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Analysis of the Impact of Wind Power Generation on the Kenyan Power System's Small Signal Stability with Excitation Controllers For Conventional Generators.

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Abstract
Kenya is an industrializing nation in Africa and envisions transforming itself into a newly industrializing, middle-income country by 2030, with a globally competitive and prosperous economy. In order for the Government of Kenya to meet the increased power demand, it has invested heavily on the increased generation of renewable sources such as hydro, solar and wind. The Government is targeting to increase wind penetration to 2036MW by 2030. Wind is carbon emission free hence environmental concerns are met, however, the electrical system and the mechanical system are decoupled hence the rotor angle stability is affected. It is thus necessary to investigate the impacts of wind power penetration on the dynamic behavior of the power system concerned such as small signal stability studies.
Small signal stability is done to analyze small disturbances such as continuous and small variations in loads and generation which make the power system exhibit small deviations from the equilibrium point.
The aim of this project was to analyze the impact of wind power generation on the Kenyan Power System's small signal stability. This is because wind generators in this case DFIGs rotate at different speeds as compared to the speed of the synchronous generators causing the machines to fall out of synchronism hence affecting the rotor angle stability. To correct this the controllers are used for coupling of the two machines and maintain synchronism of the generators in the system hence stability. The first objective of this project was to model the Kenyan Power System and run a load flow analysis which was achieved. The modal analysis of the system was done to analyze the stability of the system and damping of the system. The generator controllers were modelled to observe their effect on the systems stability and damping. The WTGs were then modelled at Lake Turkana, Prunus and Kipeto giving a total of 460MW which accounts for 20% of the total injection generation of the system. The load flow analysis was done. A modal analysis of the system with the injected WTGs was done to determine the stability and damping ratio of the system from their electromechanical modes of oscillation. The effect of the controllers on the system when wind generation was injected was also analyzed.
It was observed that the Kenyan power system was not stable. With controllers the stability of the system was improved and the damping ratios increased to above 10% for almost all of oscillatory modes. When wind is injected into the system, the system is noted to be stable. When an AVR is added into the system the system became unstable due to the integral part of the AVR pulling the root locus to the right side of the plane. A PSS was added and the system became stable, since the PSS negates the effect of the AVR on the system. This was achieved using the DigSILENT Power Factory Software

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I. Introduction

The exploitation and use of renewable energy technologies has exhibited significant growth in power systems mainly due to critical factors such as the fast increase in fuel prices, limited available primary energy resources used in conventional power plants, environmental concerns. Wind technology has experienced the fastest growth among all types of renewable generation technologies being investigated. In the past years, wind energy penetration limit has risen from 5% to slightly higher than 20%.

The Kenyan Government has a +5000 MW generation capacity project currently under implementation which is expected to supply sufficient electricity to meet the growing demand by flagship projects under the country's development plan. The wind technology is still a growing technology but the growing interest has led to its progress. The most recent investment in wind energy are the 300 MW Lake Turkana wind farm. A further 360MW are to be developed by Independent Power Producer's comprising; 60MW Aeolus Kinangop wind, 100MW Aeolus Ngong' wind, 60MW Osiwo Ngong' wind, 60MW Aperture Green Ngong', 30MW Daewoo

Ngong' wind, Prunus 50MW and Kipeto 100MW. The Best wind sites in Kenya are Marsabit district, Samburu, parts of Laikipia, Meru north, Nyeri, Nyandarua and Ngong hills. On average the country has an area of close to 90,000 square kilometers with very excellent wind speeds of 6m/s and above.

The resultant generation capacity by share and percentage indicate that by 2024 the generation mix would be dominated by geothermal, coal, and gas, providing 27%, 25% and 18% of the installed capacity, respectively. Hydropower and wind would respectively provide 12% and 8% of the generation capacity respectively, by the year 2024. The output generation results from the system during dry, average and wet hydrological conditions, indicate that outputs from wind and geothermal, remain fairly stable under the three hydrological conditions.

This increasing penetration of renewable sources of energy, in particular, wind energy, in the conventional power system may put tremendous challenge to the power system operators/planners, who have to ensure the reliable and secure grid operation. As power generation from Wind energy is significantly increasing, it is of paramount importance to study the effect of wind integrated power systems on overall system stability

The objective of this project is to thus analyze and determine the impact of wind power generation on the power system small-signal stability with excitation controllers for conventional generators.

1.1 PROBLEM STATEMENT

The increased power demand due to population increase and industrialization has led to the importance of having a reliable power in the entire country, Kenya. Due to this, renewable sources of energy like wind have been deemed useful in correcting the power output problem and also since they are better when it comes to environmental concerns; less emissions hence environmental friendly.

Studies on small signal stability are performed to determine the system's response to small changes in operating parameters of the power system. The changes experienced lead to electromechanical oscillations that mostly decay with time and so the system returns to its equilibrium point. The wind generation systems lead to reduction of overall system inertia pegged to the network in relation to the installed capacity. Problems in power systems occur usually due to lack of sufficient damping of the electromechanical oscillations which are dependent on the systems inertia and this may lead to loss of synchronism.

Since the Kenyan system is operated close to its security limit due to technical and economical limitations, the integration of wind generation will adversely affect the small signal stability mainly due to the fact that the mechanical system is decoupled from the electrical system and also due to its intermittency of wind

1.2 PROJECT JUSTIFICATION

Wind energy is the most mature in terms of commercial development in the world as compared to other renewable energy sources. The potential for advancement in wind technology in the world is huge compared to the total world's energy consumption. This is drawn from statistics of worldwide total capacities reaching about 60,000MW from wind energy with a yearly production of about 100 TWh.

As the demand for power in Kenya increases at the rate of roughly 8% per year in the near future as outlined in the vision 2030, wind energy is a good prospect as it meets the environmental concerns and is cheap. From Kenya's Least Cost Power Development Plan (LCPDP) as from 2011- 2031, wind energy has been forecasted to produce 9% of the total capacity required.

With the amount of wind power constantly increasing, a detailed analysis on the impact of wind power on the system security and operation has been done. The findings of these studies are related to super imposition of various aspects of wind power like its varying nature, generator technologies and distributed locations of wind farms. Due to wind resources being located at different locations than conventional power stations, power flows are considerably different in the presence of high amount of wind power and systems are usually not optimized for wind transport, hence, maybe more or less fatal.

Hence, it can be seen that integration of wind energy comes with its challenges. Studies of the Kenyan Power System have been done without generator controllers like automatic voltage regulator and power system stabilizers. In this project, the stability of the Kenyan Power System is done with integration of this controllers and the response of the system observed in order to assist in developing solutions to the problems encountered.

1.3 MAIN OBJECTIVE

The main aim of this project is to analyze the impact of wind generation at various locations in the Kenya Power System Grid on the small signal stability for a fixed 20% wind penetration level.

1.4 SPECIFIC OBJECTIVE

1. To model and perform a modal analysis of the Kenyan Power System with wind and without wind as the base cases and analyze the small signal stability of the system
2. To model automatic voltage regulators in the system, perform a modal analysis and analyze the small signal stability in the Kenyan Power System with wind and without wind.

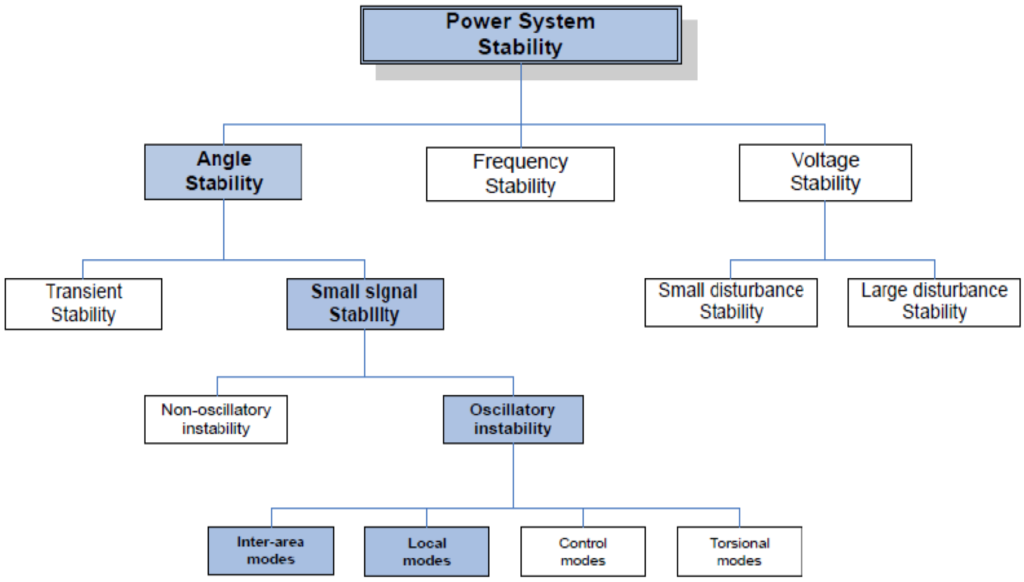
3. To model power system stabilizers in the system, perform a modal analysis and analyze the small signal stability in the Kenyan Power System with wind and without wind.

II. Literature Review

2.1 POWER SYSTEM STABILITY

Stability of a power system stability may be defined as that property of a power system that enables it to remain in a state of operating equilibrium under normal operating conditions and to regain an acceptable state of equilibrium after being subjected to a disturbance.

Power System stability can be broadly classified as shown in the figure below:



2.1.1 Voltage stability

This is the ability of a power system to maintain steady acceptable voltages at all buses in the system under normal operating conditions and after being subjected to a disturbance. The main factor causing instability is the inability of the power system to meet the demand for the reactive power.

2.1.2 Rotor Angle stability

This is the ability of interconnected synchronous machines of a power system to remain in synchronism. A fundamental factor in this problem is the manner in which the power outputs of synchronous machines vary as their rotor oscillate. It is further categorized into:

2..1.2.1.Transient Stability

It is defined as the ability of the power system to maintain synchronism when subjected to large or severe disturbance such as short circuits, loss of a tie-line between two generators or loss of large loads or generation. Transient stability depends on the initial operating conditions of the system as well as the type, severity and location of the disturbance.

Due to a large disturbance, the machine load angle changes as a result of sudden acceleration of the rotor shaft. The objective of the transient stability study is to ascertain whether the load angle returns to a steady value following the clearance of the disturbance during the critical clearing time.

2..1.2.2.Small-signal Stability

This is defined as the ability of a power system to remain stable under continuous small variations or disturbances. These small disturbances occur due to random fluctuations in loads and generation levels. In an interconnected power system, these random variations can lead to catastrophic failure as this may force the rotor angle to increase steadily.

The nature of system response to small disturbances according to depend on a number of factors including the initial operating conditions, the transmission system strength, and the type of generator excitation controls used. For a generator connected radially to a large power system, in absence of AVR (i.e. with constant field voltage) the instability is due to lack of sufficient synchronizing torque. This results in instability through a non-oscillatory mode, that is, increase in rotor angle of the generator. With continuously acting voltage regulators, the small –disturbance stability problem is one of ensuring sufficient damping of system oscillations. Instability is

usually oscillations of increasing amplitude.
Of particular importance in the analysis of small signal stability is the determination of the electromechanical modes of oscillation (EMO).The electromechanical modes involve the rotors of individual generators oscillating or swinging against each other and they can be subdivided into inter-area, local-area or intra-station modes.

According to the stability of the following types of oscillations are of concern:

a) Local modes or machine-system modes

These are associated with the oscillation of units at a generating station with respect to the rest of the power system. The term local is used because the oscillations are localized at one station or a small part of the power system.

b) Inter area modes

These are associated with the swinging of many machines in one part of the system against machines in other parts. They are caused by two or more groups of closely coupled machines being interconnected by weak ties.

c) Control modes

These are associated with generating units and other controls. Poorly tuned exciters, speed governors, HVDC converters and static VAR compensators are the usual cause of instability of this mode.

d) Torsional modes

These are associated with the turbine-generator shaft system rotational components. Instability of torsional modes may be caused by interaction with excitation controls, excitation controls, speed governors, HVDC controls, and series-capacitor-compensated lines.

The stability of a linear system is entirely independent of the input, and the state of a stable system with zero input will always return to the origin of the state space, independent of the finite initial state. In contrast, the stability of a nonlinear system depends on the type and magnitude of input, and the initial state. These factors have to be taken into account in defining the stability of a nonlinear system.
In control system theory, it is common practice to classify the stability of a nonlinear system into the following categories, depending on the region of state space in which the state vector ranges:

- Local stability or stability in the small
- Finite stability
- Global stability or stability in the large

Local stability

Local stability is said to occur when a system, subjected to small perturbations, remains within a small region surrounding the equilibrium point. It does not require that the state return to the original state and, therefore, includes small limit cycles. Local stability conditions can be studied by linearizing the nonlinear system equations about the equilibrium point in question.

Finite stability

If the state of a system remains within a finite region R, it is said to be stable within R. If the state of the system returns to the original equilibrium point from any point within R, it is asymptotically stable within the finite region R.

Global stability

The system is said to be globally stable if R includes the entire finite space.

2.1.3.State-space Representation

The behavior of any dynamic system, such as a power system, may be described by a set of n first order nonlinear ordinary differential equations of the following form:

$$\dot{x} = f_i(x_1, x_2, \ldots, x_n; U_1, U_2, \ldots, U_r; t) \qquad i = 1,2, \ldots, n \qquad (2.1)$$

Where n is the order of the system and r is the number of inputs. This can be written in the following form by using vector-matrix notations shown below:

$$\dot{x} = f(x, u, t) \qquad (2.2)$$

Where

$$x = \begin{bmatrix} x_1 \\ x_2 \\ . \\ . \\ . \\ x_n \end{bmatrix} \qquad u = \begin{bmatrix} u_1 \\ u_2 \\ . \\ . \\ . \\ u_r \end{bmatrix} \qquad f = \begin{bmatrix} f_1 \\ f_2 \\ . \\ . \\ . \\ f_n \end{bmatrix} \qquad (2.3)$$

The column vector x is referred to as the *state vector* and as x_i the state variables. The column vector u is the vector of *inputs* to the system. Time is denoted by t, and the derivative of a state variable x with respect to time is denoted by $\dot{x}$. If the derivatives of the state variables are not explicit functions of time, the system is said to be autonomous. In this case, equation 2.2 is simplified to-:

$\dot{x} = f(x,u)$ (2.4)

The interest often lies in the output variables which can be observed on the system. This is expressed in terms of state variables and the input variables in the following form-:

$y = g(x,u)$ (2.5)

Where

$$y = \begin{bmatrix} y_1 \\ y_2 \\ . \\ . \\ . \\ y_m \end{bmatrix} \qquad g = \begin{bmatrix} g_1 \\ g_2 \\ . \\ . \\ . \\ g_m \end{bmatrix} \qquad (2.6)$$

The column vector y is the vector of outputs and g is a vector of non-linear functions relating state and input variables to output variables.

2.1.3.2.Linearization

Linearization of equation 2.1 of a dynamic system is described below. Let x_0 be the initial state vector and u_0 the input vector corresponding to the equilibrium point about which the small-signal performance is to be investigated. Since x_0 and u_0 satisfy equation 2.4, we have-:

$\dot{x} = f(x_0, u_0) = 0$ (2.7)

According to the system is said to be disturbed from the above state if we let;

$x = x_0 + \Delta x$ (2.8)

$u = u_0 + \Delta u$ (2.9)

Where Δ denotes a small deviation. The new state must satisfy equation 2.4, hence-:

$\dot{x} = \dot{x}_0 + \Delta\dot{x}$ (2.10)

$x = f[(x_0 + \Delta x), (u_0 + \Delta u)]$ (2.11)

As the disturbances are assumed to be small, the non-linear functions $f(x,u)$ can be expressed in terms of Taylor's series expansion. The linearized forms of equation 2.4 and equation 2.5 are then obtained as below-:

$\Delta\dot{x} = A\Delta x + B\Delta u$ (2.12)

$\Delta y = C\Delta x + D\Delta u$ (2.13)

In the above equations,

Δx – is the state vector of dimension n

Δy – is the output vector of dimension m

Δu –is the input vector of dimension r

A –is the state or plant matrix of size $n \times n$

B –is the control or input matrix of size $n \times r$

C –is the output matrix of size $m \times n$

D –is the feed-ward matrix of size $m \times r$

By taking the Laplace transform of the above equations, we obtain the state equations in the frequency domain:

$S\Delta\dot{x}(s) - \Delta x(0) = A\Delta x(s) + B\Delta u(s)$ (2.14)

$\Delta y(s) = C\Delta x(s) + D\Delta u(s)$ (2.15)

The block diagram of the state-space representation described by equations (2.14) and (2.15) above can be drawn as shown below-:

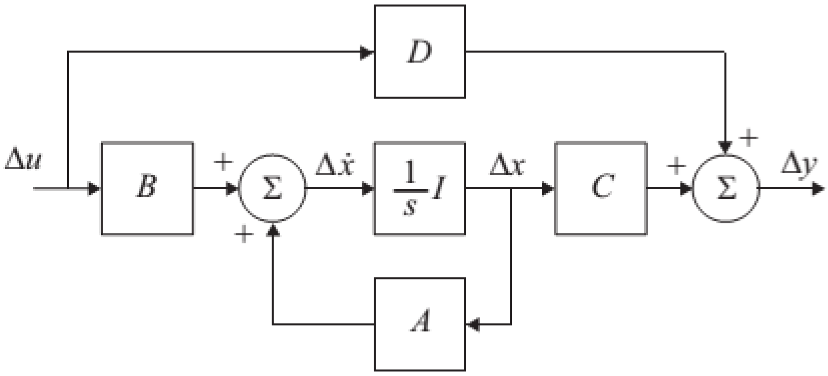


Figure 2.2: Block Diagram of State Space Representation

A formal solution of the state equations can be obtained by solving for $\Delta x(s)$ and evaluating$\Delta y(s)$. From the result, it can be seen that the Laplace transforms of Δx and Δy are seen to have two components, one dependent on the initial conditions and the other on the inputs. These are the Laplace transforms of the *free* and *zero-state components* of the state and output vectors .

