impedance loading curves were also used to point out instability in the network when ASVT systems were connected.

Voltage stability of a transmission line network can be analyzed by use of surge impedance loading curves (sil curves). The SIL curve is drawn by plotting the reactive power absorbed or supplied by the line against the various levels of active power provided to a load with a unity power factor.

The SIL curve was determined by measurement of the active and reactive power transmitted the 132kV transmission network. In this case, the database will have practical SIL curves for various power factor loads. The benefits to this SIL curve above that of the traditional curve is that the reactive power that has to be provided to the load is included in the graph, since the load has a non-unity power factor. Decisions that have to be made to determine the extra reactive support for power transmission will be easier

A more accurate SIL curve ensures that the stability limits and the loading level is more accurate on the line.

3.8 Maungu village Load Demand (case study)

A case study of Maungu village along Nairobi-Mombasa highway was used in this research. The village has 18 households and a shopping centre.The village has been used to evaluate the cost which can be incurred in supplying it with electricity. Financial analysis was also carried out to determine if the power utility company can realize returns on investment. A model was used to carry out the analysis, first when the village was supplied with electricity using conventional sub-station then by non-conventional sub-station.
The features of the village were as follows:

(1) 300 metre radius from the high voltage transmission line

(2) 30 kilometres away from the nearest conventional sub-station

(3) Sparsely populated.

The distance from the conventional distribution sub-station to final consumer depends on the following parameters:

(1) The distribution voltage from the sub-station

(2) The voltage drop along the distribution lines.

The loading of a sub-station stands out as the key aspect considered in determing the distribution distance of a conventional sub-station. An 11kV distribution sub-station can supply upto a maximum of 4KM at maximum loading in an urban set up, while 11kV sub-station with below 30% loading transmitting current to rural areas where electricity demand is low can transmit power upto 40KM from the distribution sub-station.
The voltage drop along the distribution lines and the cost of the accessories and transmission cables is another key factor considered in determining the maximum distance of supply from the conventional distribution substation. These factors must be considered to ensure that an Auxiliary service voltage transformer will be installed

in an appropriate distance where setting up a conventional substation will not be viable.

A study was set out to generate baseline data and information through the analysis of secondary energy consumption data available from the Kenya Power and Lighting Company Ltd (KPLC) for domestic households in Nairobi region, both urban and rural based. The accuracy of the econometric model used for forecasting residential energy demand for the purposes of planning was assessed. Through interviews, observations and ownership of electrical appliances, end use patterns for the various income groups of households were analysed.

It was established that ownership of household appliances and their standard consumption have an influence on the total energy demand. The average annual consumption per household in the urban high, medium, and low income groups was $5,767$kWh, $1,642$kWh and 451kWh respectively, while that of the rural high, middle and low income households was $1,634$kWh, 733kWh and 218kWh per household per year.[21] This means the electricity demand in rural areas is 21800Wh $\div$ 365 = 597.26Wh per day.

Taking the consumption of electricity in rural areas to be in 4hrs, then the domestic demand is 2389.04watts.

The above study reveals an average load demand for a domestic supply to be 2400watts. The load demand for a single household ranges from 2000watts to 3000watts. This means a single household ought be supplied with 3kVA. A sparsely populated village may have approximately 20 households.

$20 \times 3KVA =$ 60kVA. .

The calculation of the required ASVT sub-station rating to supply Maungu village put into consideration the diversity factor of residential areas. Diveristy factors have been developed for main feeders supplying a number of feeders and typically 1.2 to 1.3 diversity for residence consumers and 1.1 to 1.2 for commercial loads are used.

Diversity factor $= \frac{\text{sum of individual maximum demand}}{\text{maximum demand of the system}}$

considering a residence diversity factor of 1.2,

Required ASVT system $= 60kVA \div 1.2 = 50kVA$

In this case a 50kVA ASVT sub-station will be used to supply the village.

The future growth of Maungu village will lead to increased electricity demand. The consumption of electricity by urban low income earners has been used to determine the ASVT sub-station rating to be installed to meet their demands.
The average annual consumption per household in the urban low income group is 451kWh. Considering 365 days of the year, then the average daily consumption of electricity for low income urban centres will be given by 45100Wh $\div$ 365 = 1235.616Wh
Taking the consumption of electricity by low income earners in urban centres to be in 4hrs, then the domestic demand will be 4942.466watts. This means an average load demand of 5000watts. Thus the load demand for each house hold will be 5kVA. This village has 20 households, hence the total load demand will be $20 \times 5KVA$ = 100kVA. In this case an ASVT rated 100kVA will be prefered, beyond this point it will imply that the village load demand has growth extensively and the village will now be a middle urban class level. The power utility company will now realize returns on investment if they set up conventional sub-station to supply the village.
Local price quotations will be used in carrying out the costing of the sub-stations premises.

The rural area load demand in Maungu area are classified into three, namely:

(1) Household load

(2) Internet cafe load

(3) Shopping centre load

Table 3.1: Maungu household load demand

EQUIPMENT	POWER REQUIREMENT (W)
Computer	300
Lights	120
Iron box	1200
T.V colour	80
Radio cassette	6
Total	1706

From table 3 above it can be seen that a typical rural household will require about 506W of power. The power requirement of each equipment were taken from manufacturere's data sheet.

Table 3.2:Typical power requirement of Maungu internet cafe load

EQUIPMENT	POWER REQUIREMENT (W)
3 Computer	900
Lights	60
T.V colour	80
Radio cassette	6
Total	1046

The power requirements for an internet cafe shown in the table are basically for a small business. This would enable rural communities to access internet that is an important ICT tool in the telecommunication industry.

Table 3.3:Maungu shopping centre.

EQUIPMENT	POWER REQUIREMENT (W)
Air coditioning unit	960
Lights	120
Refridgerator unit	242
Radio cassette)	6
Total	1328

Table 5 depicts the power requirements for a shop. A cost effective power source would enable the shop to provide cold drinks to the rural dwellers of Maungu area since temperatures are extremely high.

The load densities are usually below 0.5 KVA per kilometer. Any single customers maximum demand will typically be less than 3.5kVA, but larger loads upto the capacity of the transformer can also be supplied. [6]

The Maungu village has 18 households, if each household consumes the maximum allowable power then a maximum demand of the village will be 63kVA. practically all loads cannot be switched on at the same time in the same household i.e. a household cannot turn on both television and radio cassette at the same time. Similarly in rural areas lights are only essential during the night as from 1900 hours to 2200 hours. The households are expected to carry out demand side management to minimize load and cosequently lower the electricity bills. The above power demand management will lead to each village utilizing a maximum demand of 3.0kVA.

Maungu village with 18 households has a maximum demand of $18 \times 3 = 54kVA$. A diversity factor of 1.2 is used, hence an Auxiliary Service Voltage Transformer Sub-station of 50kVA will be used to supply this village.

CHAPTER FOUR

SIMULATION RESULTS AND CONTRIBUTIONS

4.1 Background information

In this chapter analysis of a mathematical model of transmission line and transformer model are employed to construct ASVT models. The system simulation is carried out using SIMULINK software. Tabulation of voltage profile for various distances is also presented. The aim of these simulations are to investigate the penetration point and level of ASVT substation on a high voltage transmission line network without violating it's voltage profile. Construction of SIL curves are implemented and used to determine the voltage stability of the high voltage transmission line.

4.2 Penetration point and Maximum penetration level of ASVT sub-station on 132kV transmission line

Figure 4.1 was used in simulation of data for the determination of penetration point and maximum penetration level of ASVT sub-stations on 132kV transmission line without voltage profile violation.

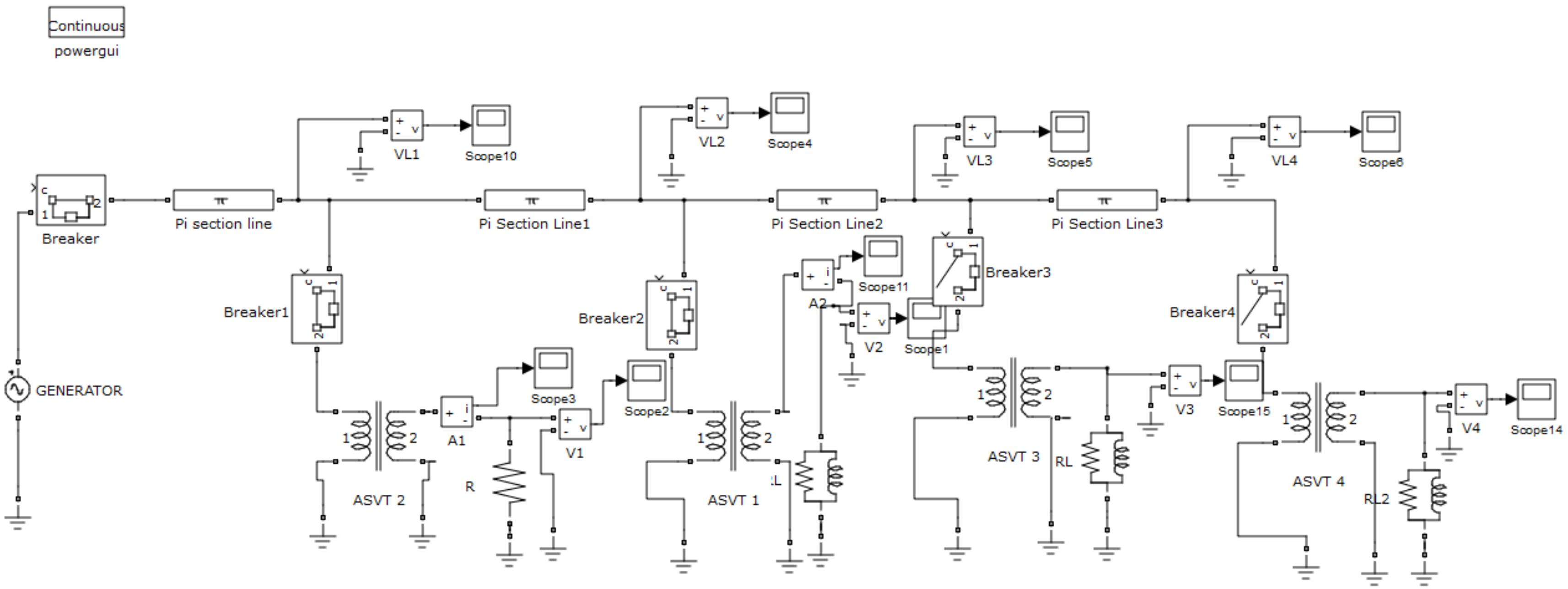

Figure 4.1: ASVT simulation model

Table 4.1:penetration point of ASVT sub-stations on 132kV transmission line.