The poles of $\Delta x(s)$ and $\Delta y(s)$ are the roots of the equation:

$\det(s\boldsymbol{I} - \boldsymbol{A}) = 0$ (2.16)

The values of **s** which satisfy the above are known as *eigenvalues* of matrix **A**, and the above equation is referred to as *characteristic equation* of matrix **A**.

2.1.3.3.Analysis of stability

There are two main methods for analyzing power system small signal stability, and are described below as follow:

- ***Frequency domain analysis method based on the transfer function matrix***

The frequency domain model of power systems described by the transfer function matrix, i.e.

$$y(s) = G(s)U(s)$$

Can be obtained by appropriately choosing the input and output variables,

Where; y(s) - output vector
G(s)-Transfer function matrix
U(s)-Input vector

The system is stable under small disturbance, which is equivalent in the negative real part of all poles of G(s) and can be examined by multivariable nyquist stability criteria.

- ***Eigen value analysis method based on the state space model***

Eigen value analysis method, which is based on the linear system theory and Lyapunov stability theory, has been recognized as one of the broadest methods to analyze small signal stability. In this method the complex power system can be linearized around a stable operating point which can give a close approximation to the system to be studied. And then, stability analysis is done by computing Eigen values as well as the left and right Eigen vectors of its state matrix, hence the judgment information for system stability, such as oscillation frequency, the attenuation factor, the impact factor and the strongly correlated state variables can be obtained.Modal analysis method, which involves Eigen value analysis will be used in this project because it proves superior compared to other methods, as it provides additional information to identify the critical generators that may be used to determine the location of eventually needed stabilizing devices in order to influence the system damping efficiently.

2.1.3.4.Eigenvalues

The eigenvalues of a matrix are given by values of the scalar parameter **λ** for which there exist non-trivial solutions (i.e. other than Φ = 0) to the equation:

$A\Phi = \boldsymbol{\lambda}\Phi$ (2.17)

Where -: A – is the $n\times n$ matrix (real for physical systems such as power systems) Φ – Is $n\times 1$ *vector.*

To find the eigenvalues equation, equation 2.17 may be written in the form:

$(A-\boldsymbol{\lambda})\Phi = \mathbf{0}$ (2.18)

For anon-trivial solution:

$\det(A - \boldsymbol{\lambda}\mathbf{I}) = \mathbf{0}$ (2.19)

Expansion of the determinant gives the characteristic *equation.* The n *solutions* of $\boldsymbol{\lambda} = \boldsymbol{\lambda}_1, \boldsymbol{\lambda}_2, \dots \boldsymbol{\lambda}_n$ are the eigenvalues of **A**.

2.1.3.4.Eigenvectors

For any eigenvalue λ_i, the n-column vector Φ_i which satisfies the equation 2.17 is called the right eigenvector of **A** associated with the eigenvalue λ_i. Therefore we have:

$A\Phi_i = \lambda_i\Phi_i$ Where $\boldsymbol{i}$ = 1,2,3…. (2.20)

Similarly, the n-row vector ψ which satisfies the equation 2.18 is called left eigenvector of **A** associated with the eigenvalue λ_i and we have-:

$A\psi_i = \psi_i\lambda_i$ (2.21)

The right eigenvector gives the observability information whereas the left eigenvectors gives the controllability information.

2.1.3.4.Eigenvalue and stability

The time dependent characteristic of a mode corresponding to an eigenvalue **λ** is given by . Therefore, the stability of the system is determined by the eigenvalues as follow:

a) A real eigenvalue normally corresponds to a non-oscillatory mode. A negative real eigenvalue represents a decaying mode (damped oscillation). The larger the magnitude, the faster the decay. A positive real eigenvalue represents aperiodic instability (oscillation of increasing amplitude).

b) Complex eigenvalues occur in conjugate pairs, and each pair corresponds to an oscillatory mode. The real value of the eigenvalue gives the damping, and the imaginary component gives the frequency of the oscillation.

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The parameters can be used to evaluate the damping effects of the power system stabilizers on the power oscillation. The damping ratio ζ determines the rate of decay of the amplitude of the oscillation. It is obvious that higher damping ratio and lower oscillation frequency generate better damping effects to enhance the stability of the power system.

2.1.3.5. Small signal Analysis using Lyapunov's first method

The stability in the small of a nonlinear system is given by the roots of the characteristic equation of the system i.e. by eigenvalues of **A**.

i. When the Eigen values have negative real parts, the original system is asymptotically stable.

ii. When at least one of the Eigen values has positive real part, the original system is unstable.

iii. When the Eigen values have real parts equal to zero, it is not possible on the basis of first approximation to say anything in general.

2.1.3.6. Participation factor

One problem in using right and left eigenvectors individually for identifying the relationship between the states and the modes is that the elements of the eigenvectors are dependent on units and scaling associated with the state variables. As a solution to this problem, a matrix called participation matrix (P), which combines the right and left eigenvectors as follows is used as a measure of association between the state variables and the modes:

Participation factors are generally indicative of the relative participation of the respective states in the corresponding modes. They give a good indication of the general system dynamic oscillation pattern. These values can be used to determine the location of stabilizing devices in a system for damping power system oscillations.

2.2EXCITATION SYSTEMS

2.2.1 EXCITER MODEL

The basic function of an excitation system is to provide direct current to the synchronous machine field winding. In addition, the excitation system performs control and protective functions essential to the satisfactory performance of the power system by controlling the field voltage and thereby the field current.

The control functions include the control of voltage and reactive power flow, and the enhancement of system stability. The protective functions ensure that the capability limits of the synchronous machine, excitation system, and other equipment are not exceeded.

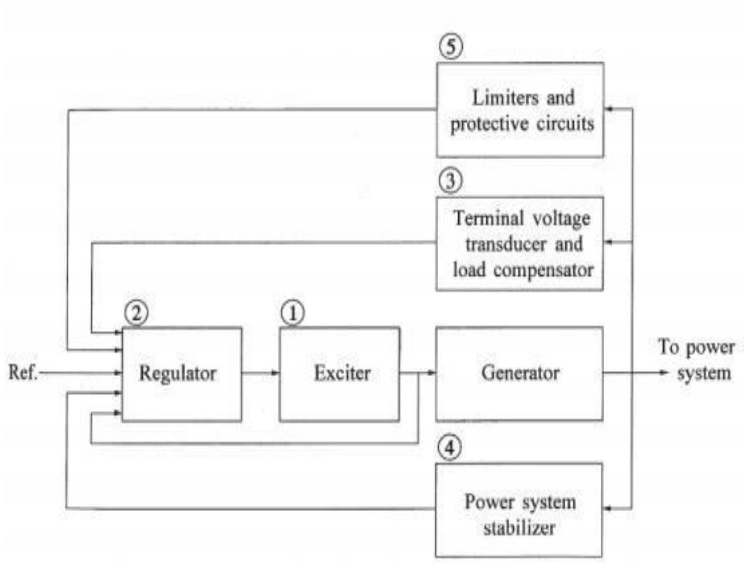


Figure 2.11: Functional block diagram of a synchronous generator excitation control system

Types of excitation systems:

- DC excitation systems: used on dc generators
- AC excitation systems: on ac machines
- Static excitation systems: on static systems i.e. non stationary systems

2.3 OPERATION OF AUTOMATIC VOLTAGE REGULATORS

It is necessary to provide constancy of the alternator terminal voltage during normal small and slow changes in the load. For this purpose the alternators are provided with an Automatic Voltage Regulator. It is used primarily for testing and start up, and to cater for situations where the ac regulator is faulty. It is also necessary to develop the control system o the machine hence the AVR is used in electrical power field to obtain the stability and good regulation of the electric system. The AVR maintains a constant voltage up to a certain level of load current independently of generator speed and load.

The AVR loop must regulate the terminal voltage to within the static accuracy limit, have sufficient speed of response and be stable. Mathematically the time response depends upon the eigen values or closed loop poles, which are obtained from the characteristic equation. The location of the eigen values in the s plane depends upon the upon loop gain K and the time constants and of these only the gain is adjustable.

In modern large inter connected system, annual regulation is not feasible and therefore automatic generation and automatic and voltage regulation equipment is installed on each generator. The AVR may be discontinuous or continuous type. The discontinuous type is simpler than the continuous type but it has a dead zone where no single is given, therefore its response time is longer and less accurate.

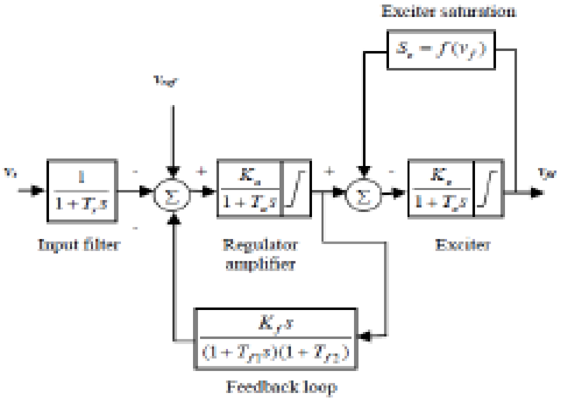
Modern Static continuous type automatic voltage regulator has the advantage of providing extremely fast response times and high field ceiling voltages for forcing rapid changes in the governor terminal voltage during system faults. Response time variation can cause the AVR to degrade the system stability.

The models of AVR used in this project arethose on the various generators in the Kenyan power system:

a) EXCIA
b) EXDC2
c) EXST1

2.4 TYPES OF AUTOMATIC VOLTAGE REGULATORS

An AVR can be designed, and it is necessary to know certain factors about the input and the required accuracy of the output voltage together with certain information of the load. The following are various types of voltage regulators:



2.4.1.Supply type automatic voltage regulator
In this type it is necessary to state the type of input, whether direct or alternating, its nominal voltage and, if alternating its nominal frequency. Most automatic voltage regulators are operated over a limited range of input voltage. If the frequency of the input is likely to vary, the range of variation of the frequency may have a considerable influence.
The output voltage is to be variable; the range of variation must be stated. The maximum output current must be known and also the variation of the output current over which the regulator is to operate.

The following factors are connected with the output voltage :
1. Response time: All regulators take a finite time to effect a change in the supply voltage or load. This time is referred to as time constant of the regulator or the response time. In most cases the response time is dependent on magnitude of the change of the output voltage, but the rate of change remains constant. The maximum allowable response time depends upon the type of application and it is desirable to make the response time as small as possible to reduce the transients in the output voltage.

2. Waveform Distortion: It is important in AC voltage regulators and the ripple voltage in DC voltage regulators. Care should be taken to reduce distortion as much as possible.

2.4.2 Generator type Automatic Voltage Regulator
It is a control device which automatically regulates the voltage at the exciter of an alternator, to hold the output voltage constant within specified limits. The perfomace can be expressed in terms of the whole equipment as this is determined by the characteristics of the generator. The short period accuracy of the output voltage is usually specified as the percentage change of load, speed and power factor. The long period accuracy may not be so important.

2.5 OPERATION OF A POWER SYSTEM STABILIZER
The basic function of the power system stabilizer (PSS) is to add damping to the generator rotor oscillations by controlling its excitation using auxiliary stabilizing signals. When a disturbance occurs, the generator speed and

power will vary according to the swing equation about the steady state operating point.
The action of the PSS is to extend the angular stable limits of a power system by providing supplemental damping to the oscillation of synchronous machine rotors through the generator excitation. To provide damping, the stabilizer must produce a component of electrical torque in phase with the rotor speed deviations. The supplementary control is very beneficial during line outages and large power transfers.
However, power system instabilities can arise in certain circumstances due to negative damping effects on the rotor. This is because the PSS's are tuned around steady state operating point; their damping effect is only valid for small excursions around this operating point. During severe disturbances, a PSS may actually cause the generator under its control to lose synchronism in an attempt to control excitation field.

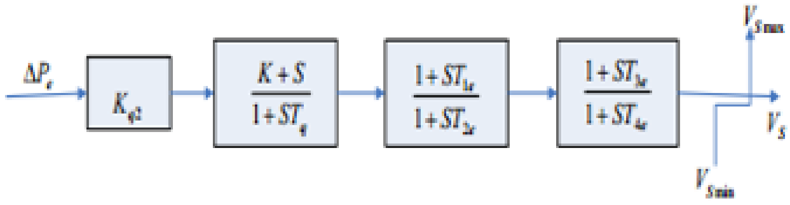


Figure 2.12: Functional block diagram of a Synchronous generator PSS.

In the Figure above, T1e, T2e, T3e and T4e are the time constant of phase shift link. The application of PSS can improve the damping characteristic of the system and then its static stability as well. Besides, the small signal stability of the wind power integration can also be improved by changing the installation location and the parameters of PSS. PSS is only installed in high magnification rapid response of excitation system of synchronous machine so that the system's low frequency oscillation should be inhibited efficiently.

2.6 CONSTRUCTION AND OPERATION OF WTGs

WTGs extract energy from wind and convert it into electricity through an aerodynamic rotor, which is connected by a transmission system to an electric generator. Today's mainstream WTGs have three blades rotating on a horizontal axis, upwind of the tower. Two-blade WTGs and vertical-axis WTGs are also available as shown in the figures below:

Figure 2.3: Three-blade WTG

Figure 2.4: Vertical - axis WTG

In general, a WTG can begin to produce power in winds of about 3 m/s and reach its maximum output around 10 m/s to 13 m/s. Power output from a WTG increases by the third power of wind speed, i.e. a 10 % increase in wind speed increases available energy by 33 %, and is directly proportional to the rotor-swept area (the area swept by the rotating blades). Power output can be controlled both by rotating the nacelle horizontally (yawing) to adapt to changes in wind direction, and rotating the blades around their long axes (pitching) to adapt to changes in wind strength.

Typical commercial WTGs at present have a capacity of 1.5 MW-3 MW; larger ones can reach 5 MW-6 MW, with a rotor diameter of up to 126 meters. Since a single WTG has limited capacity, much less than a conventional power generator, a WPP, usually called "wind farm") normally consists of many WTGs connected together by overhead lines or cables.

Their power output is collected and transmitted to the grid through an alternating current (AC) or direct current (DC) line, after voltage step-up at the substation in the WPP. Some WPPs now have a capacity comparable to that of conventional power generators.

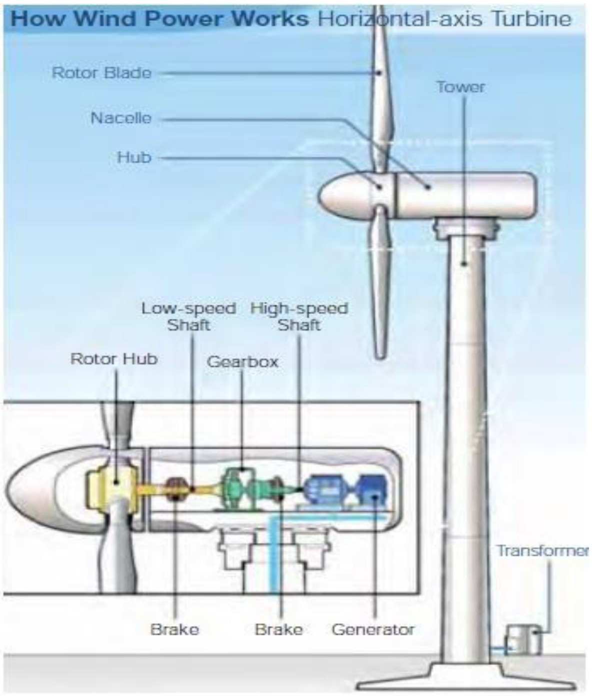


Figure 2.5: Basic operation of the two blade WTG

2.6.1.WIND TURBINE GENERATOR TECHNOLOGIES

A generator is a device which converts mechanical energy into electrical energy. It uses magnetic fields to convert the rotational energy into electrical energy. Asynchronous or induction generators are mostly used as wind turbines as they can be operated at variable speed unlike synchronous generator. Induction generators are

widely and commercially available and also inexpensive.
WTGs currently in operation mainly include the following four types; fixed speed induction generator (SCIG), variable-slip induction generator, doubly fed induction generator (DFIG) and full-power conversion WTG.