Penetration point(KM)	Voltmeter reading (pu) ASVT at 1KM	Voltmeter reading (pu) ASVT at 62.857KM,	Voltmeter reading (pu) ASVT at 377.142KM	Voltmeter reading (pu) ASVT at 62.857KM, transmission line of 600KM
1	1.00	1.00	1.00	1.00
62.857	1.01	1.01	1.01	1.01
85.714	1.01	1.02	1.02	1.02
147.34	1.02	1.02	1.02	1.03
188.571	1.03	1.03	1.03	1.04
251.428	1.03	1.03	1.03	1.05
293.68	1.03	1.04	1.04	1.05
342.856	1.04	1.04	1.04	1.06
377.142	1.04	1.04	1.04	1.07
440	1.04	1.04	1.04	1.07
514.285	-	-	-	1.07

The data tabulated in table 4.1 was obtained when a constant sending end voltage of 132kV was applied as a voltage source. The consumer load to be supplied by each ASVT sub-station was set at 50kw. The study considered an unloaded transmission line.

The above data revealed that when an ASVT sub-station was terminated at 1KM, 62.857KM, 377.142KM on the 132kV transmission line from the voltage source, the voltage profile of 132000 ± 7920 volts was maintained. The voltage profile was violated when the transmission line length was increased from 440KM to 600KM, this justified the calculation performed in chapter two on transmission line voltage stability as captured in equation 2.13 using transmission line typical values.

The receiving end voltages are higher than the sending end voltages. These voltages appear to increase as the penetration point is moved away from the voltage source. One of the key reasons for the voltage being higher at the receiving end than the sending end is the light load on the 132kV transmission line. An ASVT sub-station with a load of 50kw was terminated on the transmission line. The second reason being the fact that termination of the ASVT sub-station on the transmission line affects the absorbtion of reactive power on the line. The absorbtion of the reactive power reduces as the penetration point of the ASVT sub-station is moved away from the source voltage. This makes the production of the reactive power to be higher than the absorbtion of reactive power resulting to voltage increase towards the receiving end of the line.

This research has revealed that an ASVT sub-station can be terminated at any point along the 132kV transmission line without voltage profile violation. This means setting up an ASVT sub-station will entirely depend on the location of the village to be supplied with electricity.

4.2.1 Result analysis and contribution on Penetration point of ASVT sub-station on 132kV transmission line.

The voltage level results of table 4.1 displays voltage within the range $132,000 \pm 7,920$ Volts after ASVT sub-stations were terminated at the points 1KM, 62.587KM, 85.714KM, 188.571KM, 342.856KM, 377.142KM of the 440KM high voltage transmission line. These results showed that the voltage profile of the transmission line was maintained regardless of the point of penetration of ASVT sub-station on the transmission line. This meant that the termination point of the ASVT sub-station does not affect the voltage profile of the high voltage transmission line.

To further carry out the analysis on the voltage profile of the transmission line on terminating an ASVT sub-station, the data of table 4.1 was used to draw transmission line voltage level graph as shown in Figure 4.2.

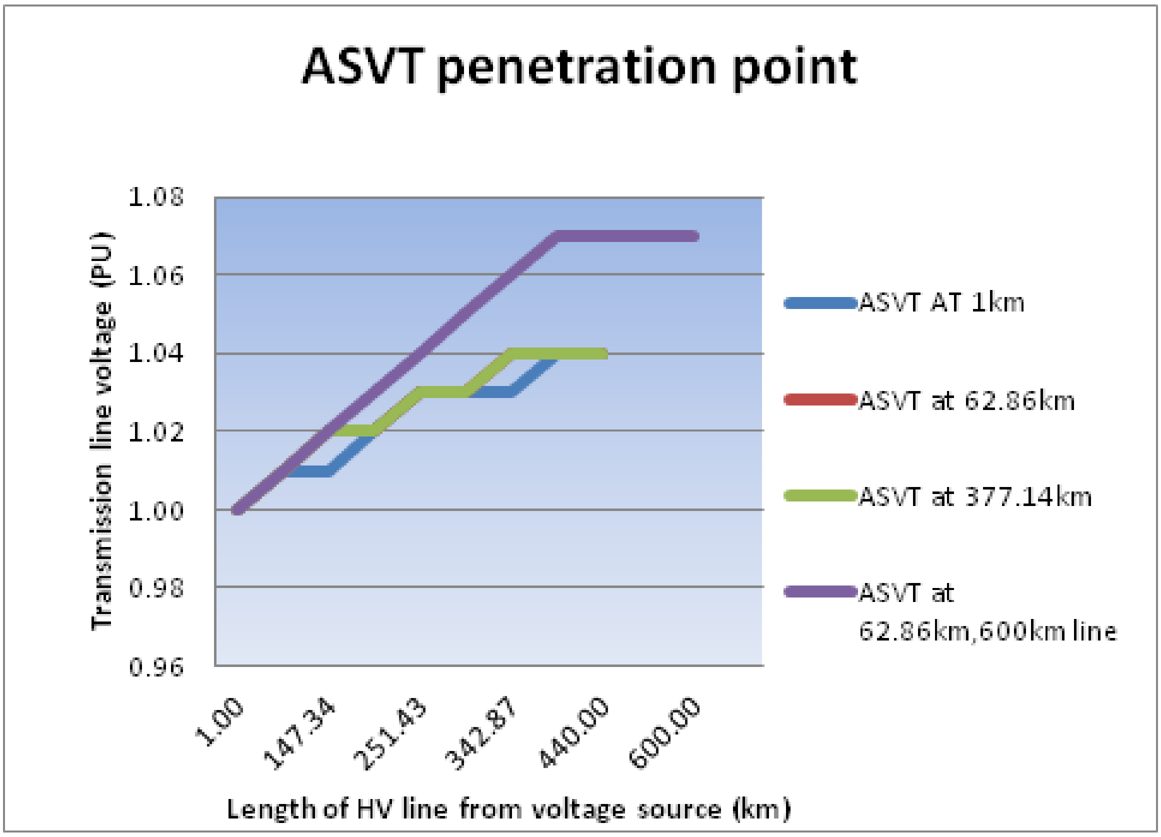

Figure 4.2:penetration point graph

Figure 4.2 shows that the voltage profile of a 132kV, 440KM transmission line is maintained regardless of the termination point of the ASVT sub-station.

When the length of the 132kV transmission line was adjusted from 440KM to 600KM, the voltage profile of the transmission line was maintained upto 251.428KM termination point from the generation station, beyond this point the voltage level of the transmission line increased beyond 139920kV hence violation of the voltage profile of the transmission line. The 600km transmission is a typical transmission line with reference to no known transmission network.

From the observations made on table 4.1 and Figure 4.2 it was realized that the first ASVT sub-station can be terminated at any point of the 440KM transmission line, thus the point of setting up the ASVT sub-station will depend on setlement of the villages and their distance from the high voltage transmission lines.

Table 4.2:penetration level of ASVT sub-station on 132kV transmission line.

Penetration point(KM)	Voltmeter reading (pu), 3 ASVT terminated	Voltmeter reading (pu) 7 ASVT terminated	Voltmeter reading (pu), 9 ASVT terminated	Voltmeter reading (pu), 10 ASVT terminated
62.857	1.01	1.01	1.01	0.92
125.714	1.02	1.02	1.02	0.84
188.571	1.03	1.03	1.02	0.76
251.428	1.03	1.03	1.03	0.68
314.285	1.04	1.04	1.03	0.61
377.142	1.04	1.04	1.04	0.54
391.12	1.04	1.04	1.04	0.43
440	1.04	1.04	1.04	0.40

The investigation revealed that termination of nine ASVT sub-stations on a 132kV-transmission line does not change it's voltage profile. The voltage profile was violated immediately the tenth ASVT sub-station was terminated on the 132kV transmission line. This data is captured in table 4.2.

4.2.2 Results analysis and contribution on Penetration level of ASVT sub-station on 132kV transmission line.

Table 4.2 shows voltage levels measured when ASVT sub-stations were terminated on a transmission line. These transmission line voltage levels were compared with the expected transmission line voltage profile i.e. $132,000 \pm 7,920$ Volts and conclusion drawn on the state of the voltage profile. When one upto a maximum of nine ASVT sub-stations were terminated on the high voltage transmission line, the obtained voltage levels were within the recommended transmission line voltage profile. The voltage levels of the 132kV line were at high levels at the receiving end than the sending end. This was because of the fact that the transmission line considered for this study was unloaded, and termination of 50kVA sub-stations supplying 50kw loads provided light loads to the system. This phenomenon led to ferranti effects on the transmission line.

When the tenth ASVT sub-station was terminated on the 132kV transmission line, its clear from table 4.2 that the transmission line voltage profile was violated.

The drastic change on the voltage levels meant there was an acute imbalance between the production and absorption of reactive power due to termination of ten ASVT sub-stations leading to violation of voltage profile.

The above results led to a conclusion that a maximum of nine ASVT sub-stations can be effectively terminated on a 440KM, 132kV transmission line without voltage profile violation. If the tenth ASVT sub-station is terminated on the line, then the transmission line voltage profile will be violated.

Further analysis was carried out by plotting results of table 4.2 on a graph as displayed on Figure 4.3 [14]

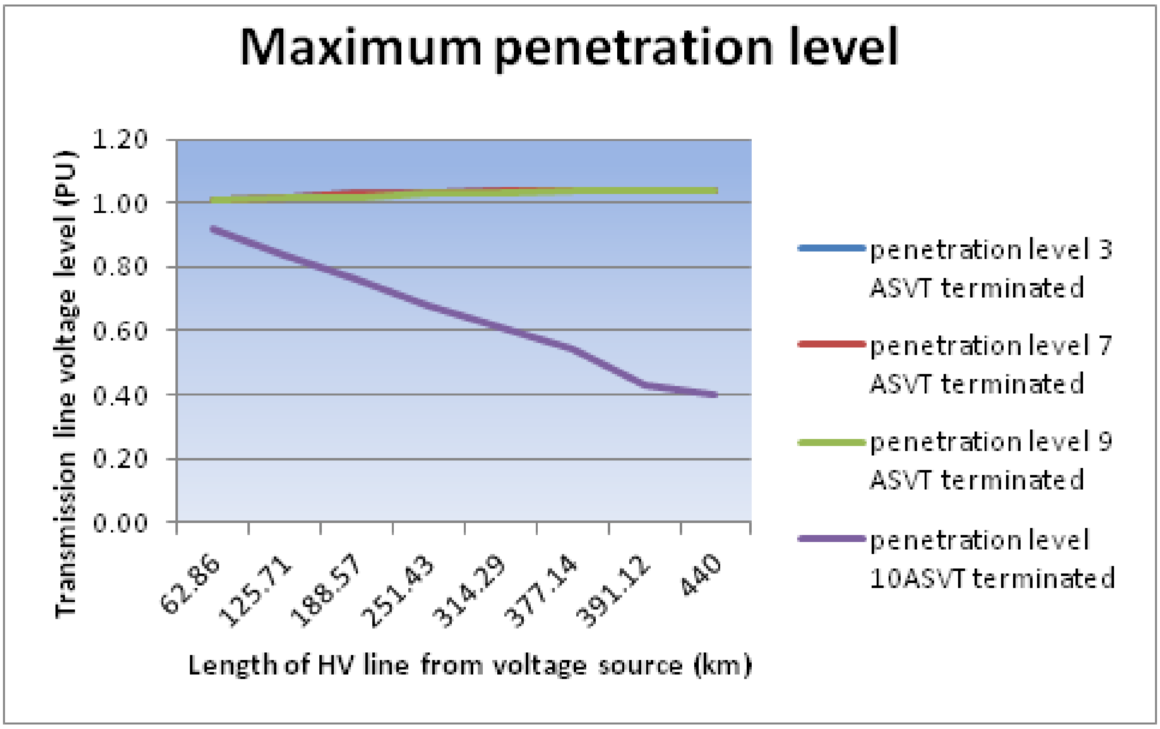

Figure 4.3:Maximum penetration level on 132kV line

Figure 4.3 displays the 132kV transmission line voltage profile when upto 10 ASVT sub-stations were terminated. Terminating one upto nine ASVT sub-stations on the 132kV transmission line had no advance effects on the transmission line voltage profile, but when the tenth ASVT sub-station was terminated the voltage level of the 132kV transmission reduced drastically implying a voltage violation.

This led to a conclusion that the maximum penetration level on 440KM, 132kV transmission is nine ASVT sub-stations.

4.2.3 Penetration level of ASVT sub-stations on Nairobi-Rabai loaded transmission line

The penetration level of ASVT sub-stations on Nairobi-Rabai 132kV transmission line were studied using the line model shown in figure 1b.

Table 4.3 displays the Nairobi-Rabai transmission line voltage levels per unit for uncompensated loaded transmission line, compensated transmission line without ASVT sub-stations and compensated transmission line with ASVT sub-stations terminated on the line to supply villages within the close proximity of the H.V line with electricity.

Table 4.3:Penetration level of ASVT sub-stations on Nairobi-Rabai 132kV loaded transmission line

Penetration point(KM)	Voltmeter reading (pu), uncompensated line	Voltmeter reading (pu), compensated line	Voltmeter reading (pu), compensated line 5ASVT terminated	Voltmeter reading (pu), compensated line 10 ASVT terminated
15	0.93	1.00	1.00	1.00
25	0.88	1.00	1.00	1.00
30	0.86	1.00	1.00	1.00
60	0.75	1.00	1.00	1.00
68	0.72	1.00	1.00	0.99
98	0.65	1.00	1.00	0.99
106	0.64	1.00	1.00	0.99
126	0.62	1.00	1.00	0.99
156	0.59	1.00	1.00	0.99
165	0.59	1.00	1.00	0.99
195	0.56	1.00	1.00	0.99
225	0.53	1.00	1.00	0.99
240	0.0.50	1.00	1.00	0.99
260	0.0.48	1.00	1.00	0.99
296	0.0.47	1.00	1.00	0.99
326	0.46	1.00	1.00	0.99
356	0.46	1.00	1.00	0.99
371	0.45	1.00	1.00	0.99
386	0.45	1.00	1.00	0.99
416	0.45	1.00	1.00	0.99
434	0.44	1.00	1.00	0.99

The above data was then plotted using line graphs as shown in figure 4.4

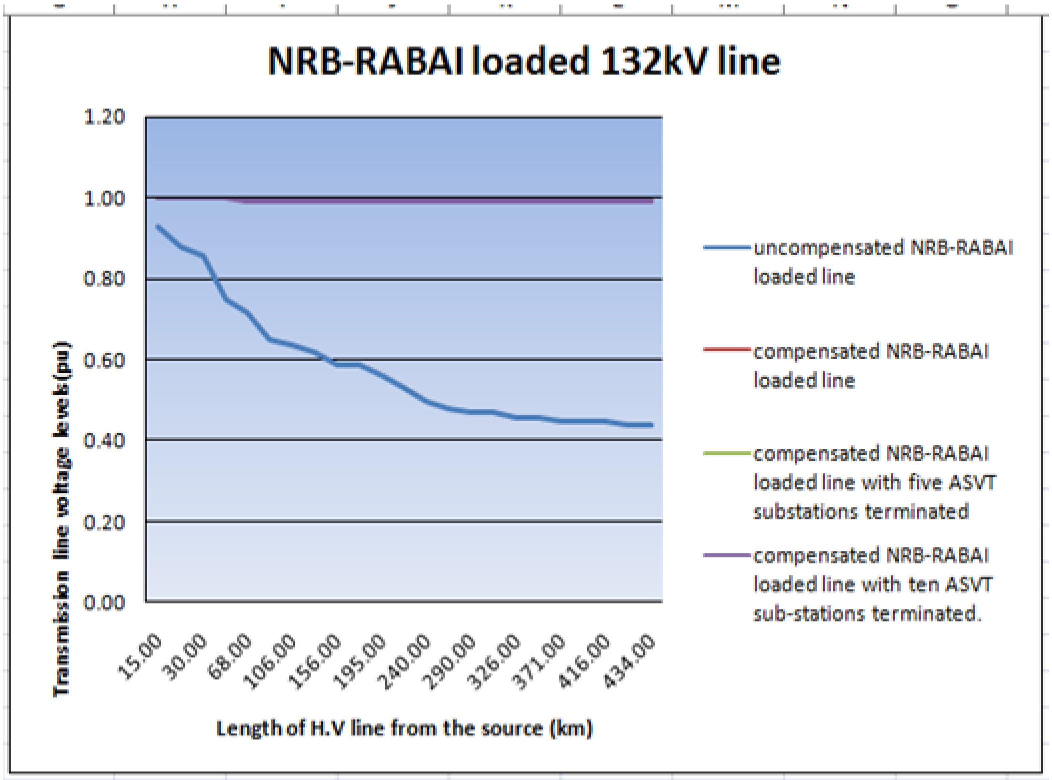

Figure 4.4:Nairobi-Rabai 132kV loaded transmission line

The presence of loads on Nairobi-Rabai 132kV transmission network led to violation of the line voltage profile. The loaded Nairobi-Rabai power network was first compensated to realise a flat voltage profile before ASVT sub-stations were terminated. It was observed that unlike the voltage levels obatained in table 4.1 and table 4.2, where voltage levels where higher at the receiving end compared to the sending end, the voltage levels were the same in this case. The above phenomenon was due to the fact that the Nairobi-Rabai power network has loads thus ferrenti effect was not experienced in this study.

The data analysis presented on the line graph of figure 4.4 shows that ten ASVT sub-stations can be terminated on 132kV loaded Nairobi-Rabai transmission network without voltage profile violation. This is because the penetration of the 10 ASVT sub-stations on the 132kV transmission line added a total load of 0.5Mw to the already existing 54Mw. The total load to the transmission line became 54.5Mw. This was by far below the 60Mw total loading capacity of the Nairobi-Rabai transmission line.

The results also implied that the absorption of the line reactive power was not altered and this led to voltage levels of the line being maintained.
This meant that the villages living at close proximity to the high voltage line can be supplied directly from the transmission network without violating the voltage profile of the Nairobi-Rabai transmission network.

4.3 Transmission line voltage profile at various consumer loads

Table 4.4 represents transmission line voltage levels in per unit for various consumer loads at maximum penetration level of ASVT sub-stations.

Table 4.4:Transmission line voltage level at various consumer loads.

ASVT termination point (KM)	Voltmeter reading (pu), 25kw loads	Voltmeter reading (pu), 50kw loads	Voltmeter reading (pu), 100kw loads	Voltmeter reading (pu), 250kw loads
49.00	1.01	1.01	1.01	1.01
98.004	1.02	1.02	1.02	1.02
147.00	1.02	1.02	1.02	1.02
196.00	1.03	1.03	1.03	1,03
245.00	1.03	1.03	1.03	1.03
294.00	1.03	1.03	1.03	1.03
343.00	1.04	1.04	1.04	1.04
392.00	1.04	1.04	1.04	1.04
441.00	1.04	1.04	1.04	1.04

This data was used to plot line graph for the analysis of the transmission line voltage profile at various consumer loads, as captured in Figure 4.5.

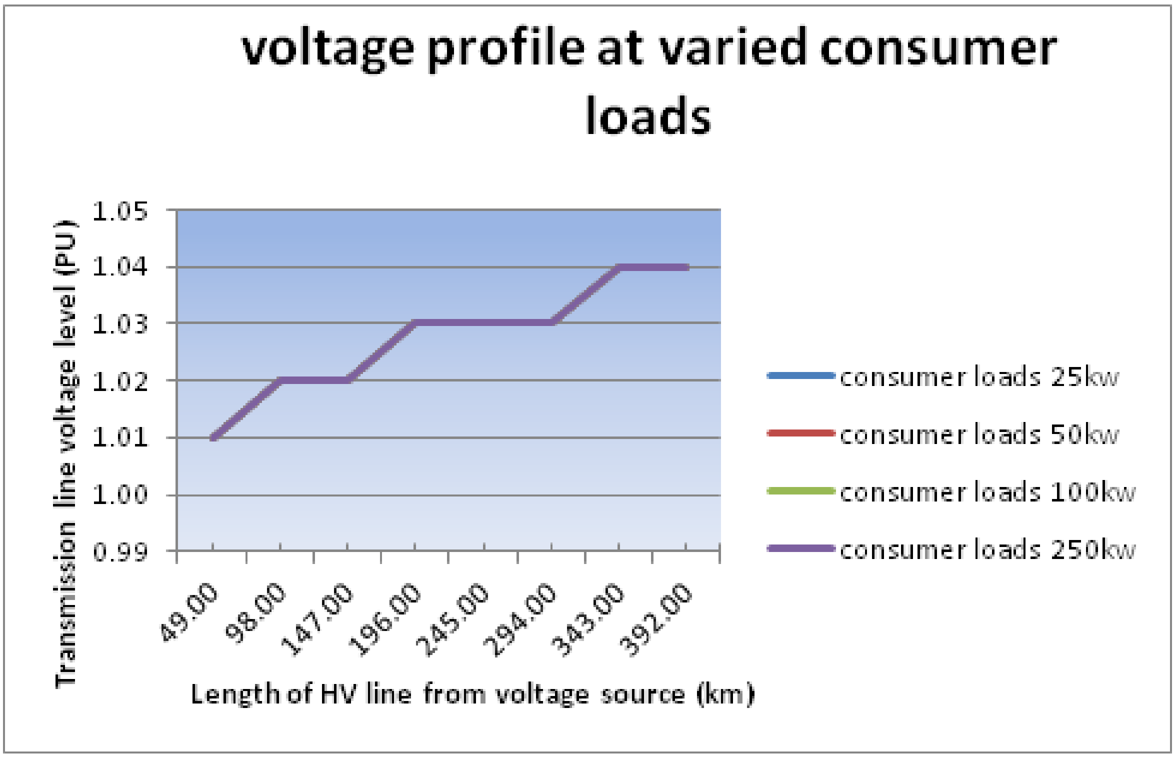

Figure 4.5:Transmission line voltage profile at various consumer loads

The voltage levels of the 132kV, 440km transmission line was not affected by variation of the consumer loads from 25kw to 50kw, from 50kw to 100kw and from 100kw to 250kw. This shows that the voltage profile of the transmission line network is independent of the consumer loads supplied by ASVT sub-stations.