2.6.1.1 Fixed Speed Induction Generator (SCIG)
Also called squirrel cage induction generators. When the turbine is directly connected to the grid, the rotor and the generator must rotate at a fixed speed in order to produce power at main frequency [16]. This means that regardless of the wind speed, the wind turbines rotor speed is fixed and determined by the frequency of the supply.

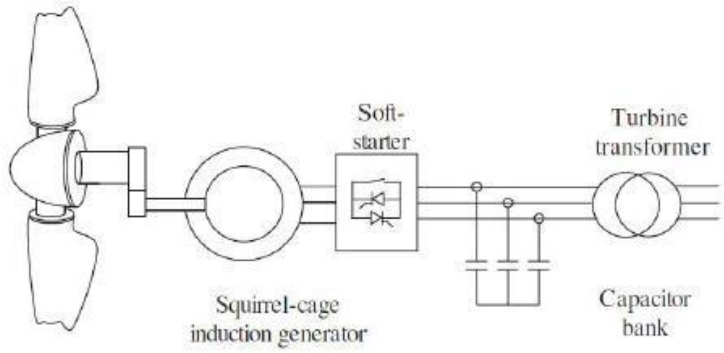


Figure 2.6: Squirrel Cage Induction Generator

2.6.1.2 Doubly fed induction generator (DFIG)
Most wind turbines are now equipped with induction generators. The converters of these generators are divided into two components i.e. the rotor side converter and the grid side converter. These machines are operated either at fixed speed or variable speed. As mentioned before, generators driven by fixed speed turbines can be directly connected to the grid. However, variable speed generators need a power electronic converter interface for interconnection to the grid. Compared to the fixed speed devices they have some The advantages.

- They have better energy capture than fixed speed generation.
- Less stress in the gearbox and the generator.
- Acoustic noise reduction.

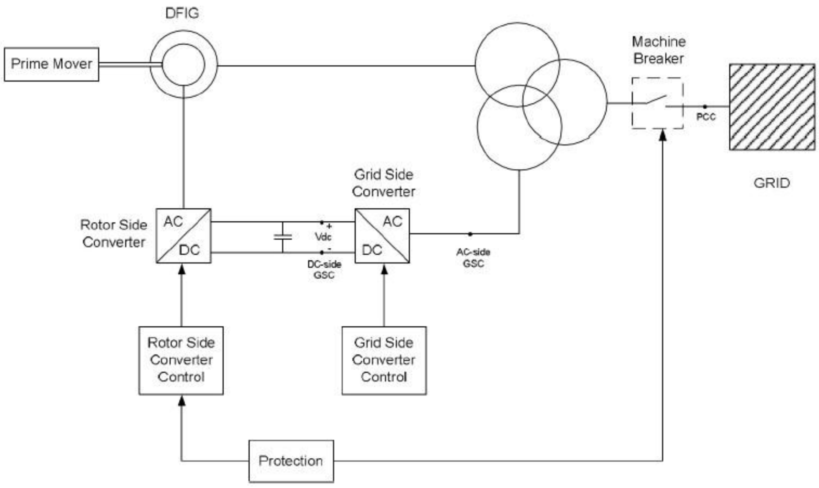


Figure 2.7: Doubly Fed Induction Generator

2.7 POWER SYSTEM COMPONENT MODELS
The modelling of generator control models controls is critical in small signal analysis. It is also important that the excitation systems and power system stabilizers are modelled correctly and in detail for small signal characteristics. The various power systems components are described below:
2.7.1Synchronous machines
They form the principle source of electrical energy in power systems. Keeping synchronous machines in

synchronism is one of the largest power system stability problems. Synchronous generator can be represented by the mathematical model of second, third, fifth, sixth and seventh order .The models are briefly described below:

a) The second order model

The second order model is the simplest model of synchronous generator which describes only the dynamics of rotor rotation [18]. Only two state variables are needed to model the classical machine model, hence called the second-order model.

Dynamic behaviors are considered to be finished and values have reached stationary amounts. This model neglects dynamic processes of damper rotor windings on rotor movement. Influence of speed on armature voltage is completely neglected which means that electromagnetic moment is equal to force.

b) Detailed Model

In this model of synchronous machine, the field coil on the direct axis (d-axis) and damper coil on the quadrature axis (q-axis) are considered. The machine consists of two essential elements: the field and the armature. The field winding carries direct current and produces a magnetic field which induces alternating voltages in the armature windings.

c) Third order model (one axis model)

To improve the classical machine model is expanded with one equation describing the time derivative of the flux in the field winding $\varphi_f$and one equation describing the field current in the field winding, I_f. In this way, the time variation of the *d*-axis reactance is considered. Third order model takes in to consideration dynamic of rotor and excitation system and neglects dynamics of other physical quantities. In this model grid voltage is symmetrical without higher harmonics.

This model of generator, because of its simplicity and good dynamic description, has higher usage for analysis and synthesis of control system. This order neglects frequency deviations, higher harmonics and behaviors in damping windings.

d) Fifth order model

Damper windings are included in the *d* and *q*-axis. The fast changing conditions of the machine are considered. Normally this model is used for water turbine generators. The fifth order model neglect DC components in stator and AC components in rotor windings. It is used because it is simpler than model of seventh order.

e) Sixth order model (Four winding model)

In the 6th-order model, four windings are considered, two on the q-axis and two on the d-axis.

However, the network and stator transients are neglected.

f) Seventh order model

Model of seventh order is the most complex and it describes generator most accurately [12]. This model is used for analysis of dynamic behaviors in normal conditions and in conditions of generator failure. This model neglects asymmetry of stator windings, higher harmonics of flow in air gap, parameter changing because of external condition, non-linearity of iron magnetic characteristics, skin effect in stator and rotor windings and iron losses.

In this project the fifth order (hydro) and the sixth order (thermal) will be used.

2.7.2 Load

Stable operation of a power system depends on the ability to continuously match the electrical output of generating units to electrical loads on the system. Consequently, load characteristics have an important influence on system stability. The load models are traditionally classified into two

a) **Static load models**

A static load model expresses the characteristics of the load at any instant of time as algebraic functions of the bus voltage magnitude and frequency at that instant. The active power and reactive power are considered separately.

b) **Dynamic load models**

Studies of inter area oscillations, voltage stability and long term stability often require load dynamics to be modelled.

The loads can be modelled using constant impedance, constant current and constant power static models.

i. **Constant impedance load model (constant Z)** is a static load model where the real and reactive power is proportional to the square of the voltage magnitude. It is also referred to as constant admittance load model.

ii. **Constant current load model (Constant I)** is a static load model where the real and reactive power is directly proportional to the voltage magnitude.

iii. **Constant power load model (Constant P)** is a static load model where the real and reactive powers have no relation to the voltage magnitude. It is also referred to as constant MVA load model.
In this project constant Z static load model will be used.

2.7.3 Transformers

They enable the system to operate in different voltage levels. In power transfer, the transmission voltages need to be high to reduce losses but during generation and consuming, it is not practical to operate at this high voltages. The transformers are used in transformation of voltages from high to low and vice versa, also in voltage control and reactive power flow. To enable the transformation principle all generators used in bulk power transmission have taps in one or more windings for changing the turn ratio hence the voltage. There are two types of tap changing transformers which are off load tap changing transformers and on load tap changing transformers.

The off load tap changing requires that the transformer be de- energized for tap changing. It is used when the ratio is changed to meet long term variation e.g. variations due to load growth, system expansion or seasonal changes. On load transformers are used to take care of the daily/hourly variations in system conditions. In this system, tap changing is normally performed on load and there is no interruption to supply.

Transformers can be two winding three winding or auto transformers or phase shifting transformers or combination of above cases. The two winding transformer will be used in this study for simplicity whose equivalent circuit is shown below;

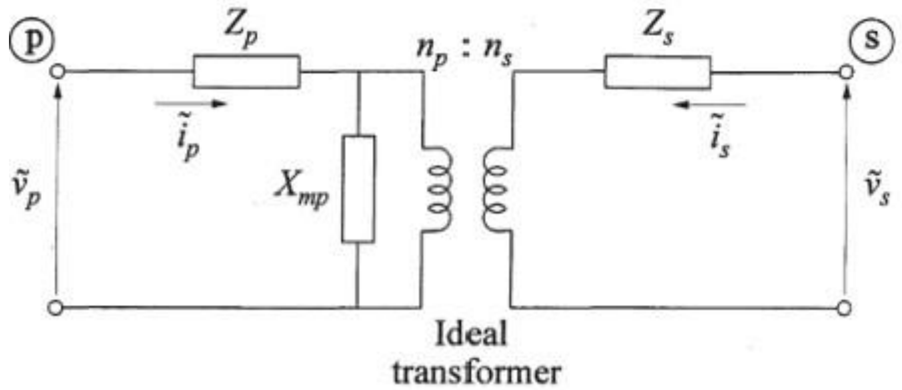


Figure 2.8: Equivalent circuit of a two-winding transformer

The nominal-turns ratio *(n_pln_s)* is taken to be equal to the ratio of line-to-line base voltages on both sides of the transformer irrespective of the winding connections (Y -Y, D-D, or Y-D). For Y-Y and D-D connected transformers, this makes the ratios of the base voltages equal to the ratios of the nominal turns of the primary and secondary windings of each transformer phase. For a Y-D connected transformer, this in addition accounts for the factor √3due to the winding connection.

In the case of a Y-D connected transformer, a 30° phase shift is introduced between line-to-line voltages on the two sides of the transformer. The line-to-neutral voltages and line currents are similarly shifted in phase due to the winding connections.

It is usually not necessary to take this phase shift into consideration in system studies and this was adopted in this study. The zero degree phase shift was used in modal analysis of this project since it does not affect small-signal stability of the system.

2.7.4 Transmission line models

Electrical power is transferred from generating stations to consumers through overhead lines or underground cables. Overhead lines are used for long distances whereas underground cables are used in urban areas for under water crossing.

a) Overhead lines

A transmission line is characterized by four parameters: series resistance R due to the conductor resistivity, shunt conductance G due to leakage currents between the phases and ground, series inductance L due to magnetic field surrounding the conductors, and shunt capacitance C due to the electric field between conductors.

b) Underground lines

Underground cables have the same basic parameters as overhead lines: series resistance and inductance; shunt capacitance and conductance. However, the values of the parameters and hence the characteristic of cables differ significantly from those of overhead lines for the following reasons:

1. The conductors in a cable are much closer to each other than are the conductors of overhead lines.
2. The conductors in a cable are surrounded by metallic bodies such as shields, lead or aluminum sheets, and steel pipes.
3. The insulating material between conductors in a cable is usually impregnated paper, low viscosity oil, or an inert gas.

Since G is negligible and R is small, the characteristic impedance Z_C with losses neglected is commonly referred to as the *surge impedance*. It is equal to $M\sqrt{D}$ and has the dimension of a pure resistance. The power delivered by a transmission line when it is terminated by its surge impedance is known as the natural load or surge impedance load (SIL).

2.8 PREVIOUS STUDIES ON IMPACT OF WIND GENERATION ON SSS WITH INCORPORATION OF CONTROLLERS

The impact of wind power on the small signal stability of a power system has been studied on four machine two area network and the IEEE bus system as a bench mark. From the studies, wind power has positive influence on the damping o local area modes. The DFIG has a better damping influence on the inter area mode than the SCIG.

The influence of wind power on the small signal stability of a power system is analyzed in factors like power dispatch, generator technology, wind farm location and wind power integration level. The oscillation modes that arise as a result of changes in the system operating conditions are computed using modal analysis.

Mostly the power system stabilizer with speed as input was used named PSS1A and test were run to test if this can dampen the system. The PSS was chosen since it has a simple design and is easy to implement in the system. It was noted that increasing the gain on the PSS causes instability since the eigen value moves to the right hence increasing the oscillatory frequency of the eigen value. Decreasing the gain moves the eigen velues slightly to the left and leads to a decrease of oscillatory frequency.

The AVR gain was also reduced to see how the system would react to the change of AVR settings. It was observed that the instable oscillatory eigen value moved to the left, becoming more stable and its oscillatory frequency reduced but this was observed when the test was done by the manufacturer. This barely made the system stable and it was noted that the reduction of AVR value to 1, the system was poorly damped and the oscillations were observed after 60s.

The wind generator model from the DIgSILENT library will be used where a given number of parallel machines will be aggregated and represented by a single generator. There are three WTG models in DIgSILENT library. They include fully rated converterWTG, Variable rotor resistance WTG and the DFIGs WTG. Variable speed (DFIGs) is the type of wind turbine that will be used in this project since it is most commonly used type of wind turbine and it resembles the actual WTG used in Lake Turkana wind farm.

The generators will be modelled to generate at 0.69 KV. Power generated by each turbine will be gathered at a 33 KV-collecting grid using a 0.69 KV/33 KV Step-up transformer. The collecting grid will be connected to a power transmission sub-station-represented by a bus bar, at the project site from where the electricity will be transmitted to the national grid at 132 KV transmission line. The two stage step- up design modelling resembles the actual design of the system and is used in this project since WTGs produces very few MW.

In this project, an aggregated wind farm of 300MW will be modelled to represent the Lake Turkana wind farm. This contributes to approximately 10% of the wind power required in this project. The other 10% will be achieved by having aggregated wind farms of 60MW, 100MW and 40MW.

Once these wind farms have been modelled, they will integrated into the above modelled Kenyan system by distributing them at different locations in the Kenyan power system. Load flow calculations will then be performed before a modal analysis for small signal condition is simulated. The system will be analyzed if it is small signal stable using Lyapunov's analysis method described in section

III. Methodology

3.1. Modelling of a Single Machine Infinite Bus and its controllers

In order to understand the Kenyan Power System, I began with modelling a single machine infinite bus (SMIB). I analyzed the small signal characteristics of the single machine infinite bus system about the steady state operating condition following the loss of a transmission line for different excitation control modes. The SMIB system in question is a shown in the fig. 1 below:

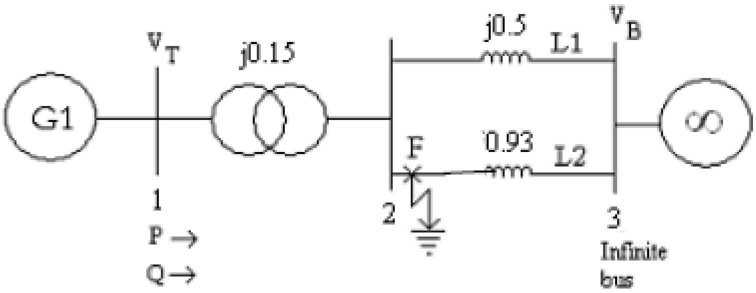


Figure 3.0: SMIB System representation

The table below shows the data used in modelling the SMIB.