Further research on the waveforms of the signal being transmitted by the transmission line were investigated and the following results were obtained.

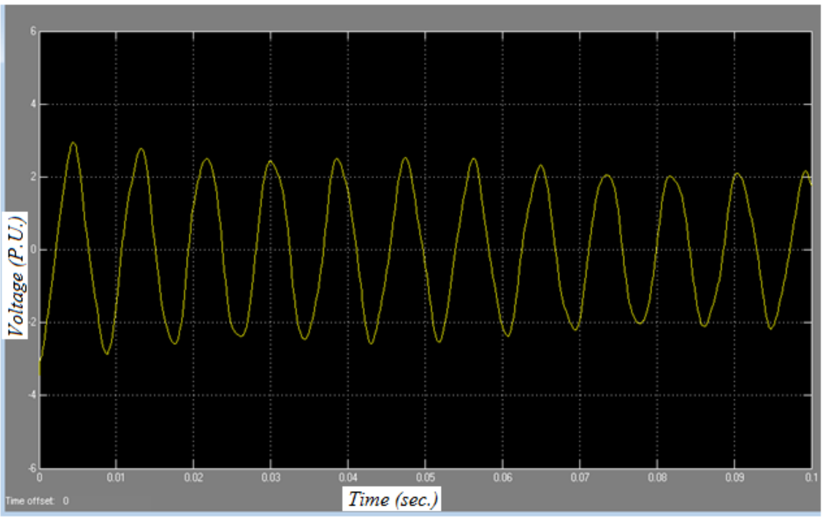

Figure 4.6:Transmission line voltage waveform after terminating first ASVT

The waveform of the ASVT sub-station was displayed as shown in Figure 4.7

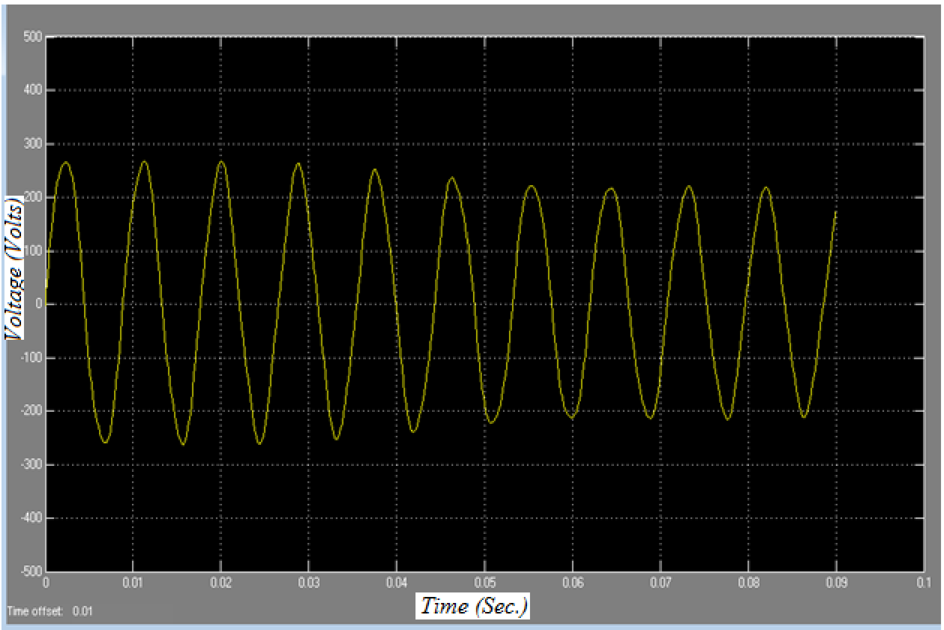

Figure 4.7:ASVT 1 output voltage waveform

The transmission line voltage waveform after the sixth ASVT termination was displayed as captured in Figure 4.8

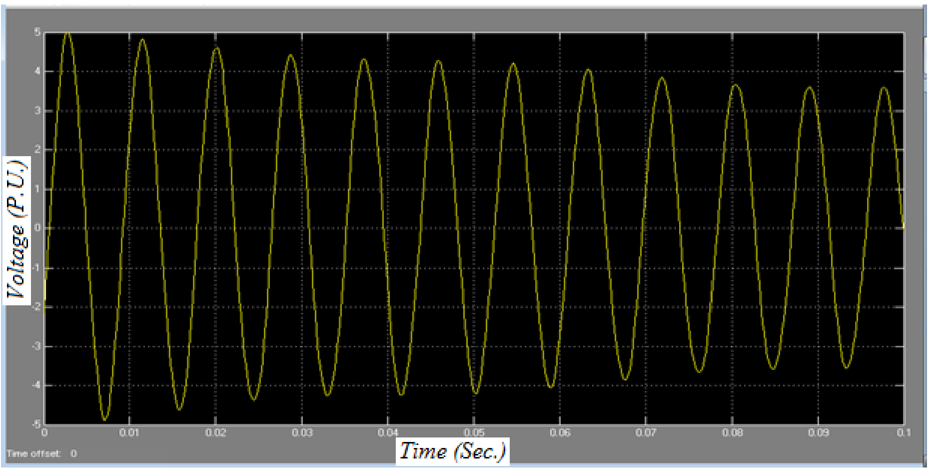

Figure 4.8: Transmission line voltage waveform after terminaton of sixth ASVT sub-station

The corresponding output voltage waveform of the sixth ASVT substation is as captured in Figure 4.9

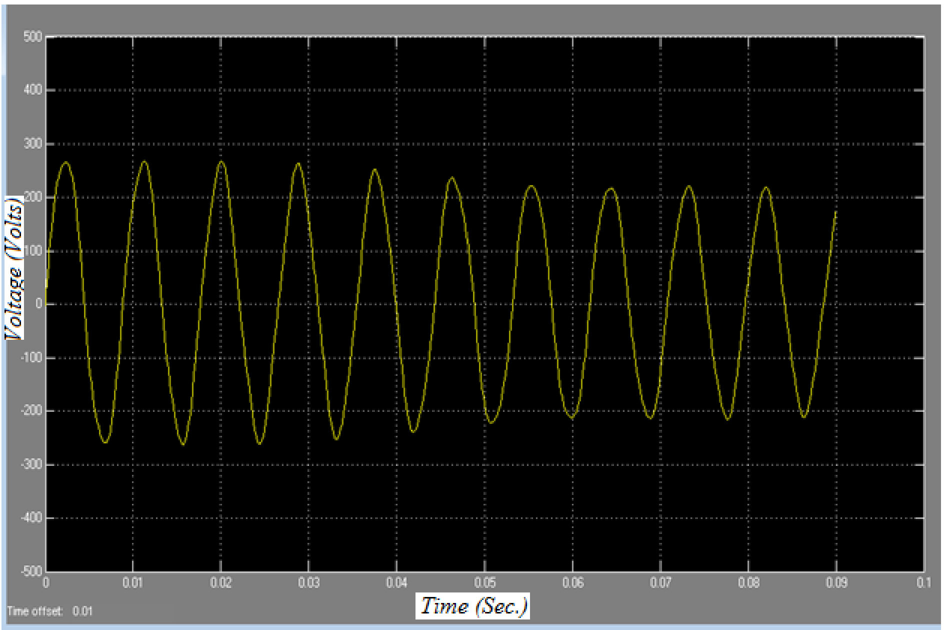

Figure 4.9: ASVT 6 output voltage waveform

The transmission line voltage waveform after the ninth ASVT substation termination was displayed as captured in Figure 4.10

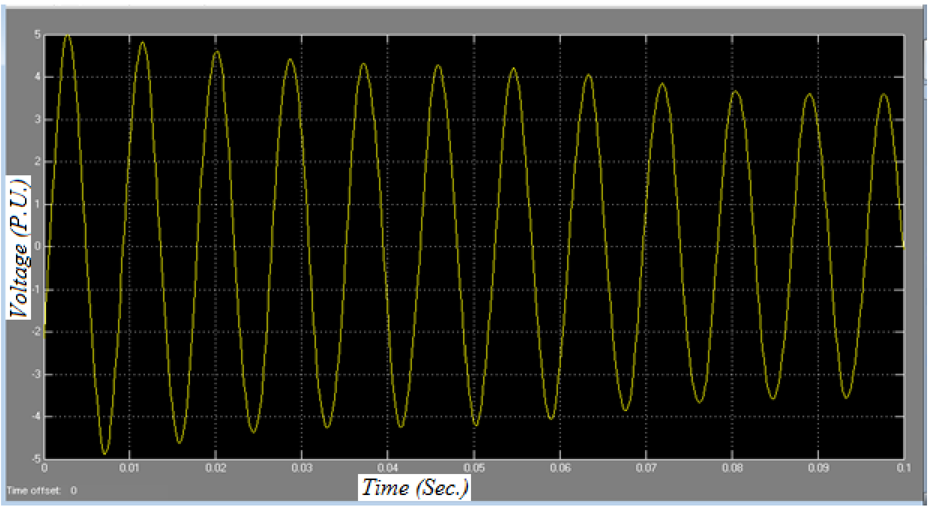

Figure 4.10: Transmission line voltage waveform after terminaton of ninth ASVT sub-station

The corresponding output voltage waveform of the ninth ASVT substation is as capture in Figure 4.11

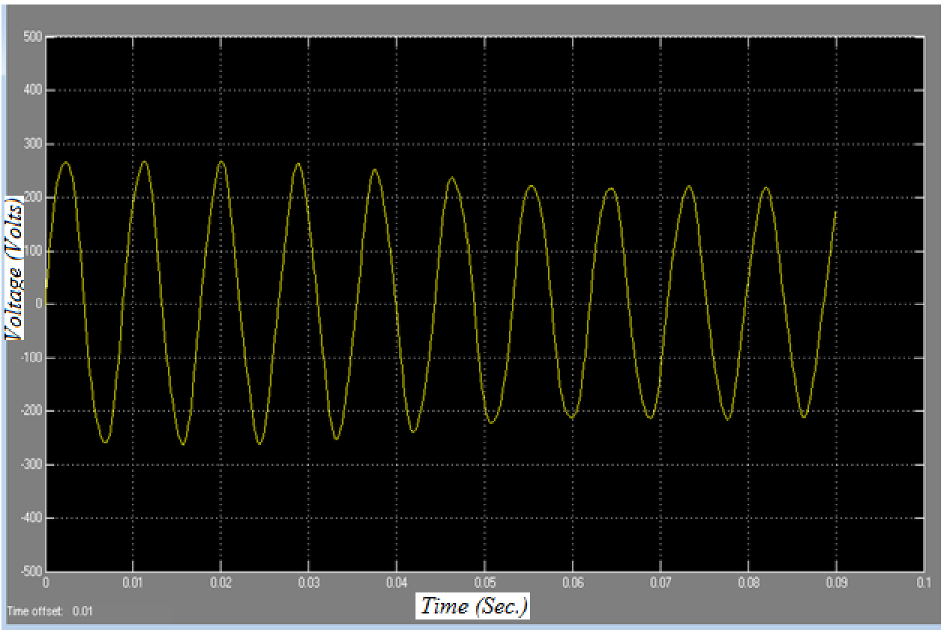

Figure 4.11: ASVT 9 output voltage waveform

The obtained voltage levels indicated that the transmission line voltage profile was violated when the tenth ASVT sub-station was terminated on the transmission line.

The transmission line voltage waveform after the first ASVT sub-station appeared as shown in Figure 4.12

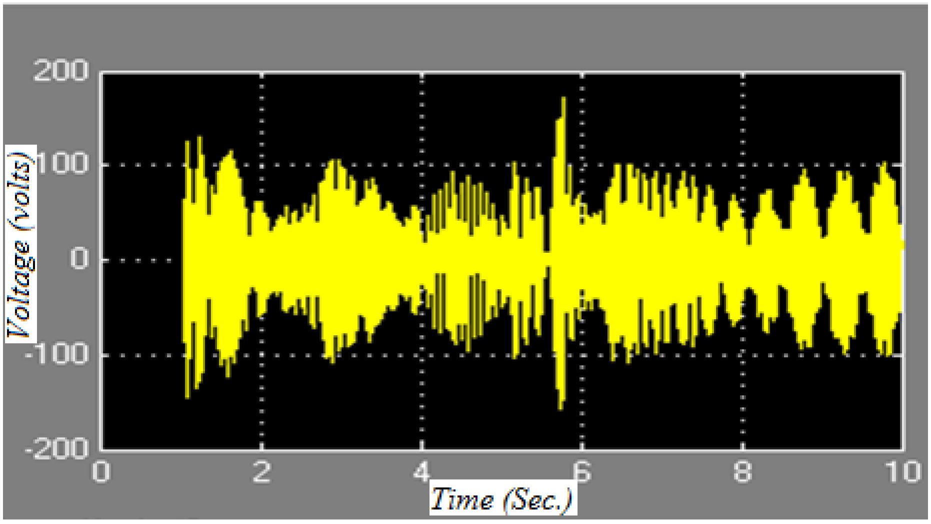

Figure 4.12Transmission line voltage waveform after the first ASVT sub-station

The ASVT sub-sations voltage output waveforms when ten ASVT sub-stations were terminated on a transmission line were as captured in Figure 4.13

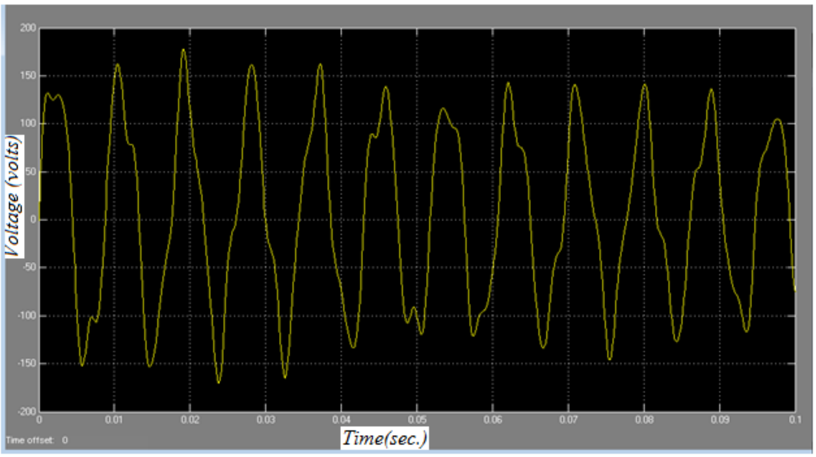

Figure 4.13: ASVT output voltage waveform after ten ASVTs were terminated

The transmission line voltage waveform after the sixth ASVT sub-station appeared as shown in Figure 4.14

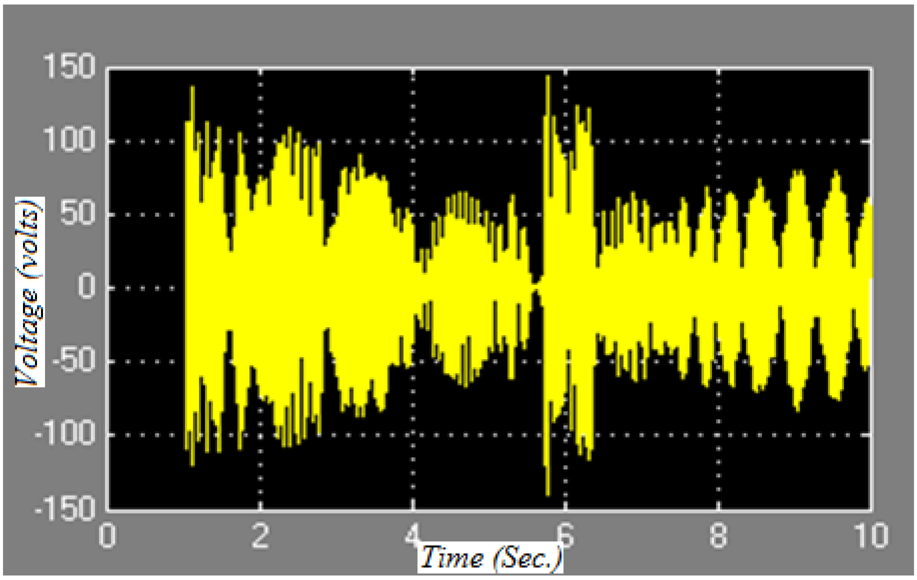

Figure 4.14: Transmission line voltage waveform after the sixth ASVT sub-station

The transmission line voltage waveform after the tenth ASVT sub-station appeared as shown in Figure 4.15

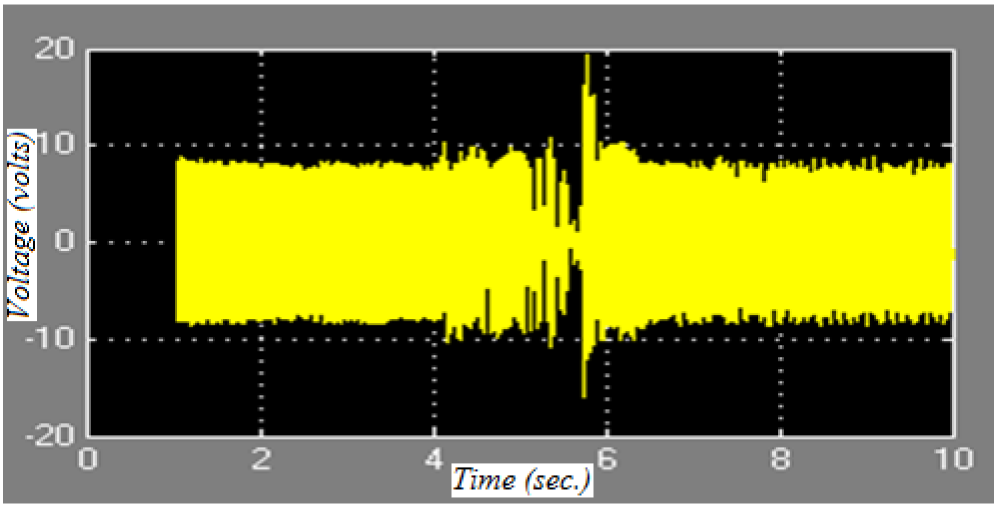

Figure 4.15:Transmission line voltage waveform after the tenth ASVT sub-station

The voltage waveforms of the transmission line after the violation of the voltage profile is distorted as captured in Figures 4.13, 4.14 and 4.15.

The distortion of voltage waveform is normally brought forth by introduction of electrical and electronic devices made for power control, power rectification or shaping of power signal. In this case introduction of several ASVT sub-stations on the line led to distortion of the wave signal.

This means compensation devices have to be incorporated in the transmission line before terminating another ASVT.

The above observation was further strengthed by the display of the waveforms of the transmission line signal. Figure 4.6, 4.7, 4.8, 4.9, 4.10 and 4.11 shows that a sinusoidal waveform was realized when upto nine ASVT substations were terminated on the 132kV transmission line. When the the tenth ASVT sub-station was terminated, the obtained waveforms were distorted as captured in Figures 4.13, 4.14 and 4.15 Thus the maximum penetration level of ASVT sub-stations on a 132kVtransmission

CHAPTER FIVE

TECHNO-ECONOMIC COMPARATIVE ASSESSMENT OF ASVT VERSUS CONVENTIONAL SUB-STATIONS

5.1 Background information

A research on the techno-economic comparative assessment of ASVT versus conventional sub-stations was aimed at identifying the equipments used in stepping down voltages from 132kv to low voltages for distribution purposes and their corresponding life cycle cost (LCC). The prices of the local manufacturers were quoted where necessary and for equipments not found in the local markets international prices were quoted.

The above research was used to draw conclusion on the most economical sub-station to be used to supply electricity to villages living 500 meters radius from the high voltages transmission lines and the maximum number of ASVT sub-stations that can be terminated to supply electricity to these villages beyond which a conventional sub-station will be more economical.

5.2 Conventional sub-station to supply Maungu village

A case study of Maungu village located along Nairobi - Mombasa highway was used to analyse the cost of setting up a conventional sub-station to supply the village. The features of the village are as follows:

(1) Has 18 households and a shopping centre.

(2) Located 300 metres from the 132kv transmission line.

(3) 40KM away from the nearest conventional sub-station

(4) Sparsely populated.

The conventional sub-station is a fully flashed sub-station that terminates the transmission line and as a result maintains a high level of service.
It is designed with a large amount of redundancy in terms of transformers, disconnect switches, circuit breakers, bus bars in order to provide continued operation under failure or high load.
This sub-station uses transformers which step down voltage from 132kV to 66kV then 66kV to 11kV. This sub-station cannot be used to step down voltage from 132kV tapped from transmission line to 11kV directly. This is because of the fact that the voltage level needed by different consumers is not the same. There are consumers for the mid range voltage levels such as 66kV and 33kV.
The leakage flux in such a transformer would be very high and the insulation required to overcome it will be too expensive thus making the entire process impractical. 132kV/11kV will be more economical and would carry out almost same supplies as ASVT sub-stations.