Table 1: Data for SMIB system modelling

Component	Parameters
Generator data	X_d = 1.81 X'_d = 0.3 X''_d = 0.23 X_q = 1.76 X'_q = 0.65 X''_q = 0.25 X_l = 0.16 T'_{do} = 8.0s T''_{do} = 0.03s R_a = 0.003 T'_{qo} = 1.0 s T''_{qo} = 0.07s H = 3.5 K_D = 0 S= 2220MVA V= 24kV 60 hZ
Infinite bus *Nominal voltage*	Ideal voltage source *24 kV*
Transmission lines	2220MVA and 24kV
Transformer	S= 2220 MVA 24kV
Operating condition	P= 0.9 Q= 0.3V_T = 1.0Ð36º, V_B = 0.995Ð0º

The base values were:

$$Z_{base} = \frac{{kV_{base}}^2}{MVA_{base}} = \frac{24^2}{2220} = 0.2595 \ldots\ldots\ldots\ldots (3.0)$$

$$Z_{actual} = Z_{p.u} \times Z_{base} \ldots\ldots\ldots\ldots (3.1)$$

$$L_1 = 0.2595 \times O.5i = 0.12975i\Omega \ldots\ldots\ldots\ldots (3.2)$$

$$L_2 = 0.2595 \times 0.93i = 0.241335i\Omega \ldots\ldots\ldots\ldots (3.4)$$

An AVR and a PSS were also added to improve the damping of the system. The figure of the AVR and PSS are as follows:

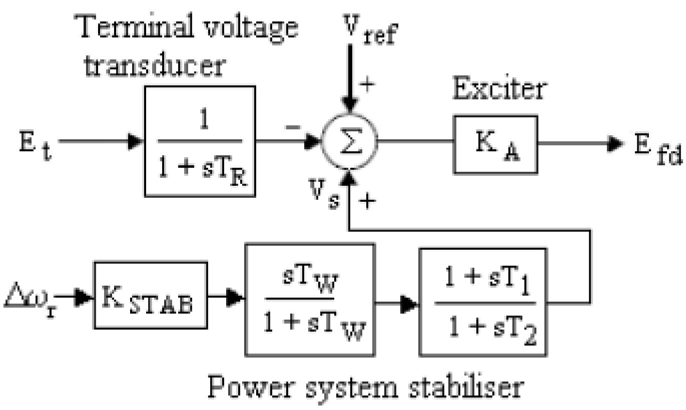


Figure 3.1: Representation of AVR and PSS

The data for the AVR (EXAC4) and PSS (pssSTAB1) were:

Excitation control data

$K_A = 200$ $T_R = 0.02$ s $K_{STAB} = 9.5$

$T_W = 1.4$ s $T_1 = 0.154$ s $T_2 = 0.033$ s

3.2. Modelling of a Two Area Four Generator System and its Controllers

The Two area four generator system (2A4G) was also modelled to study the fundamental nature of inter area oscillations. The system consists of two similar areas, connected by a weak tie-line. Each of the areas has two generators: G1 and G2 in area 1, and G3 ad G4 in area 2. The power transfer from area 1 to area 2 is 400MW. The system is modelled as below:

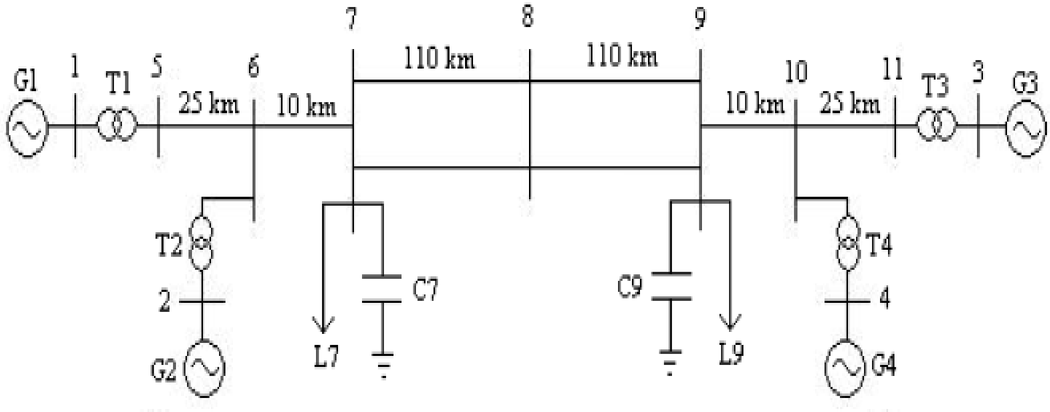


Figure 3.3: Representation of the 2A4G system.

Table 2: 2A4G system data

Component	parameters
Generator data *MVA base; 900 MVA, 20 kV, 60 Hz*	$X_d = 1.8$ $X'_d = 0.3$ $X''_d = 0.25$ $X_q = 1.7$ $X'_q = 0.55$ $X''_q = 0.25$ $X_l = 0.2$ $T'_{do} = 8.0$ s $T''_{do} = 0.03$ s $R_a = 0.0025$ $T'_{qo} = 0.4$ s $T''_{qo} = 0.05$ s $K_D = 0$ $H = 6.5$ (for G1 and G2) $H = 6.175$ (for G3 and G4)
Transmission lines *Bases: 100 MVA, 230 kV*	$r = 0.0001$ *pu/km* $x_L = 0.001$ *pu/km* $b_C = 0.00175$ *pu/km*. The transmission line lengths are shown in Fig. 3.
Transformers	Rating; 900 MVA, 20/230 kV $X = j0.15$ *pu* Off-nominal ratio = 1.0
Operating condition	G1 P = 700 MW Q = 185 MVAr $V_t = 1.03\angle 20.2°$ G2 P = 700 MW Q = 235 MVAr $V_t = 1.01\angle 10.5°$ G3 P = 719 MW Q = 176 MVAr $V_t = 1.03\angle -6.8°$ G4 P = 700 MW Q = 202 MVAr $V_t = 1.01\angle -17.0°$ Bus 7 $P_L = 967$ MW $Q_L = 100$ MVAr $Q_C = 200$ MVAr Bus 9 $P_L = 1767$ MW $Q_L = 100$ MVAr $Q_C = 350$ MVAr *Represent the loads using static models. Model the active components of the loads as constant current and the reactive components as constant impedance.*

For Line data the following calculations were done:

$$Z_{base} = \frac{kV_{base}{}^2}{MVA_{base}} = \frac{230^2}{100} = 529 \ldots\ldots\ldots\ldots (3.5)$$

$$Y_{base} = \frac{MVA_{base}}{kV_{base}{}^2} = \frac{100}{230^2} = \frac{1}{529} \ldots\ldots\ldots\ldots (3.6)$$

$$R_{base} = 529 \times 0.0001 = \frac{0.0529\Omega}{km} \ldots\ldots\ldots\ldots (3.7)$$

$$X_{base} = 529 \times 0.001 = \frac{0.529\Omega}{km} \ldots\ldots\ldots\ldots (3.8)$$

$$Y_{base} = \frac{1}{529} \times 0.00175 = \frac{3.30812\mu S}{km} \ldots\ldots\ldots\ldots (3.9)$$

I used the model of an AVR i.e. EXAC4 and PSS i.e. PSS STAB 1 in this system

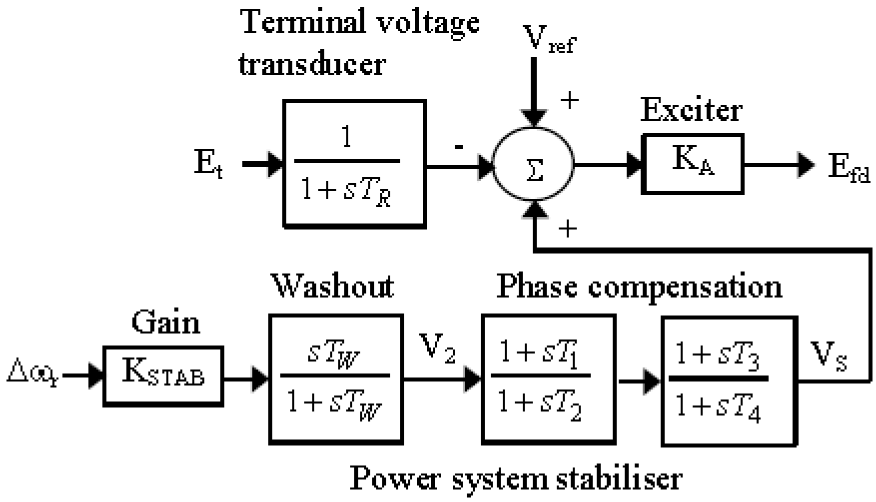


Figure 3.4:Representation of an AVR and PSS in 2A4G

3.3. Modelling of a WTG in the 2A4G system

I substituted one of the generators with a DFIG (25% injection) to analyze the stability of the system when a wind generator has been added. This was done with and without controllersF

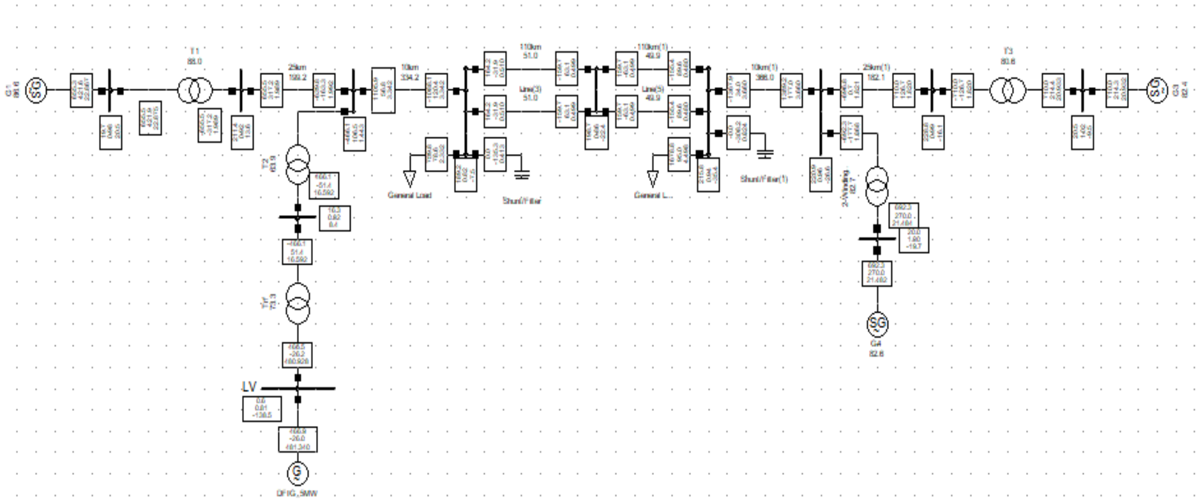


Figure 3.5: Model of 2A4G with a DFIG

The wind generator model used from DigSILENT was a 2MW machine with 350 parallel machines to give an output of 700MW. The generator was modelled to generate 0.69kV and was Stepped up to 20kV before being fed to the rest of the system. Since the converter circuit was inbuilt the generator was connected to the grid after voltage transformation. The number of parallel machines were kept constant to cater for the fixed wind penetration. The machines had an MVA rating of 2.225MVA.

3.4. Kenyan Power System Summary

The Kenyan power system has 177 buses, 99 loads, 184 transmission lines, 45 two winding transformers, 14 shunt capacitors, 15 reactors, 1 asynchronous generator and 26 synchronous generators. The system was modelled in the DigSILENT Power factory software. The initial modelled system has a total grid generation of 1828.75 MW and a load of 1733MW. The total grid losses were 95.75MW, reserve capacity of 396.34MW. This system formed the base case for analysis before incorporation of wind energy.

3.4.1 Representation of network elements in the Kenyan system

Any power system has generators, transformers, transmission lines whether overhead or underground and loads. This components and there representation in network analysis studies were discussed in the literature review. In this project the models for different elements are as under;

3.4.1.1Synchronous machine*s*

As was discussed in the literature review, the hydro generators were represented in fifth order (Gensal) while thermal turbine generators were modelled as sixth orders (Genrou). The generator buses were all set to PV buses with respective power and voltages specified, with the exception of Bujagali generator which was set as the Slack Bus.

3.4.1.2 Transmission lines

Transmission lines were represented by nominal π equivalent circuits with lumped parameters. The Kenyan system transmission system has overhead AC lines. The real values of the resistance(R) (ohms/Km), reactance(X) (ohms/Km) and susceptance (B) (Susceptance/Km) were used. The data used is at the appendix C of this document.

3.4.1.3 Transformers

Transformers with off-nominal turns ratio were be represented by equivalent circuits. The phase shifts introduced due to transformer connections (such as Δ-Y connections) were not represented. The tap ratio of the transformers was not also considered.

3.4.1.4 Loads

The load was represented as a constant Power model where the MW and MVAr were specified at the various load buses. Total load of the system was kept constant in all cases at 1486.79 MW with generation shared between the conventional generators and wind generators at different locations.

3.4.1.5 Excitation system

The data for the governor model, AVR model and the PSS model could not be found hence they were not modelled. However, using the 2A4G system, the effects of AVR and PSS on the power system was established.

3.4.1.6 Wind generation

The project considered wind power;

3.4.1.6 ***Wind generator***

The wind generator model from the DigSILENT library was used where a given number of parallel machines were aggregated and represented by a single generator. The generators were modelled to generate at 0.69kV and then stepped up to 33kV and 66kVbefore being fed to the rest of the system at either 132kV or 220kV. It is worth noting that the converter circuit and other controllers in this model are inbuilt hence the generator was connected to the grid after voltage transformation.

The number of parallel machines were kept constant to cater for the required fixed amount of wind penetration. The numbers below in give 20 % wind penetration. The types of wind turbines used in the study were variable speed (DFIGs). The DFIG model was constructed from the built-in components of power system simulation software. All the wind turbines of power approximated 1MW, resulting to a total power of 310MW, 100MW and 50MW were aggregated into equivalent DFIG machines.

Table 3: Data of WTGs modelled

BUSBAR	MVA RATING	P GENARATION	NO. OF MACHINES
Loiyalangani	1.111	0.85	365
Ngong	1.111	1	50
Ngong	1.111	1	100

The performance of the system was compared to a scenario where there was no wind generation in the system. This analysis also involved learning the effect of excitation devices i.e. an AVR and a PSS, with and without wind generation in the system.

Load flow analysis was first done on each of the system cases before small signal condition was simulated.

In the study the following scenarios were considered:

1. Without wind farms connected to the system.
2. Without wind farm connected to the system but with incorporation of the excitation devices.
3. With wind farm connected to the system.

4. With wind farm connected to the system, with incorporation of the excitation devices.

To determine the small signal stability of the grid, calculation of initial value condition is the first step taken in order to figure out oscillatory modes of the Kenyan power System.

The Kenyan power System data and figure will be shown in the appendix.

IV. Results And Discussion

4.1.1. Small signal stability of Small machine infinite bus

The modal analysis of the SMIB system was done and the following results were obtained:

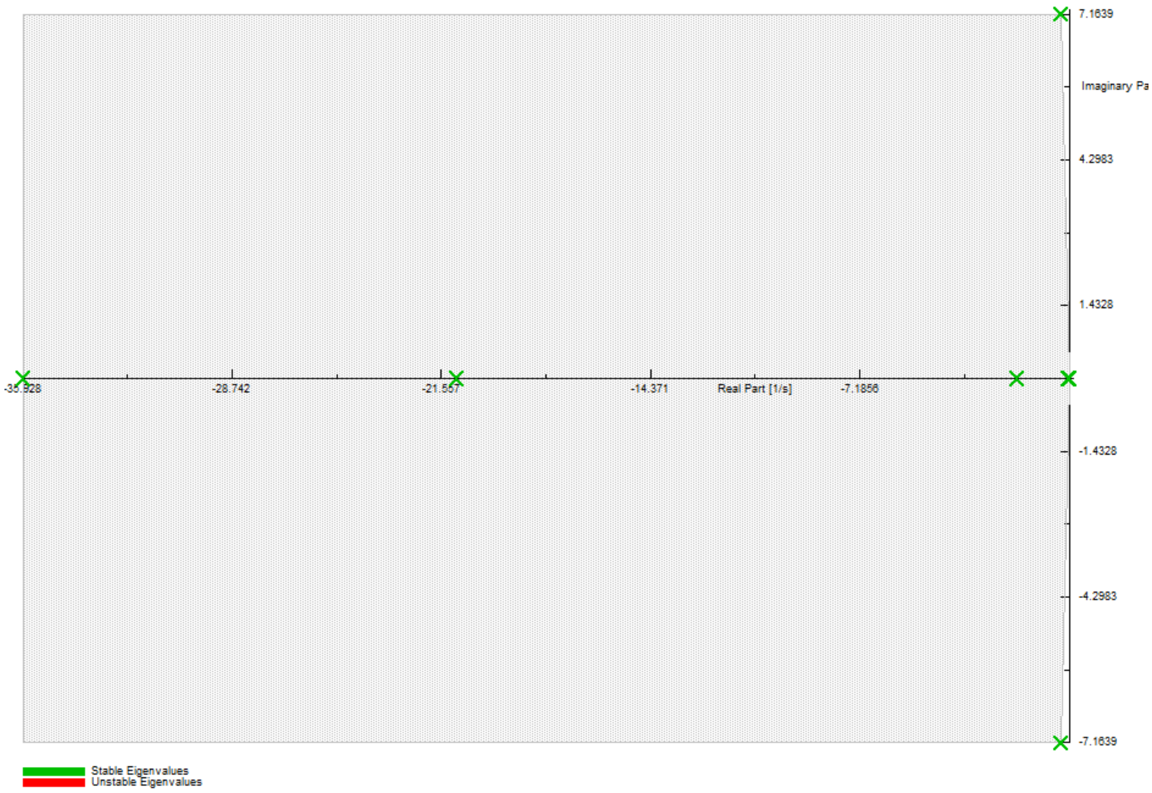


Figure 4.1. Eigen plot of SMIB

From Lyapunov stability, when eigen values are located in the left hand side of the plane, they are stable. From the above figure, we can note that the system is stable since all eigen values are located in the left hand side.

Table 4: Results of Modal analysis of the SMIB

	Eigen value	Frequency in Hz	Damping ratio
Local area mode (4 & 5)	$-0.30319 \pm 7.1638i$	1.140167	0.042145

From the above results, we have seven modes, which means we are using a thermal plant (sixth order model). The extra seventh mode comes from the AC Voltage source. We can note that only two modes are oscillating i.e. mode 4 and 5. Our damping ratio is at 4.2145% which shows that the system is under-damped. To enhance the damping ratio we put an AVR which enhances damping of the system. An EXAC4 was used for this system.