This distribution sub-station has many components involved, thus being very large and spreads over large ground area. A single line diagram of the conventional sub-station is as shown in Fig 5.1. [6]

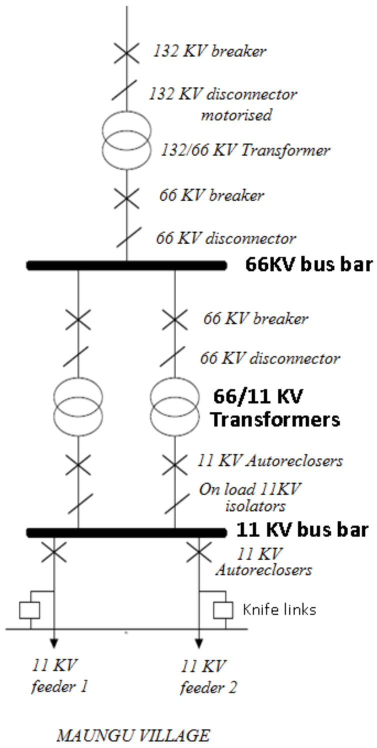

Figure 5.1: 132/66/11kv conventional sub-station single line diagram

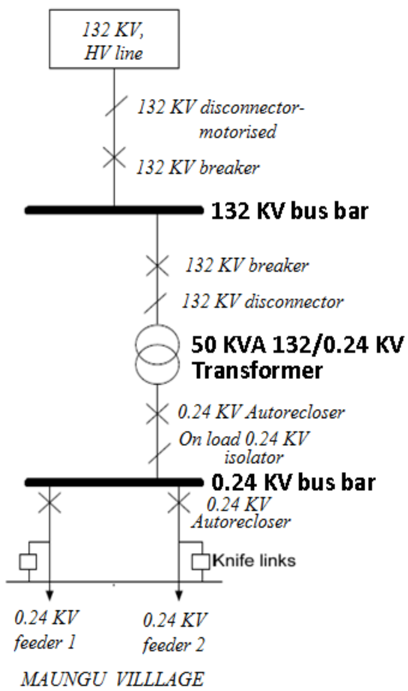

Figure 5.2: ASVT sub-station single line diagram

5.3 ASVT sub-station to supply Maungu village.

The ASVT sub-station tap power directly from the over head transmission lines through high voltage connectors and do not interrupt power flow along the transmission lines.

The ASVT sub-stations use one transformer and a bus bar to interconnect transformers . A disconnector switch and a circuit breaker are required, but to reduce further the cost of components the circuit breaker can be replaced by a disconnector switch. [6]

As a simple and cheaper alternative the circuit breaker can be replaced by a disconnector switch (or a load breaker switch) and set of fuses, significantly reducing the amount of equipment necessary to ensure operation of the ASVT sub-station.

The ASVT sub-station removes all the back up that is found in the conventional sub-station and as such when one component of the sub-station fails customers will definitely experience power outage.

This is not a serious problem to the customers in the rural villages in comparison to having no electricity supply as long as the cost of electricity connection is affordable.

A single line diagram of an ASVT sub-station is as shown in Fig 5.2.

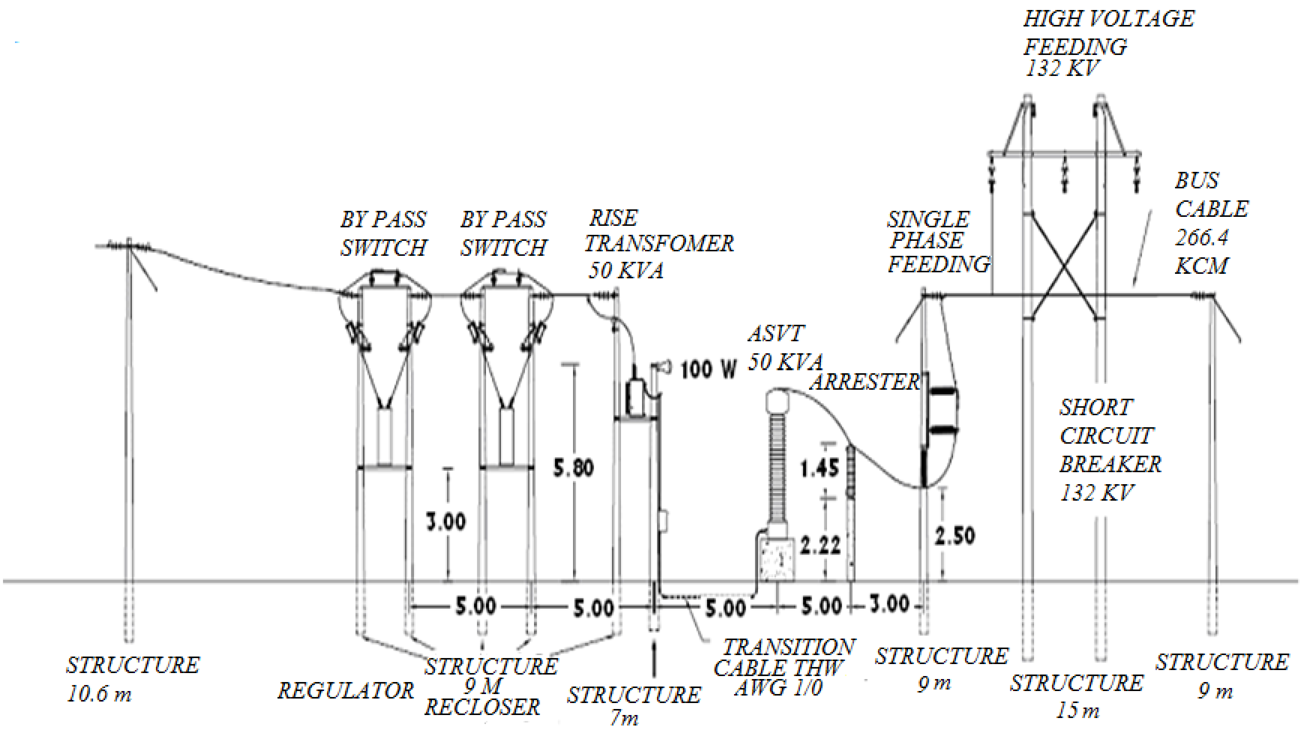

Figure 5.3: ASVT Sub-station layout

5.4 Life cycle costing of sub-stations

A life-cycle cost analysis (LCC) is geared at determining the total cost of a sub-station and expenses incurred in maintaining it.
The main reasons for carrying out LCC analysis are:

(1) Comparison of the costs incurred in setting up a sub-station.

(2) To determine the most cost-effective sub-station.

The life-cycle cost of a project can be calculated using the formula [15]:
$LCC = C + Mpw + Rpw - Spw$ where;
C= capital cost of a project i.e. initial capital expense for the equipment, the system design, engineering, and installation.

M = maintenance i.e. is the sum of all yearly scheduled operation and maintenance (O and M) costs.

Pw = the present worth of each factor.

R = replacement cost i.e. the sum of all repair and equipment replacement cost anticipated over the life of the system.

S = salvage value of a system i.e. its net worth in the final year of the life-cycle period.

Table 5.1: Life cycle costs for a fully flashed conventional versus ASVT sub-station.

		Conventional substation		ASVT substation	
Capital (C)	Price per Item (Kshs)	Qty	Total Price (Kshs)	Qty	Total price (Kshs)
132kv disconnector switch motorized	300,000	2	600,000	1	300,000
132kv breaker	1,250,000	2	2,500,000	1	1,250,000
66kv disconnector switch	300,000	3	900,000		
66kv breaker	1,250,000	3	3,750,000		
66kv busbar	1,600,000	1	1,600,000		
11kv auto recloser	1,640,000	3	4,920,000		
ON load 11kv isolator	225,000	3	675,000		
240V bus bar	100,000	1	100,000	1	100,000
240V recloser	1,000,000			3	3,000,000
ON load 240V isolator	225,000			1	225,000
Knife link	58,000	2	116,000	2	116,000
11kv busbar	100,000	1	100,000		
11kv tie bar	100,000	1	100,000		
240V tie bar	100,000			1	100,000
Civil works			4,000,000		2,000,000

		Conventional substation		ASVT substation	
Earthing			1,750,000		750,000
132/66kv, 10MVA Transformer	50,000,000	1	50,000,000		
66/11kv, 5MVA Transformer	49,000,000	2	98,000,000		
11/0.24kv, 200kVA Transformer	49,000,000	1	49,000,000		
132/0.24kv, 50kVA Transformer	49,000,000			1	49,000,000
A) SUB-TOTAL			218,111,000		56,841,000
Operation and Maintenace	Price per Item (Kshs)	Qty	Total Price (Kshs)	Qty	Total price (Kshs)
Transfo.& switch gear service(per yr)	15,000,000	2	30,000,000	1	15,000,000
B) SUB-TOTAL			30,000,000		15,000,000
REPLACEMENT (RPw) (yr)					
ON load kv isolator	225,000	3	675,000	1	225,000
66kv breaker	1,250,000	3	3,750,000		
c) SUB TOTAL			4,425,000		1,475,000
SALVAGE (SPw) (yr)					
20% of original					
D) SUB TOTAL			6,954,660		2,500,000

The life span of a conventional distribution sub-station is 40years while ASVT sub-station can operate for 20 years without failure. The future sums of money used in the operation and maintenance of a sub-station must be discounted. This is because of the inherent risks of future events not occuring as planned. Taking the long term loan interest rate of 14% as the discount rate, then the life cycle costing for the sub-station was determined as follows:

$$LCC = C + Mpw[1 + \frac{r}{100}]^n + Rpw[1 + \frac{r}{100}]^n - Spw$$

The life cycle cost for a conventional sub-station becomes:
$LCC = 218,111,000 + 30,000,000[1 + \frac{14}{100}]^{20} + 4,425,000[1 + \frac{14}{100}]^{20} - 6,954,660 = Ksh.684,275,979$
The life cycle cost for an ASVT sub-station becomes:
$LCC = 56,841,000 + 15,000,000[1 + \frac{14}{100}]^{20} + 1,475,000[1 + \frac{14}{100}]^{20} - 2,500,000 = Ksh.280,764,996$
The life cycle costing for the sub-stations within a duration of 20 years shows that setting up an Auxiliary Service Voltage Transformer sub-station to supply Maungu village with electricity is 2.4 times cheaper than setting up a conventional distribution sub-station to supply the same village with electricity.
The local price market was used. The research also relied on the competitive prices offered to Kenya Power and Lighting company by the power system equipment manufacturers.