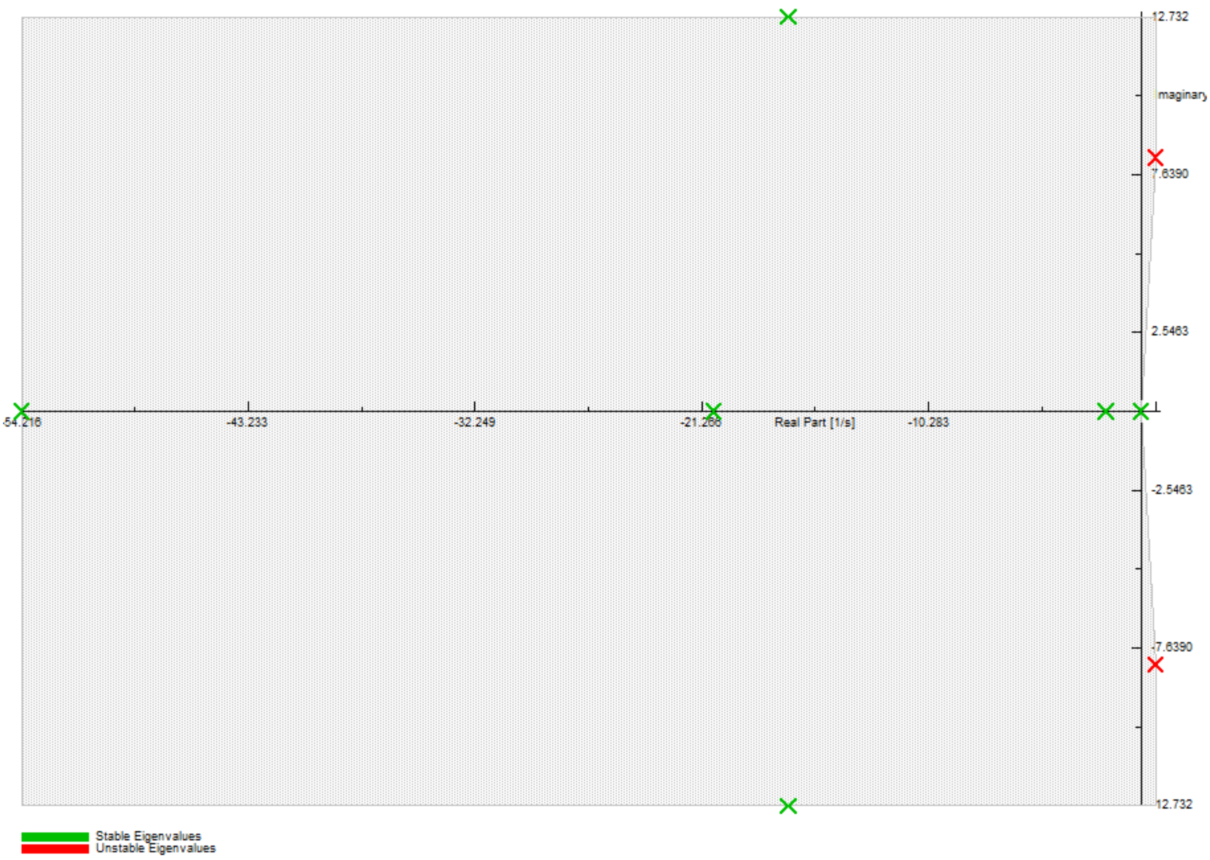


Figure 4.2: Eigen plot of an SMIB with an AVR

From the above figure, we can see that when we put an AVR, the system becomes unstable. This is because the AVR has an integral that tends to pull the root locus to the right making the system unstable. This seen from the two eigen values located in the right hand side of the plane.

Table 6: Results of modal analysis of the SMIB with an AVR

	Eigen value	Damping frequency	Damping ratio
Mode 3&4	$-17.08939 \pm 12.731599i$	2.0269	0.80192
Mode 6&7	$0.70030 \pm 8.186628i$	1.3029	-0.08523

The figure above shows the number of modes after an AVR has been put in the system. The number of modes has increased to 10 since the AVR has lead /lag blocks that add the number of modes. There are 4 oscillating modes i.e. mode 3,4,6 and 7.The damping ratio of the system has improved to 80% and 8.5%. To negate the effect of the AVR, a PSS is put in the system.

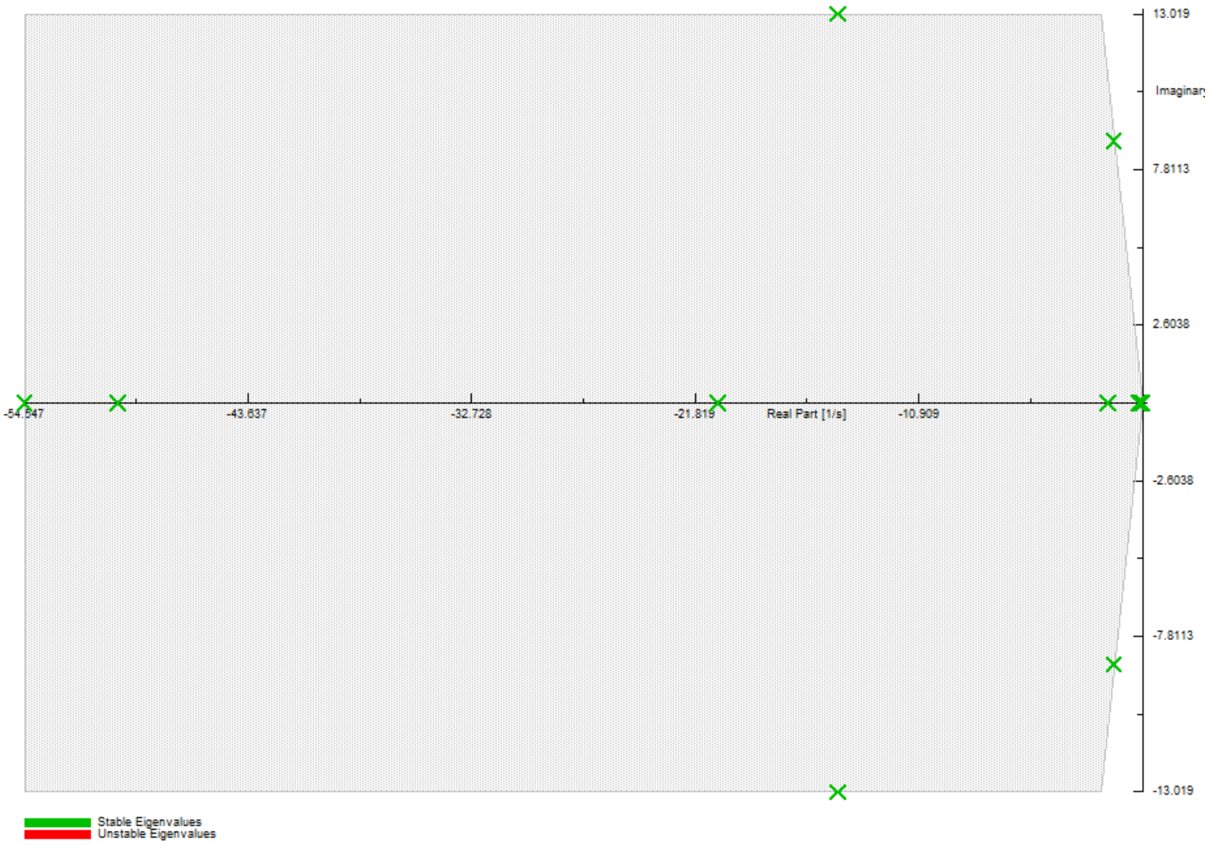


Figure 4.3: Eigen plot of modal analysis of the SMIB with an AVR and PSS

From the figure above where a PSS has been put we can see that all the eigen values are on the Left hand side, which means the system is stable. This is because the PSS negates the effect of the AVR making the system stable.

Table 7: Results of modal analysis of the SMIB with an AVR and PSS

	Eigen value	Damping frequency	Damping ratio
Mode 3&4	$-14.8485 \pm 13.0188i$	2.072	0.7519
Mode 6&7	$-1.37885 \pm 8.77258i$	1.39619	0.155271

We can see that the number of modes has increased to 13 since the PSS has lead/ lag blocks. The damping ratio of the oscillating modes has improved to 75.19% and 15.53%. This percentage is above the required percentage which is 10% hence the system is over-damped.
From the above results we can see that the AVR and the SS improve the damping and stability of the system.

4.2 Small signal stability analysis of the 2A4G system

In the 2A4G system, the load flow was run and a modal analysis done to observe the small stability of the system. An analysis was done without injecting wind to the system.

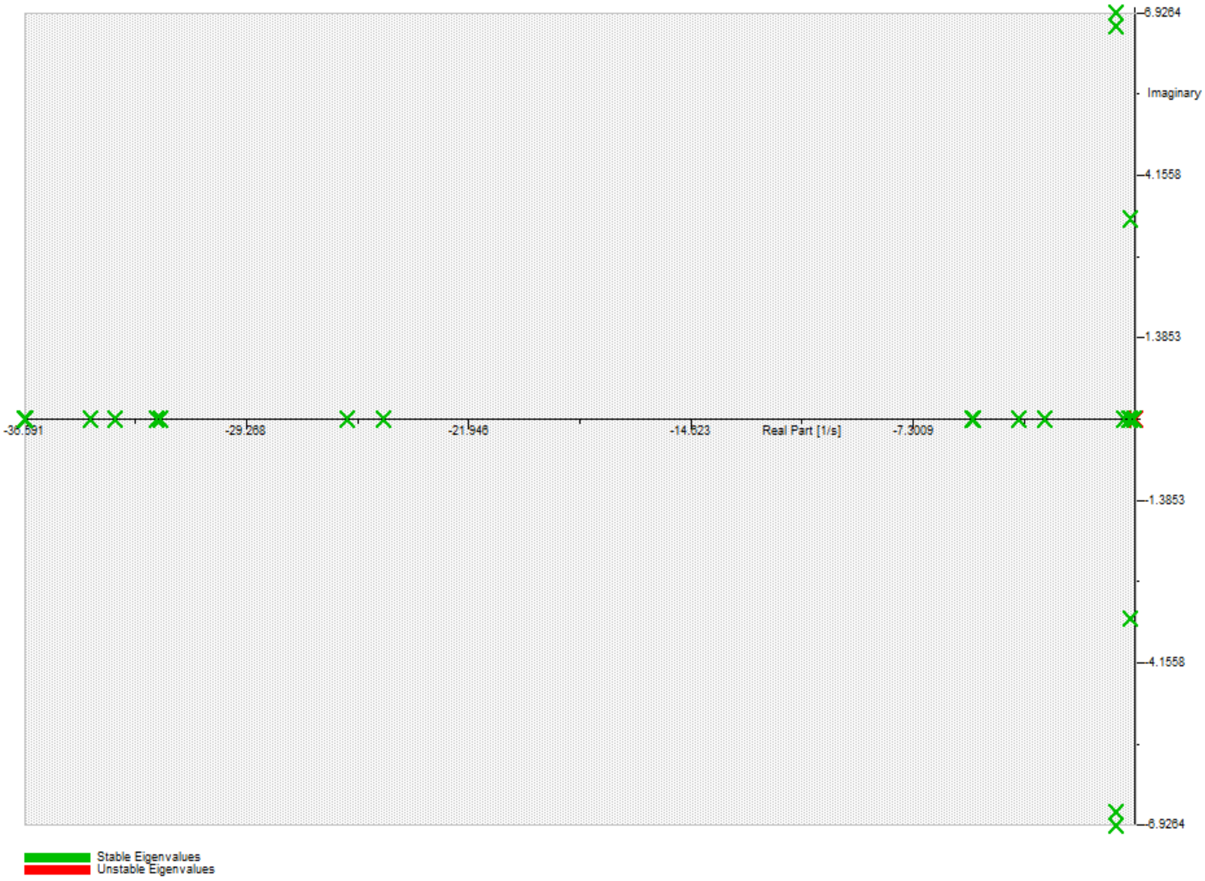


Figure 4.4: Eigen plot of modal analysis of the 2A4G

The above diagram shows that the system is not stable since there is one eigen value that is not in the left hand side. The figure below shows the results of the modal analysis without the controllers and wind turbine generators.

Table 8: Results of modal analysis of the 2A4G

	Eigen value	Damping frequency	Damping ratio
Mode 10&11	$-0.6187 \pm 6.7029i$	1.0668	0.09191
Mode 12&13	$0.62657 \pm 6.92639i$	1.1023	0.09009
Mode 14&15	$0.14375 \pm 3.4097i$	0.5426	0.04212

The type of generators used were thermal generators hence number of modes expected are 24 modes. From the results we can see that mode 21 is on the right hand side making the system unstable. The modes oscillating are mode 10- mode 15. They have a damping ratio of 4.21% and 9.19%. The damping ratio of 4.21% is under-damped hence we put an AVR to improve this.

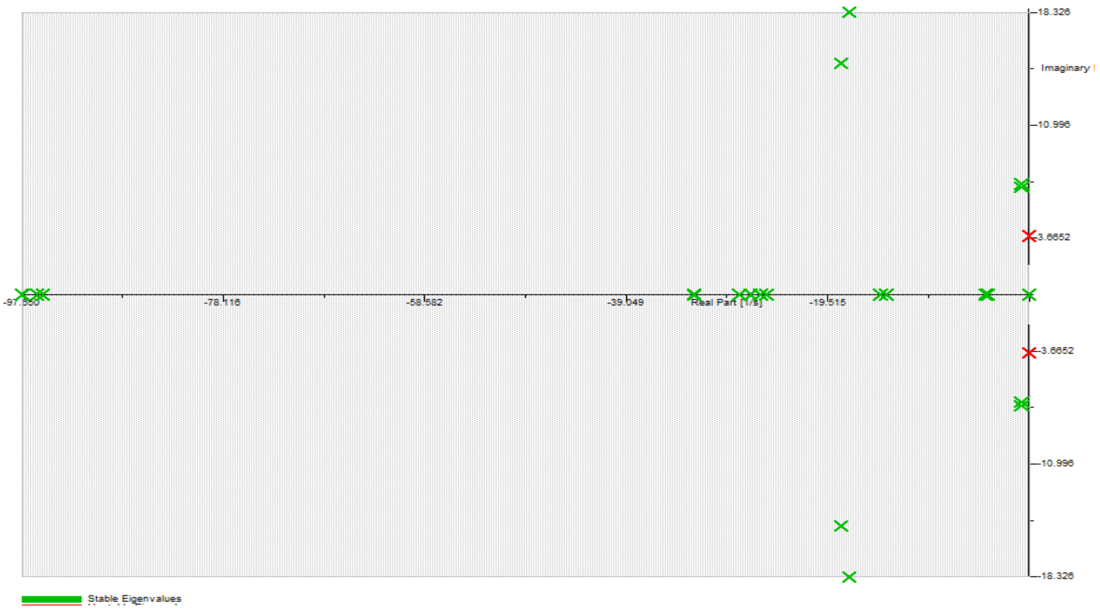
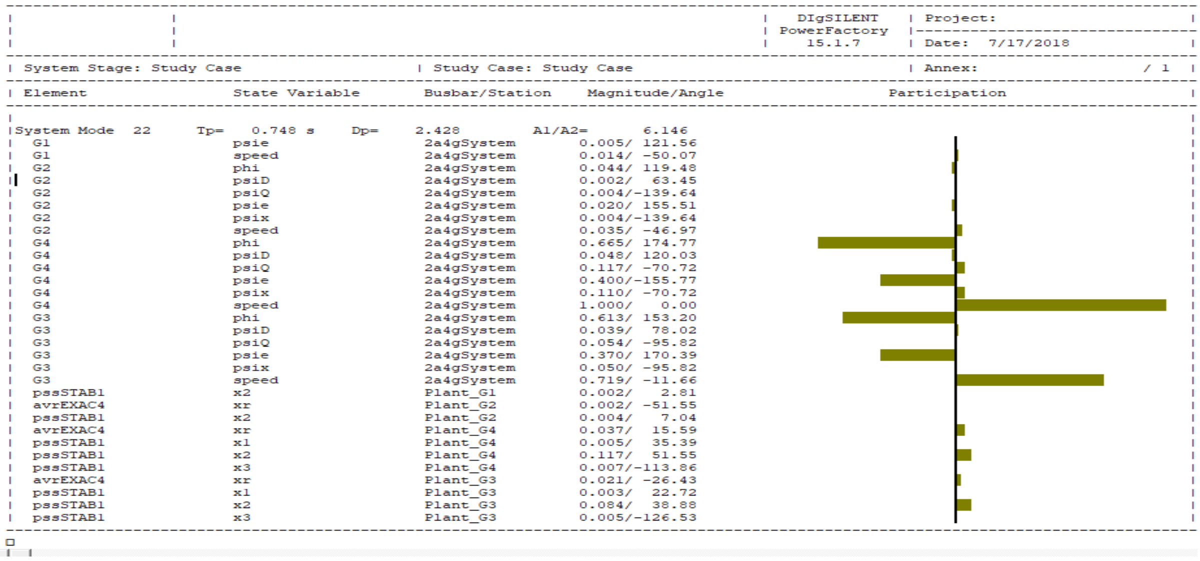


Figure 4.5: Eigen plot of modal analysis of the 2A4G with an AVR

Some of the eigen values are still in the right hand side due to the integral part which pulls the root locus to the right hand side. The damping ratio has been slightly improved to 7% on some modes. The oscillating modes with damping frequency of 0.5817Hz are inter area modes while those with damping frequency of 1.1Hz are local area modes. This relationship can be seen by the use of participation factors. When the PSS is added to the system, all the eigen values were on the left hand side hence the system was stable. The damping ratio of the system was also improved and it was above 10% which is the accepted value.