CHAPTER SIX

RESERCH CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

From this research the following conclusions were drawn:

An ASVT sub-station can be terminated at any point of 440km,132kV transmission line without voltage profile violation.
A maximum of nine 50kVA ASVT sub-stations can be terminated on a 440km, 132kV transmission line to supply villages living at close proximity with electricity without voltage profile violation.
More than Ten 50kVA ASVT sub-stations can be terminated on a loaded 132kV Nairobi-Rabai transmission network without violation of it's voltage profile. This is because the compensated line has a capacity of 6MW to be used up by the 50kVA sub-stations.
The voltage stability of the 132kV transmission network will be maintained at maximum penetration level of ASVT sub-stations.
An ASVT sub-station is 2.4 times cheaper than a conventional sub-station.

6.2 Research Recommendations

Further research should address the scientific reason behind the voltage collapse after the termination of the tenth ASVT sub-station on the 132kV unloaded transmission line.

The research should further be carried out to investigate the effects of ASVT sub-stations on the transmission line in terms of reactive power.

The research should further address the effects of changing loads of conventional sub-stations to the transmission line.

Further research should be carried out to determine the penetration level of Capacitor coupled sub-stations on a 440KM, 132kV transmission line without voltage profile violation.

The research should further investigate whether the penetration level improves if ASVT sub-stations are used together with the capacitor coupled sub-stations interchangeably on a 440KM, 132kv transmission line.

The research should also be geared at investigating whether use of reactive power compensator would lead to increased penetration level of non-conventional sub-station on the 440KM, 132kv transmission line.

The techno-economic comparative assessment of the non-conventional sub-stations should be carried out to draw conclusion on the most economically viable non-conventional sub-station that can be used to supply Maungu village with electricity and the power utility company realize return on investment.

REFERENCES

[1] *Arteche Instrument Transformer Manual(2010): ASVT245 and ASVT-145 man*ual and tecnical bronchures

[2] *World energy outlook, SBN: 978-92-6412413-4.*

[3] (2007). *power transformer design using magnetic theory finite element analysis - comparison of technique proceedings of AUPEC, western Austrilia,.*

[4] A. Omar & R. Gomez. (2010). Rural electrification in chuahua, mexico at one third of cost versus a conventional substation. *Issue 1.2 : Eradicating energy poverty.*

[5] A. Shukla & M. Sekar. (2003). Study of the effects of X/R ratio of lines on voltage stability. *IEEE transaction on power delivery*, 2:83–97.

[6] Anderson, K. & Yanev, G. (2010). Non conventional substation and distribution system for rural electrification. In *3rd IASTED Africa PES 2010 in University of Botswana.*

[7] D. Kothari & I. Nagrath (2010). *Modern Power System Analysis.* Tata Mc Graw Hill Education Private ltd.

[8] Deng, X. (2012). Exploring six phase transmission lines for increasing power transfer with limited right of way. unpublished. Master's thesis, Arizona State University.

[9] G. Dagbjartsson & C.Gaunt. (2013). Rural electrification. *A scoping report.*

[10] Gaunt, C. (2005). H.V. SWER and single phase systems. *CIGRE sc-c6 Working group (C011 2005)*, pages 1–6.

[11] Globler, M. (2007). Determination of transmission line parameters from time stamped data. unpublished. Master's thesis, Pretoria: University of Pretoria.

[12] Gray, V. (2013). Electrifying isolated communities. *Station service voltage Transformer.*

[13] J. Kitheka, M. Saulo & D. Murage (2015). The penetration level of auxiliary service voltage transformer substations on a power network for rural electrification. In *Kabarak University 5th Annual International Conference.*

[14] Kitheka J. & Murage D. (2016.). Determination of the maximum number of ASVT sub-stations that can be terminated on 132kv transmission line without voltage profile violation. In *The 2016 International Sustainable, Research and Innovation Conference held at Kenya School of Monetary Studies, Thika Road, Kenya.*

[15] Kitheka J., Murage D. & Saulo J. (2016). Techo-economic comparative assessment of ASVT versus conventional sub-stations for rural electrifiction. *American Journal of Electricl power and Energy systems.*, Vol 5 No. 2:11 – 16.

[16] Kitheka J., Saulo M. & Murage D. (2016). Determination of the penetration level of ASVT sub-stations on 132kv transmission line without voltage profile violation. *International Journal of Energy and Power Engineering*, 1.

[17] M. Glover & J. Sarma (2002). *Power system analysis and design.* 3rd ed Brooks/Cole.

[18] M. J. Saulo (2014). *Penetration level of unconventional rural electrification technologies on power networks. Unpublished.* PhD thesis, Capetown: University of Capetown.

[19] M. Saulo & C. Gaunt (2014). Implication of using auxiliary service voltage substation for rural electrification. *Internation al journal ofenergy and power engineering*, 4(2-1):1–11.

[20] M. Saulo, C. Gaunt & M. Mbogho (2012). Comparative assessment of capacitor coupled substation and auxiliary service voltage transformer for rural electrification. In *2nd Annual International Conference in Kabaraka University.*

[21] Margaret, K. (2013). End use based model for residential power consumption forecasting in Nairobi region, kenya. unpublished. Master's thesis, Nairobi: University of Nairobi.

[22] Ombuoa, A. (2006). The high voltage line becomes power distributor: Asuccessful test in congo. *Journal of Electrical systems*, 2-1:52 – 63.

[23] R. Gomez, A. Solano & C. Gaunt (2010). Rural electrification project development, using auxiliary service voltage transformer. pages 1–6.

[24] S. Catarina (Nov 2013). Calculation of power transformer equivalent circuit parameters using numerical field solutions. *IJRAS 17(1)*, VOL 7 issue 1:20 –28.

[25] S. Nayal & N. Sehgal. (2006). EHV transmission line capacity enhancement through increase in surge impedance loading level. *IEEE Transaction power delivery*, 12:1202–1209.

[26] S. Vehmansvaara (2013). Compensation strategies in cabled rural network . unpublished. Master's thesis, Tampere University of Technology.

[27] Saulo, M. & Mbogho, M. (2014). Implication of capacitor coupling substation on rural electrification planning in kenya. In *Procceedings of 3rd international Kenya Society of Electrical and Electronics Engineers Conference, KSEEE in Technical University of Mombasa.*

[28] Sung Don Cho (2002). *Parameter estimation for transformer modeling. Unpublished*. PhD thesis, Michigan Technological University.

[29] Thomas, A. (2009). Investigation and evaluation of voltage drops: A case study of guiness and ikpooa dam injection substation. *International journal of electrical and power Engineering*, 3, issue 2:105 – 111.

[30] Wilson, M. Zevenbergen & Murpy, J. (1999). Calculation of transmission line parametersfrom synchronized measurement. *Taylor and Francis*, 27:1269 – 1278.

Appendix I: ASVT design

ASVT parameters of a 100kVA rating is presented in this appendix. Basic concept of selection of number of turns for the transformer based on the equation 6.4 is presented.

$$E_t = k\sqrt{Q} \tag{6.1}$$

From the number of turns and the approximate flux- density (assumed) the gross core area can be calculated. Once the core area is known, the core diameter can easily be found using the formula

$$A_g = k_1 \Pi d^2 \tag{6.2}$$

Where d is the core diameter and k is a factor to be selected from the number of core steps. Selection of the approximate area of winding wires and strip are done on the basis of the rated current and available current density, which is generally restricted to 1.5A/sqmm for aluminum and 3.0A/sq/mm for copper material.
The diameter of round conductor for high voltage winding can be calculated from the equation:

$$Area = \frac{\Pi d^2}{4} \tag{6.3}$$

The size of the strip and their disposition is very important to minimize the skin effect. However, while selecting the strip, the limitation of size as the ratio of width and depth must remain 2 and 4.

Table 8.1: ASVT Design specifications

	Design specifications
Power rating	50kVA
No load voltage ratio	132/0.24kV
No of phase per frequency	3phase/50HZ
Connection	Delta/Star
Winding material	Copper
Tapping on H.V	2.5% TO 5% for H.V variation.
Impedance	4.5%
Maximum flux density	1.6 Tesla
Maximum current Density	3.0 A/sqmm

Voltage per phase:

$$V_{ph} = \frac{132000}{\sqrt{3}} = 76,210V \tag{6.4}$$

Current per phase;

$$I_{ph} = \frac{\text{power rating}}{3 \times V_{ph}} \tag{6.5}$$

$$I_{ph} = \frac{50,000}{3 \times 76,210} = 0.21869A \tag{6.6}$$

Taking the assumed current density of 3.0/sqmm

$$\text{Conductor area} = \frac{\text{current per phase}}{\text{current density}} \tag{6.7}$$

$$\text{Conductor area} = \frac{0.21869}{3.0} = 0.0729mm^2 \tag{6.8}$$

$$d^2 = \frac{0.0729 \times 4}{\Pi} \tag{6.9}$$

d = 0.3047 mm.

The designer chose 0.3 mm as the transformer winding diameter.

Table 8.2:Number of turns per coil.

Formula	calculation.
$E_t = k\sqrt{Q}$	k for copper = 0.45; $E_t = 0.45\sqrt{50} = 3.18V/turn$
Secondary turns per coil $= \frac{V_{ph}\sqrt{2}}{E_t}$	Secondary turns $= \frac{76{,}210\sqrt{2}}{3.18} = 34$T
Primary turns $= \frac{V_{ph} \times \text{secondary turn}}{\text{secondary}V_{ph}}$	primary turns $= \frac{76210 \times 34}{240} = 10796.4$T
additional 5% tapping voltage	$5\% \times 10,796.4 = 539.82$ T
Total primary turns	$10,796.4 + 539.82 = 11,336.22$T
Assume 4 turns per coil	
Turns per coil	$\frac{11{,}336.22}{4} = 2,834.055$T

Table 8.3:ASVT L.V Winding.