DIgSILENT PowerFactory 15.1.7 | Project: | Date: 7/17/2018

System Stage: Study Case | Study Case: Study Case | Annex: / 1

System Mode 22 Tp= 0.748 s Dp= 2.428 A1/A2= 6.146

Element	State Variable	Busbar/Station	Magnitude/Angle	Participation
G1	psie	2a4gSystem	0.005/ 121.56	
G1	speed	2a4gSystem	0.014/ -50.07	
G2	phi	2a4gSystem	0.044/ 119.48	
G2	psiD	2a4gSystem	0.002/ 63.45	
G2	psiQ	2a4gSystem	0.004/-139.64	
G2	psie	2a4gSystem	0.020/ 155.51	
G2	psix	2a4gSystem	0.004/-139.64	
G2	speed	2a4gSystem	0.035/ -46.97	
G4	phi	2a4gSystem	0.665/ 174.77	
G4	psiD	2a4gSystem	0.048/ 120.03	
G4	psiQ	2a4gSystem	0.117/ -70.72	
G4	psie	2a4gSystem	0.400/-155.77	
G4	psix	2a4gSystem	0.110/ -70.72	
G4	speed	2a4gSystem	1.000/ 0.00	
G3	phi	2a4gSystem	0.613/ 153.20	
G3	psiD	2a4gSystem	0.039/ 78.02	
G3	psiQ	2a4gSystem	0.054/ -95.82	
G3	psie	2a4gSystem	0.370/ 170.39	
G3	psix	2a4gSystem	0.050/ -95.82	
G3	speed	2a4gSystem	0.719/ -11.66	
pssSTAB1	x2	Plant_G1	0.002/ 2.81	
avrEXAC4	xr	Plant_G2	0.002/ -51.55	
pssSTAB1	x2	Plant_G2	0.004/ 7.04	
avrEXAC4	xr	Plant_G4	0.037/ 15.59	
pssSTAB1	x1	Plant_G4	0.005/ 35.39	
pssSTAB1	x2	Plant_G4	0.117/ 51.55	
pssSTAB1	x3	Plant_G4	0.007/-113.86	
avrEXAC4	xr	Plant_G3	0.021/ -26.43	
pssSTAB1	x1	Plant_G3	0.003/ 22.72	
pssSTAB1	x2	Plant_G3	0.084/ 38.88	
pssSTAB1	x3	Plant_G3	0.005/-126.53	

Figure 4.6: Participation of the generators

For mode 22, G1, G3 and G4 are both participating with their state variable being speed. Hence this is an inter area mode (0.53Hz) and local area (1.0Hz). When the exciters are added, an extra mode called the control mode is added whose frequency is 2.0Hz.

4.3. Analysis of the 2A4G with a DFIG

Replacing one of the synchronous thermal machines with a WTG i.e. is 25% injection rate, I did a modal analysis and the following were the results of the eigen value plot:

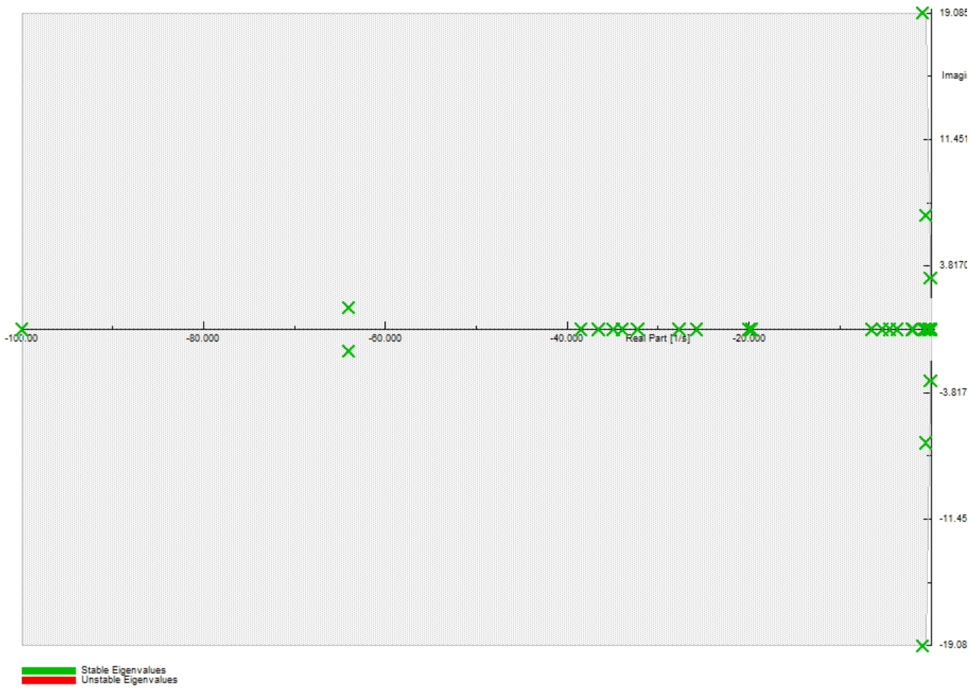


Figure 4.7: Eigen plot of modal analysis of the2A4G with a WTG

We can see that the system is stable. The following were the tabular results of the system showing various properties.

Table 9: Results of modal analysis of the 2A4G with a WTG

	Eigen values	Damped frequency	Damping ratio
Mode 3&4	$-64.0775 \pm 1.3148i$	0.20926	0.9997
Mode 5&6	$-0.90909 \pm 19.08507i$	3.03748	0.04758
Mode 14&15	$-0.61001 \pm 6.8587i$	1.09160	0.08858
Mode 16&17	$-0.09226 \pm 3.09358i$	0.49235	0.02981
Mode 24&25	$-0.05136 \pm 0.03594i$	0.00572	0.8193

From the above table we can see Mode 16 and 17 were operating in inter area mode as can be seen from the frequency of 0.49235Hz while Mode 14 and 15 were operating in local area mode with a frequency of 1.0916Hz. The damping ratio of the mode 5, 6, 16, 17 have low ratios hence to improve this an AVR was added. The diagram below shows which areas were participating and with which properties.

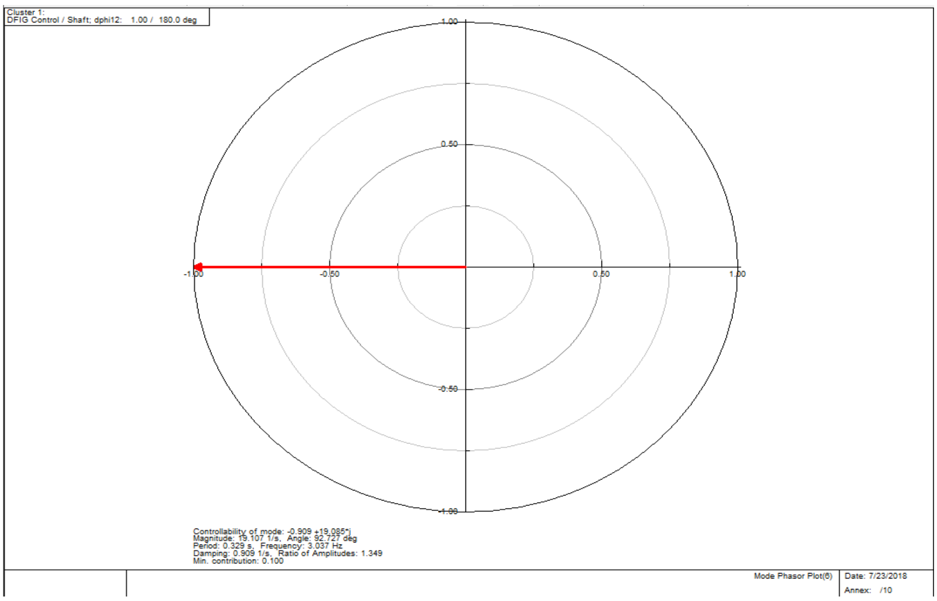


Figure 4.8: Modal phasor plot of the 2A4G with a DFIG(Mode 5)

This is a modal phasor plot of mode 5 which shows that the shaft of the DFIG was participating with a magnitude of 1 at an angle of 180 degrees. This hence is operating in control mode with a frequency of 3.03748 Hz.

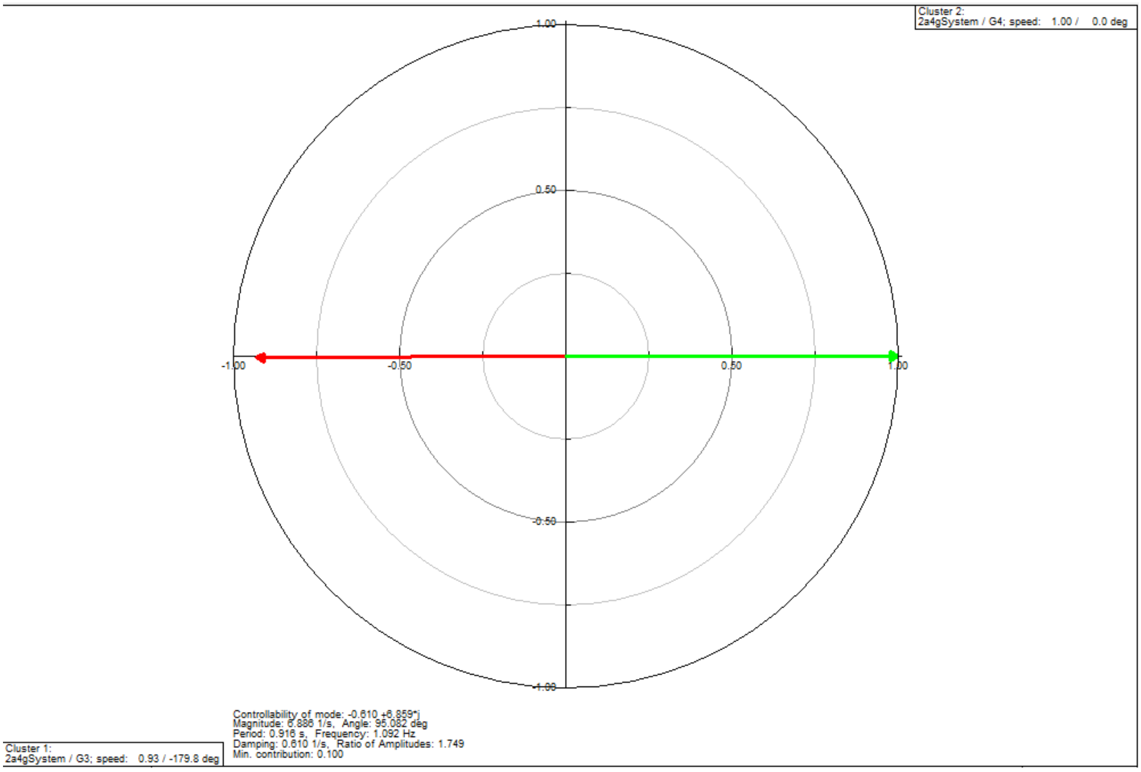


Figure 4.9: Modal phasor plot of the 2A4G with a DFIG(Mode 14)

Mode 14 is operating in local area mode with Generator 3 and Generator 4 participating with speed as the factor.

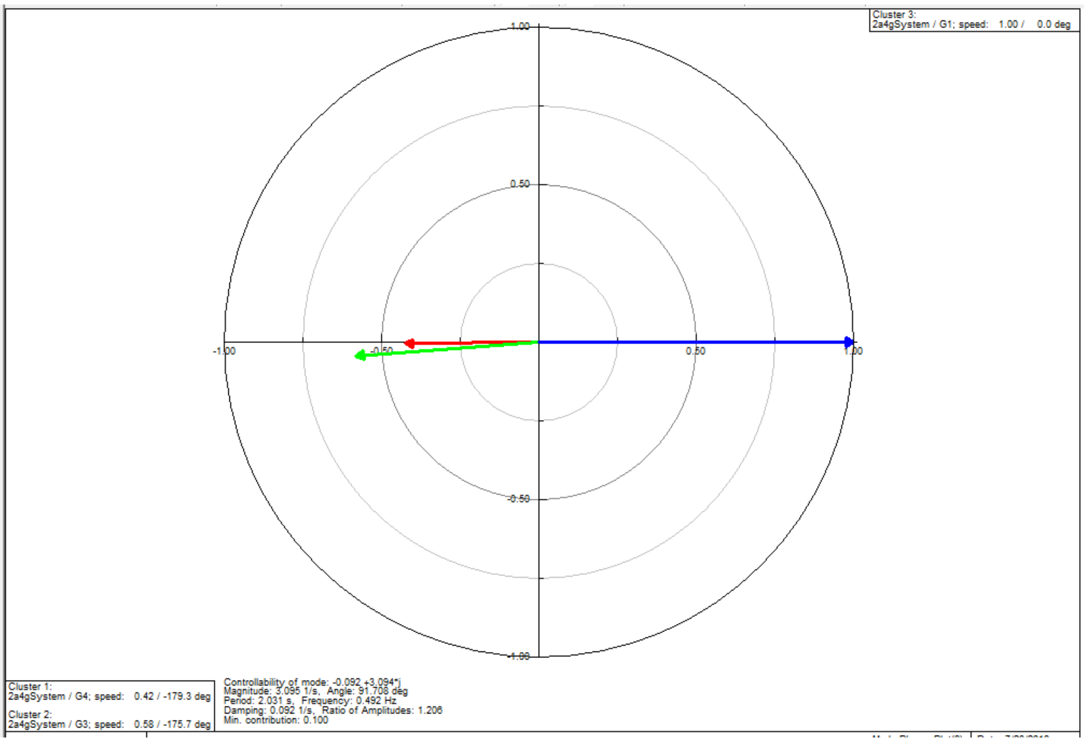


Figure 4.10: Modal phasor plot of the 2A4G with a DFIG(Mode 16)

Mode 16 is participating in inter area mode with a frequency of 0.49235Hz, with G3 and G4 participating with G1 with speed as the factor.

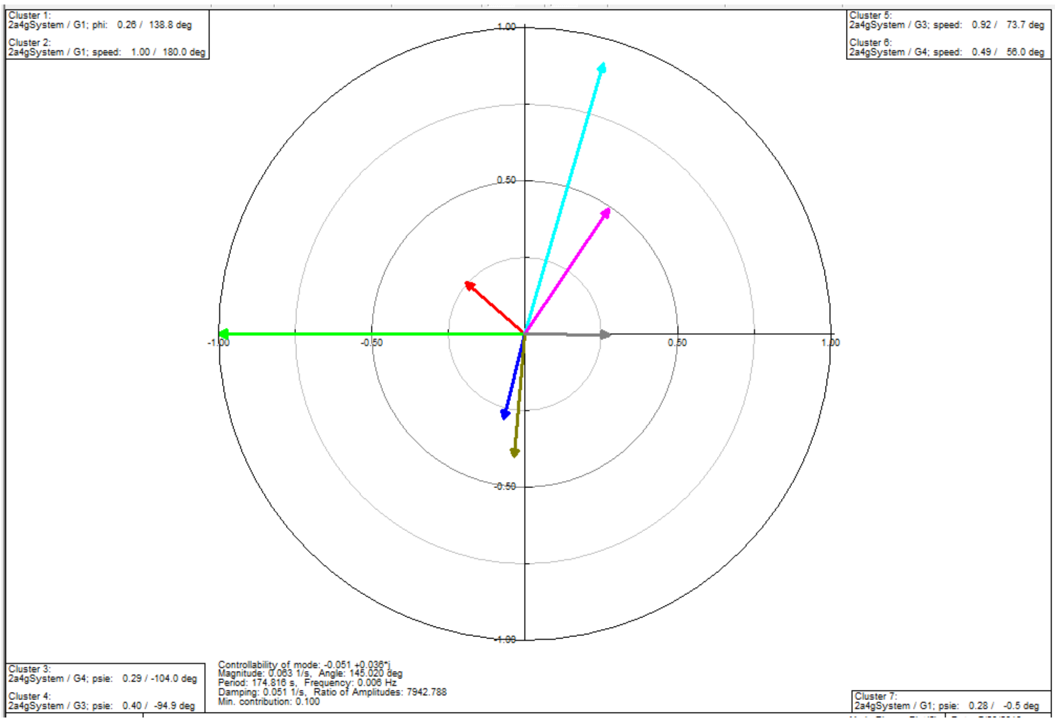


Figure 4.11: Modal phasor plot of the 2A4G with a DFIG(Mode 24)

Mode 24 has a damping frequency of 0.00572Hz and it has G1, G3 and G4 participating with speed as the variable, G1 participating with speed and G3, G4 and G1 are participating with excitation flux (psie) as the variable.