Parameter	Technical specification.
Voltage per phase	240 V
Current per phase	185.54A
Current density	3A/sqmm
Number of coils per phase	4
Turns per coil	90 T
Number of layers	2
Turns per layer	43.5

Appendix II: Unloaded 132kV transmission line model

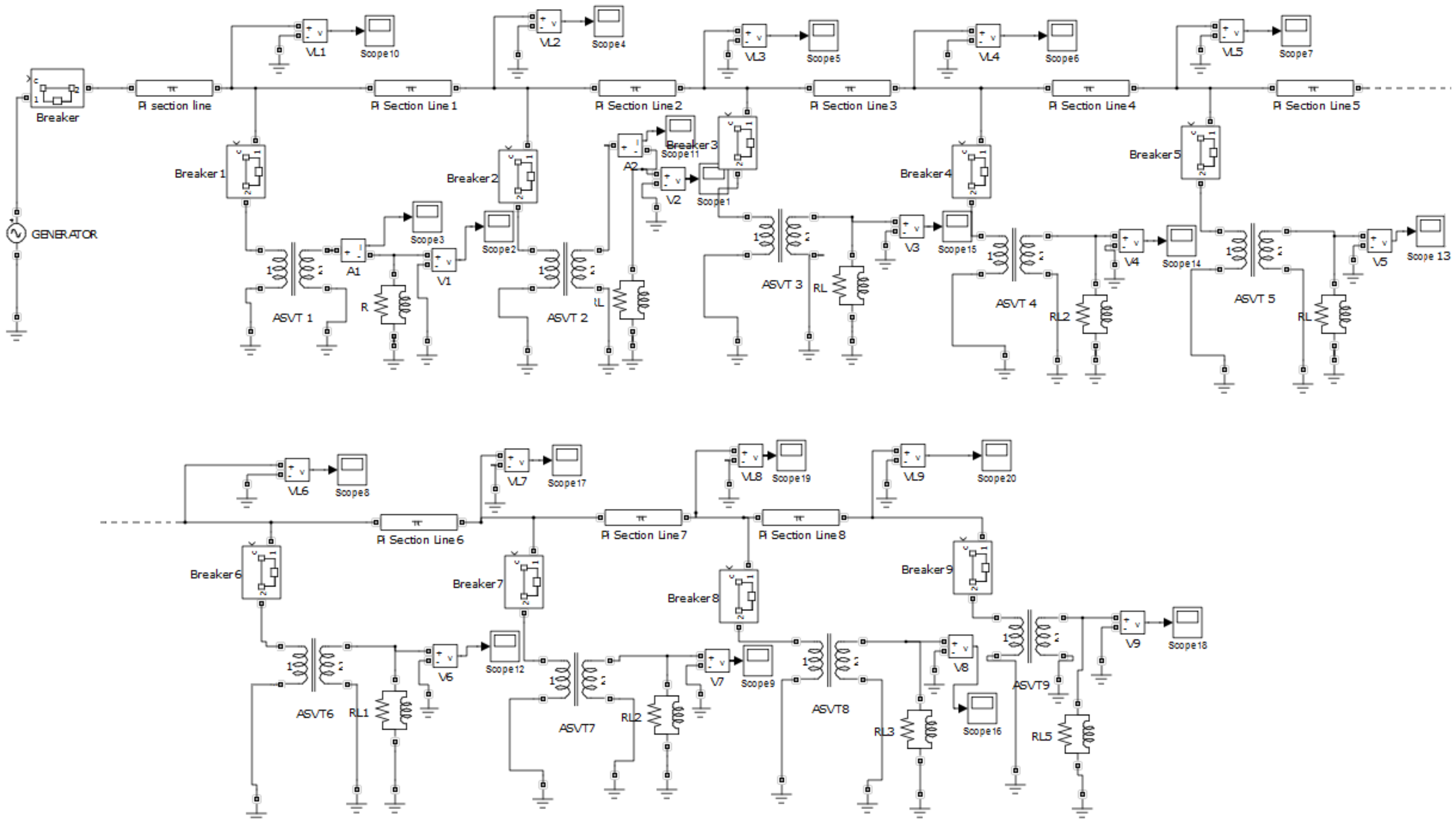

Figure 1a: Unloaded 132kV transmission line model

Appendix III: Nairobi- Rabai loaded 132kV transmission line

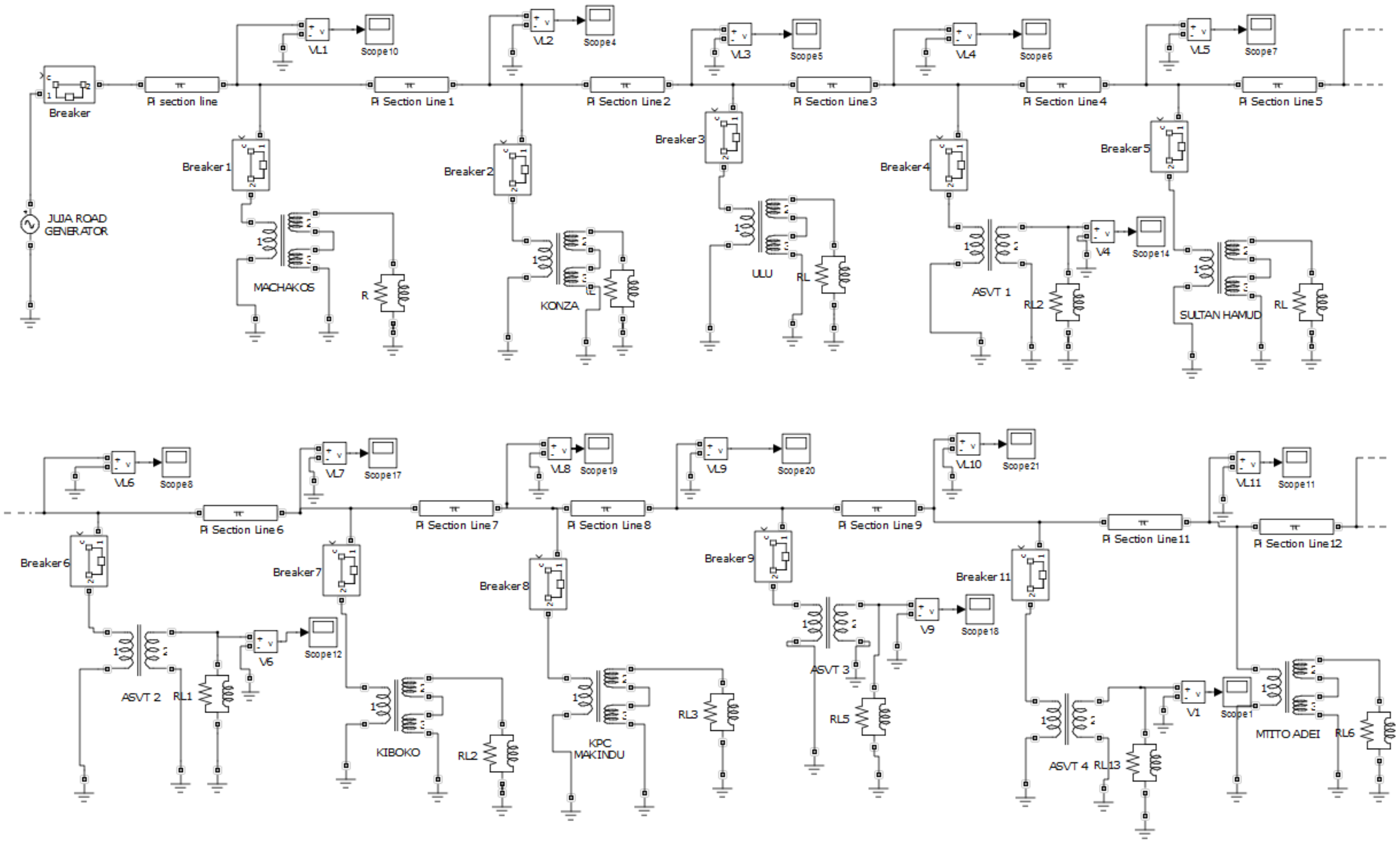

Figure 1b: Nairobi-Rabai loaded 132kV transmission line

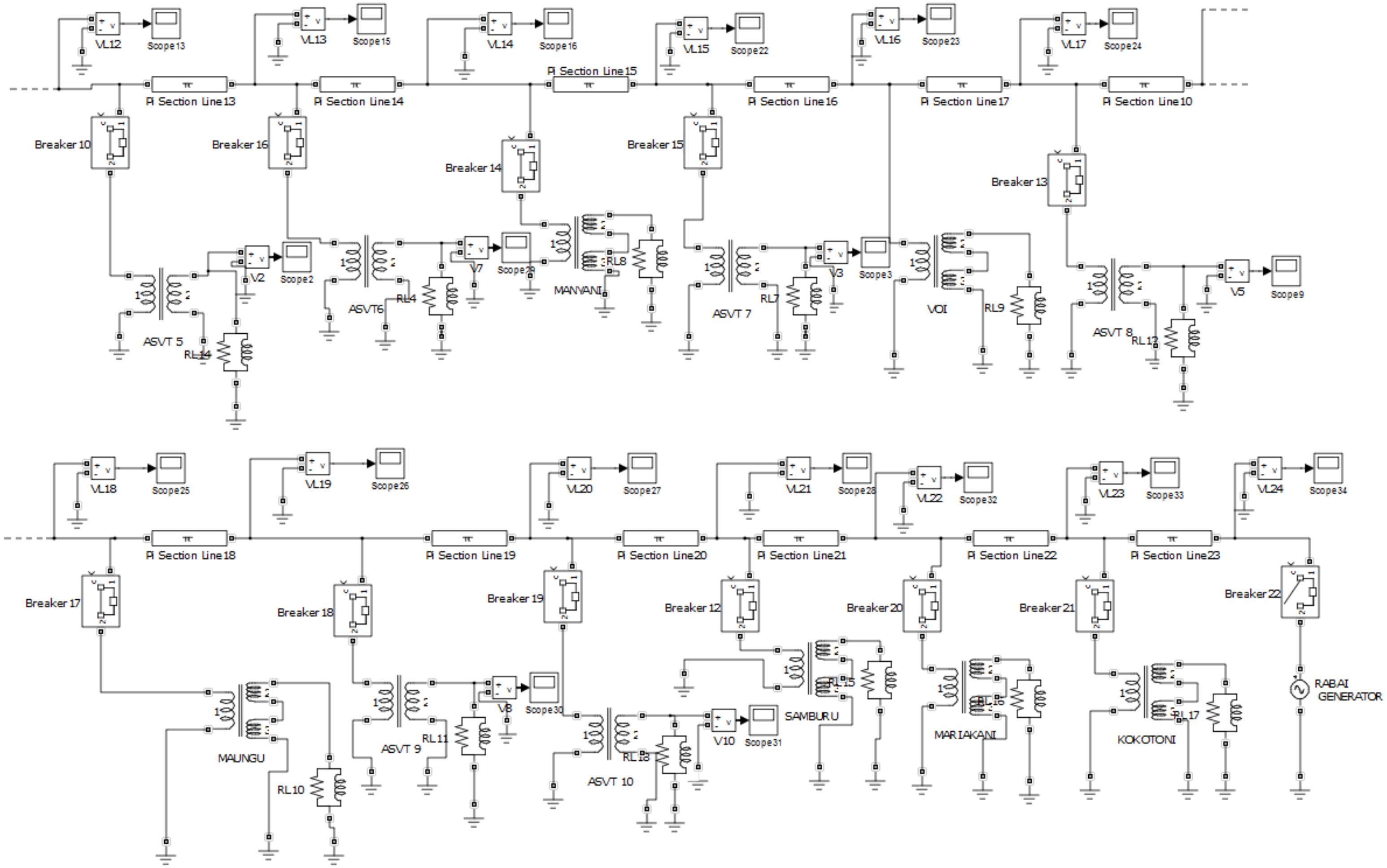

Figure 1b: Nairobi-Rabai loaded 132kV transmission line