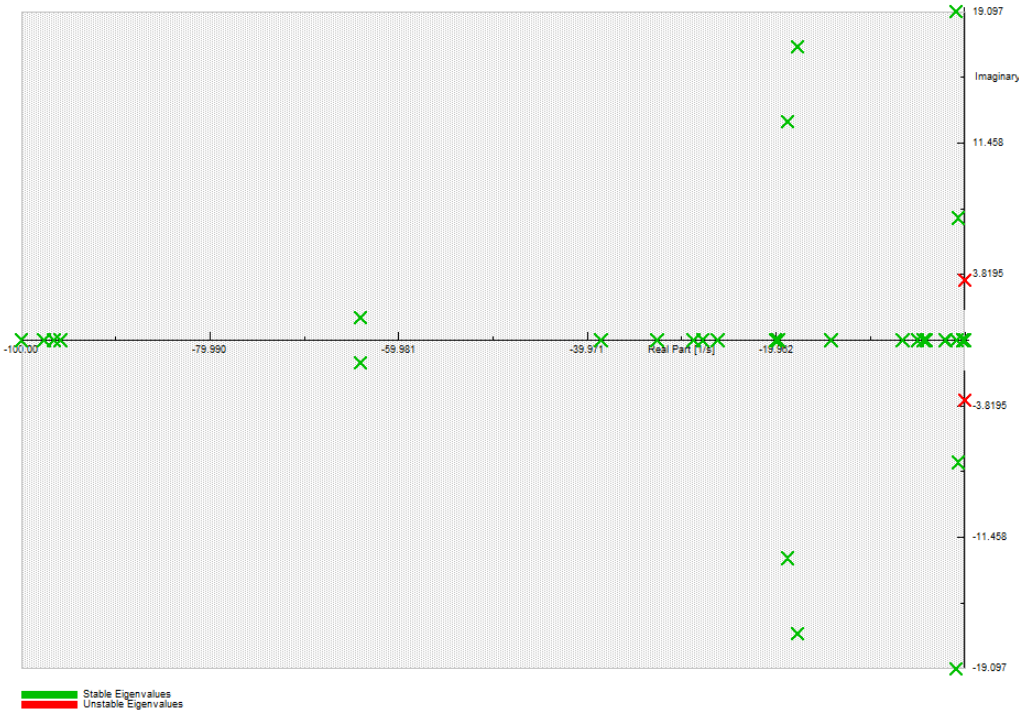


Figure 4.12: Eigen plot of the 2A4G with a DFIG and AVR

The diagram above shows the eigen plot when AVRs have been integrated into the synchronous generators. The AVR has pulled the root locus to the right making the system unstable.

Table 10:Results of the 2A4G with a DFIG and an AVR

	Eigen values	Damped frequency	Damping ratio
Mode 6&7	$-64.09686 \pm 1.31991i$	0.21	0.9997
Mode 8&9	$-0.9189 \pm 19.0974i$	3.03945	0.048062
Mode 10&11	$-17.6578 \pm 17.07152i$	2.7170	0.718942
Mode 13&14	$-18.7827 \pm 12.6898i$	2.01964	0.828614
Mode 21&22	$-0.6963 \pm 7.11765i$	1.13281	0.097362
Mode 24&25	$0.04812 \pm 3.4997i$	0.5569	-0.013749

The damping ratio of the system improved slightly as compared to the situation without an AVR. The extra modes came from the AVR added and the DFIG. Mode 8 and 9 are operating in control mode with a frequency of 3.03945Hz, mode 21 and 22 are operating in local area mode with a frequency of 1.13281Hz and mode 24 and 25 are operating in inter area mode with a frequency of 0.5569Hz.

When the system is operating with both an AVR and a PSS, the systems eigen plot is as below. The PSS has cancelled out the effect of the AVR making the system stable.

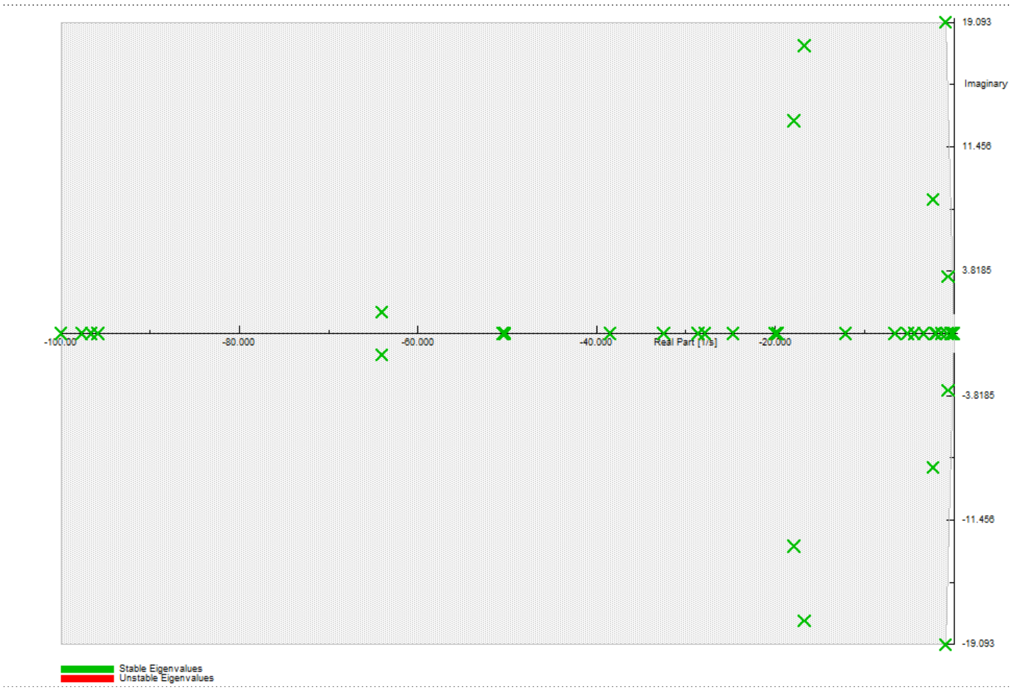


Figure 4.13: Eigen plot of the 2A4G with a DFIG, an AVR and a PSS

The table below shows the modes and their damping ratios and damping frequencies.

Table 11: Modal phasor plot of the 2A4G with a DFIG, an AVR and a PSS

	Eigen values	Damped frequency	Damping ratio
Mode 6&7	$-64.09351 \pm 1.3137i$	0.2090	0.9997
Mode 9&10	$-50.29759 \pm 0.02424i$	0.003859	0.99999
Mode 11&12	$-0.92094 \pm 19.09264i$	3.0386	0.048175
Mode 13&14	$-16.72483 \pm 17.6510i$	2.80925	0.6878
Mode 16&17	$-17.9524 \pm 13.0627i$	2.0789	0.80859
Mode 23&24	$-2.26453 \pm 8.23144i$	1.31	0.27609
Mode 27&28	$-0.6695 \pm 3.4866i$	0.5549	0.188581

From the above results we can see that the controllers have made the system stable. The damping of the system has been improved to at least above 10% for almost all of the electromechanical modes of oscillation. The system is operating in local area mode for mode 13,16 and 23, in inter-area mode for modes 27 and 6 and in control mode for mode 11.

4.4 Analysis of Kenyan power system with and without the Wind Generation

When wind was not integrated in the system, the eigen plot is as shown in the figure below. We can see that the system is unstable. Since there are 26 synchronous generators and 1 asynchronous generator the number of modes will be 154 modes. To improve the damping ratio and stability we add an AVR to observe the stability of the system. When an AVR is added the eigen plot is as follows:

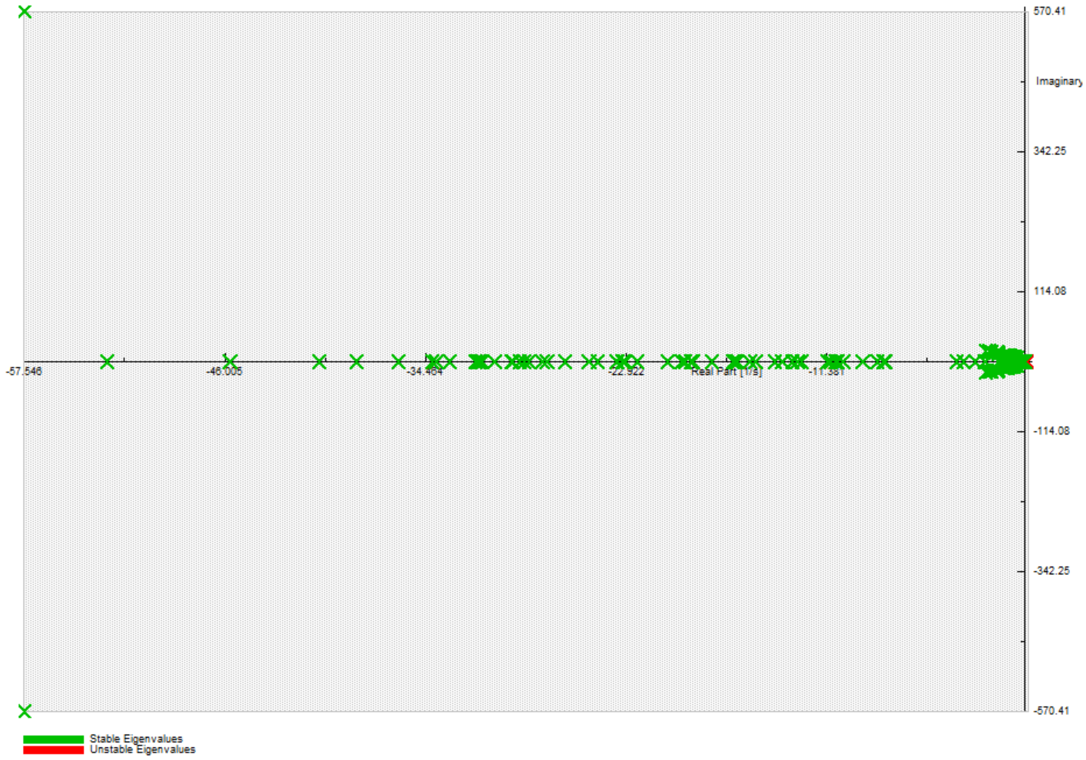


Figure 4.14: Eigen value plot of the Kenyan Power System

The system becomes stable after an AVR is put in each of the synchronous generators. The damping ratio of most of the oscillating modes has increased to above 10%. To improve the damping ratio of the system further it is advisable to put PSS's in all synchronous generators. The eigen value plot will be as follows:

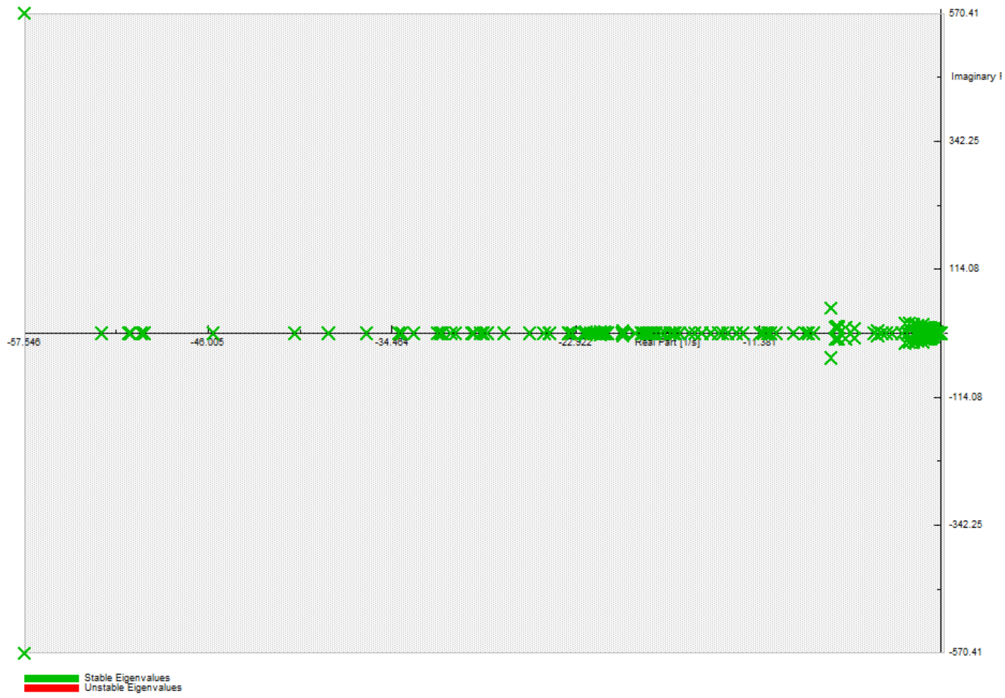


Figure 4.15: Eigen value plot of the Kenyan Power System with an AVR

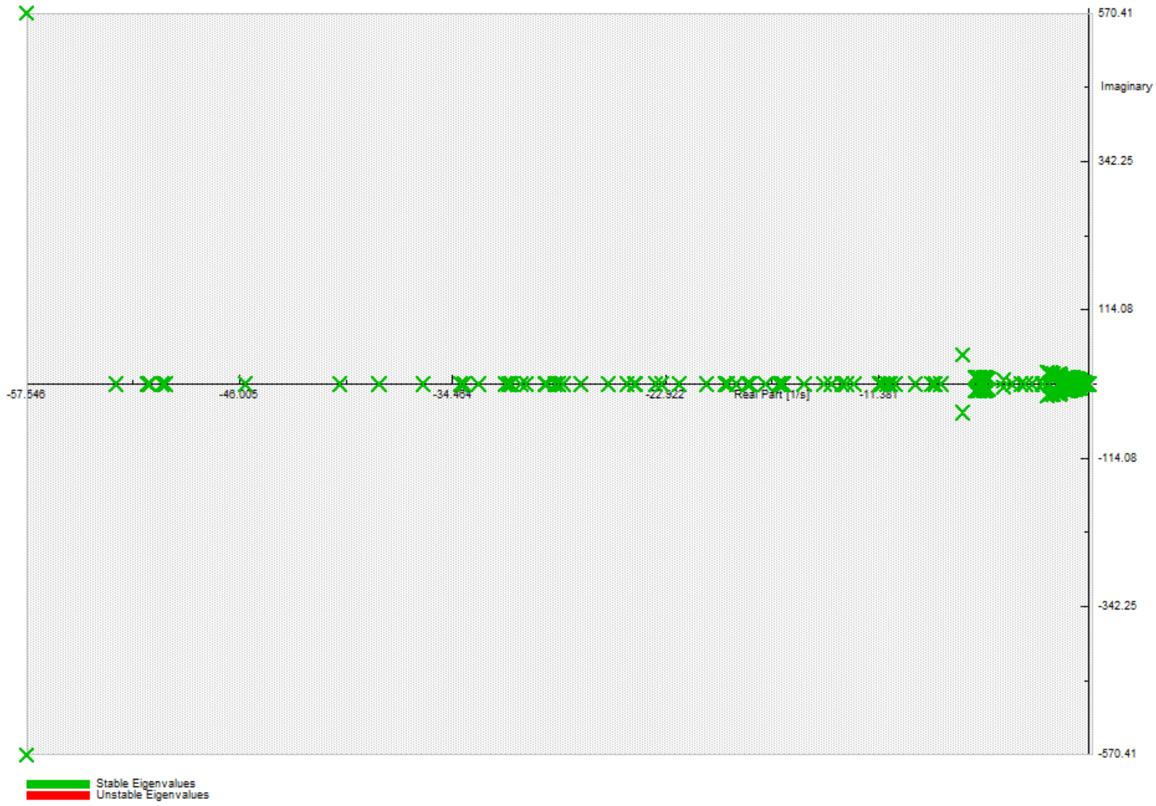


Figure 4.16: Eigen value plot of the Kenyan power system with an AVR and a PSS

In the Kenyan power system, when wind has been integrated into the system, the systems eigen plot is as shown in the figure below. This is done without the excitation parameters

I also analyzed the Kenyan power system without the excitation systems and with the integration of wind. When wind has been integrated at Lake Turkana, Prunus and Kipeto with an input of 310MW, 50MW and 100MW, the system's eigen plot is as below:

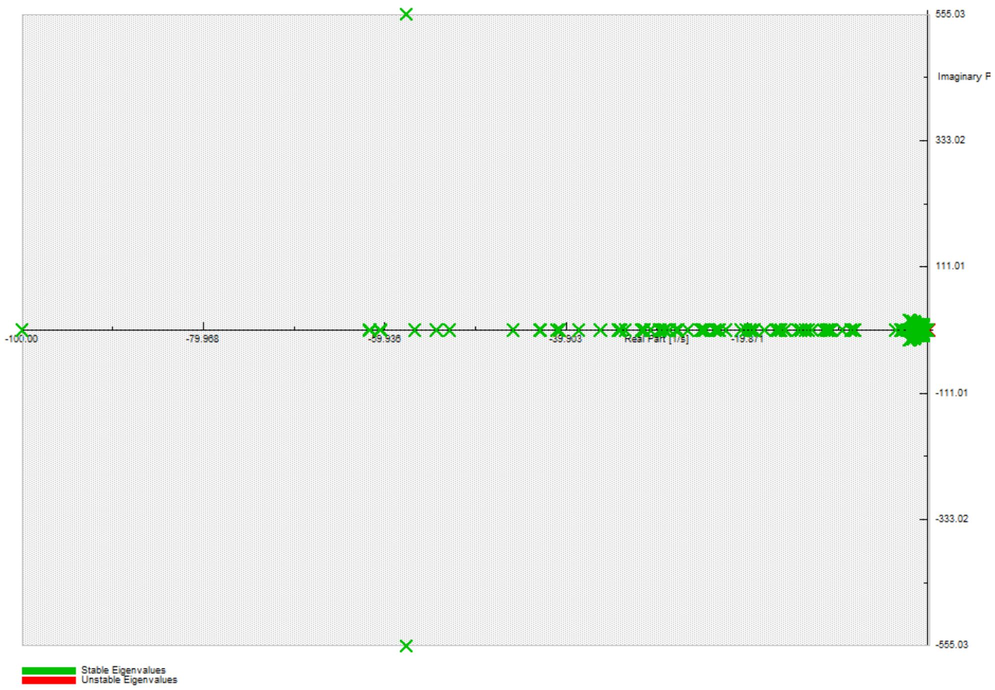
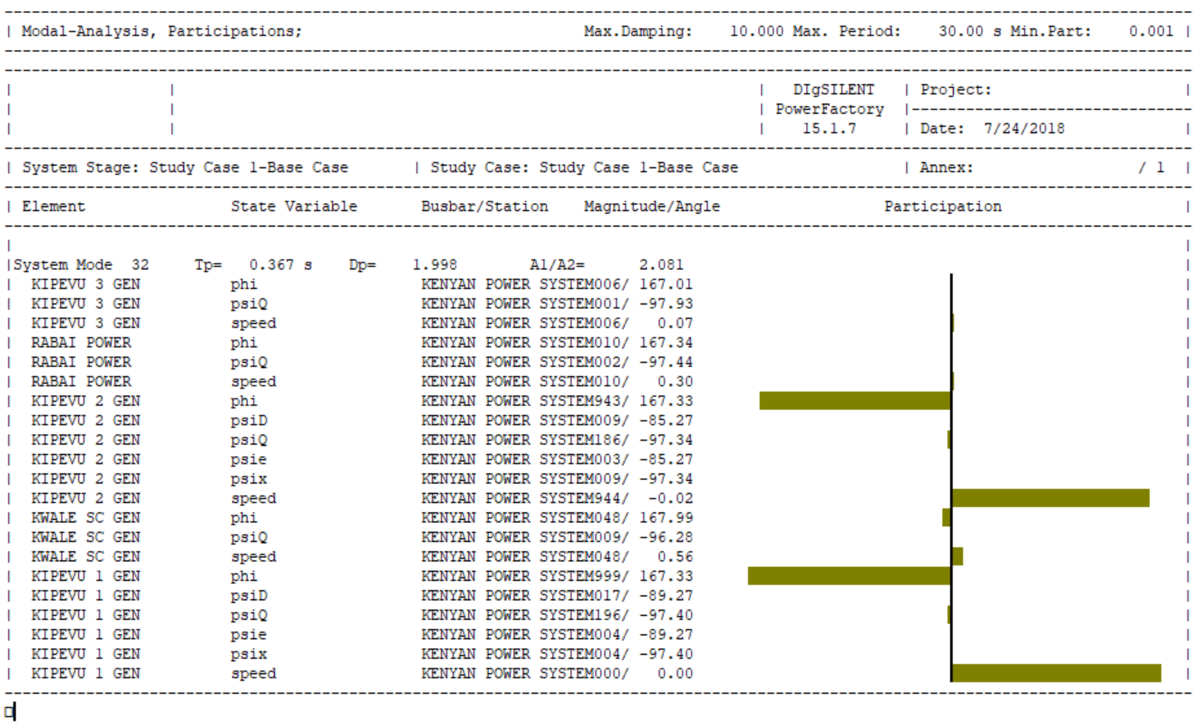


Figure 4.17: Eigen value plot of the Kenyan power system with wind generation

From the above system, it shows that the system is unstable. The damping ratio expected is about 10%. Some of the electromechanical modes of oscillation have a damping ratio of below 10% hence to improve this an AVR is put in every synchronous generator to try and improve this factor. Most of the modes are operating in local area modes of oscillation. The following diagram shows the participation of the system and their generators:



```
| Modal-Analysis, Participations;                   Max.Damping:   10.000 Max. Period:   30.00 s Min.Part:   0.001 |
|             |                                                      |  DIgSILENT   | Project:                     |
|             |                                                      | PowerFactory |------------------------------
|             |                                                      |    15.1.7    | Date:  7/24/2018             |
| System Stage: Study Case 1-Base Case      | Study Case: Study Case 1-Base Case                | Annex:              / 1 |
| Element                 State Variable      Busbar/Station    Magnitude/Angle               Participation            |
|                                                                                                                     |
|System Mode  32     Tp=   0.367 s    Dp=    1.998       A1/A2=      2.081                                            |
|  KIPEVU 3 GEN           phi                 KENYAN POWER SYSTEM006/ 167.01                                          |
|  KIPEVU 3 GEN           psiQ                KENYAN POWER SYSTEM001/ -97.93                                          |
|  KIPEVU 3 GEN           speed               KENYAN POWER SYSTEM006/   0.07                                          |
|  RABAI POWER            phi                 KENYAN POWER SYSTEM010/ 167.34                                          |
|  RABAI POWER            psiQ                KENYAN POWER SYSTEM002/ -97.44                                          |
|  RABAI POWER            speed               KENYAN POWER SYSTEM010/   0.30                                          |
|  KIPEVU 2 GEN           phi                 KENYAN POWER SYSTEM943/ 167.33                                          |
|  KIPEVU 2 GEN           psiD                KENYAN POWER SYSTEM009/ -85.27                                          |
|  KIPEVU 2 GEN           psiQ                KENYAN POWER SYSTEM186/ -97.34                                          |
|  KIPEVU 2 GEN           psie                KENYAN POWER SYSTEM003/ -85.27                                          |
|  KIPEVU 2 GEN           psix                KENYAN POWER SYSTEM009/ -97.34                                          |
|  KIPEVU 2 GEN           speed               KENYAN POWER SYSTEM944/  -0.02                                          |
|  KWALE SC GEN           phi                 KENYAN POWER SYSTEM048/ 167.99                                          |
|  KWALE SC GEN           psiQ                KENYAN POWER SYSTEM009/ -96.28                                          |
|  KWALE SC GEN           speed               KENYAN POWER SYSTEM048/   0.56                                          |
|  KIPEVU 1 GEN           phi                 KENYAN POWER SYSTEM999/ 167.33                                          |
|  KIPEVU 1 GEN           psiD                KENYAN POWER SYSTEM017/ -89.27                                          |
|  KIPEVU 1 GEN           psiQ                KENYAN POWER SYSTEM196/ -97.40                                          |
|  KIPEVU 1 GEN           psie                KENYAN POWER SYSTEM004/ -89.27                                          |
|  KIPEVU 1 GEN           psix                KENYAN POWER SYSTEM004/ -97.40                                          |
|  KIPEVU 1 GEN           speed               KENYAN POWER SYSTEM000/   0.00                                          |
```

Figure 4.18: Participation of the Generators in mode 32

We can see that in mode 18, Rabai power, Kipevu 1 and Kipevu 2 are participating with speed as their variable. Amore clear and defined diagram to explain this will be using the modal phasor plot as shown below:

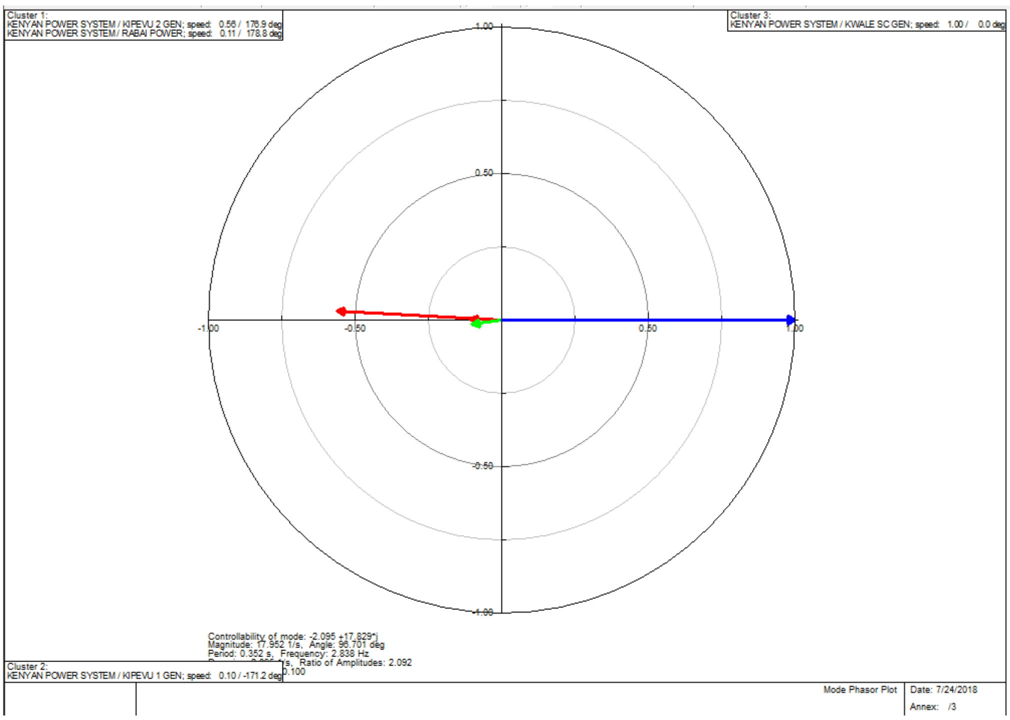


Figure 4.19: Modal phasor plot of the Kenyan power system for mode 32

It is a inter machine mode of oscillation since it is operating at a frequency of 2.8375Hz meaning the generators above are in the same area.

When an AVR has been put, the system's eigen plot will be as below:

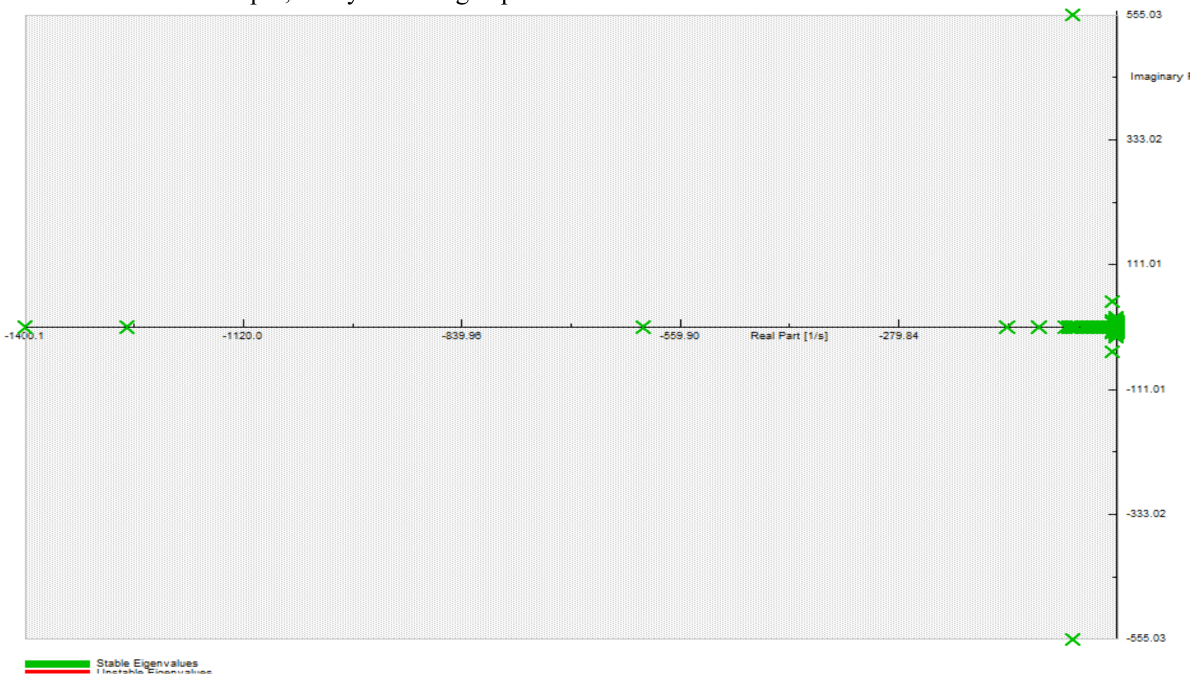


Figure 4.20: Eigen value plot of the Kenyan power system with an AVR

From the above diagram we can see that the system is stable since the eigen values are on the left hand side of the plane. The damping ratio of the whole system has also improved to above 10% hence make the system properly damped. With PSS's added to the system the following can be observed from the system.

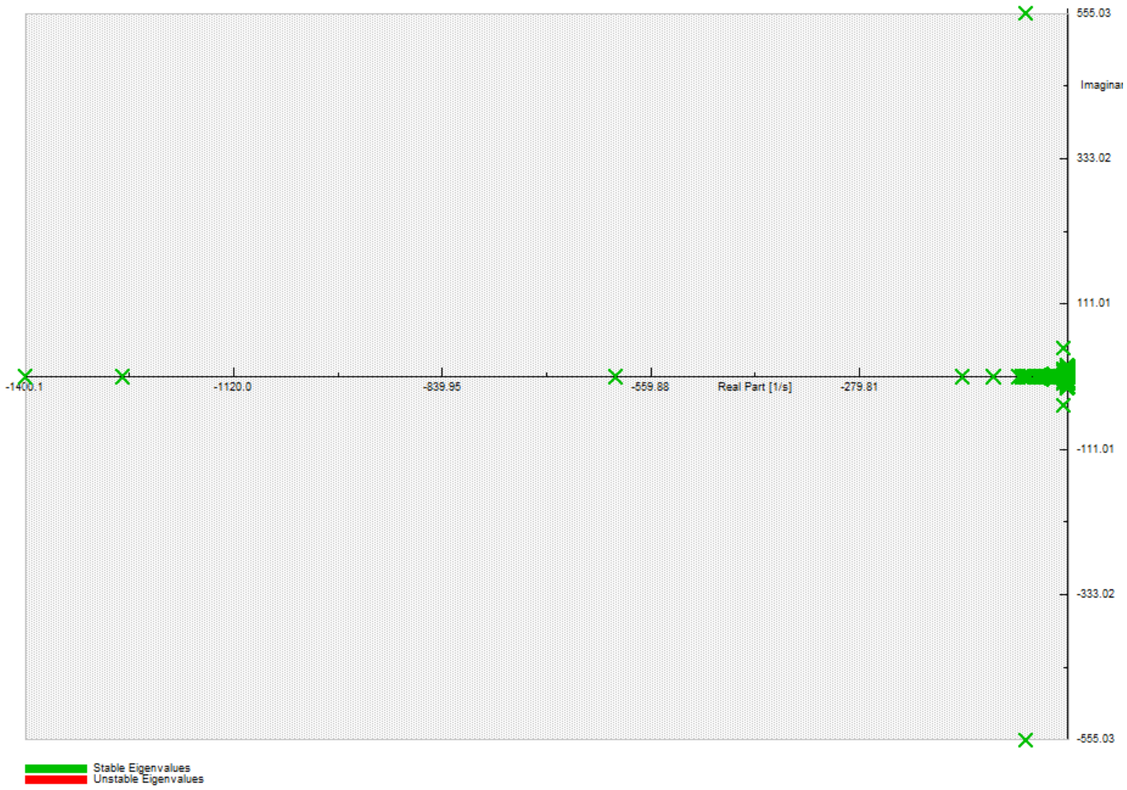


Figure 4.21: Eigen value plot of the Kenyan power system with an AVR and a PSS

From the above we can see that the system is stable. From the results we can see that the damping ratio of the system has been further improved. This shows how an AVR and PSS improve the damping of a large system.

As seen from mode 27 the system is operating in inter area mode of oscillation as seen from the damping frequency of 0.88Hz. The modal phasor plot is as shown below. It shows how different areas I the Kenyan system participate with their different variables in terms of magnitude and angle.

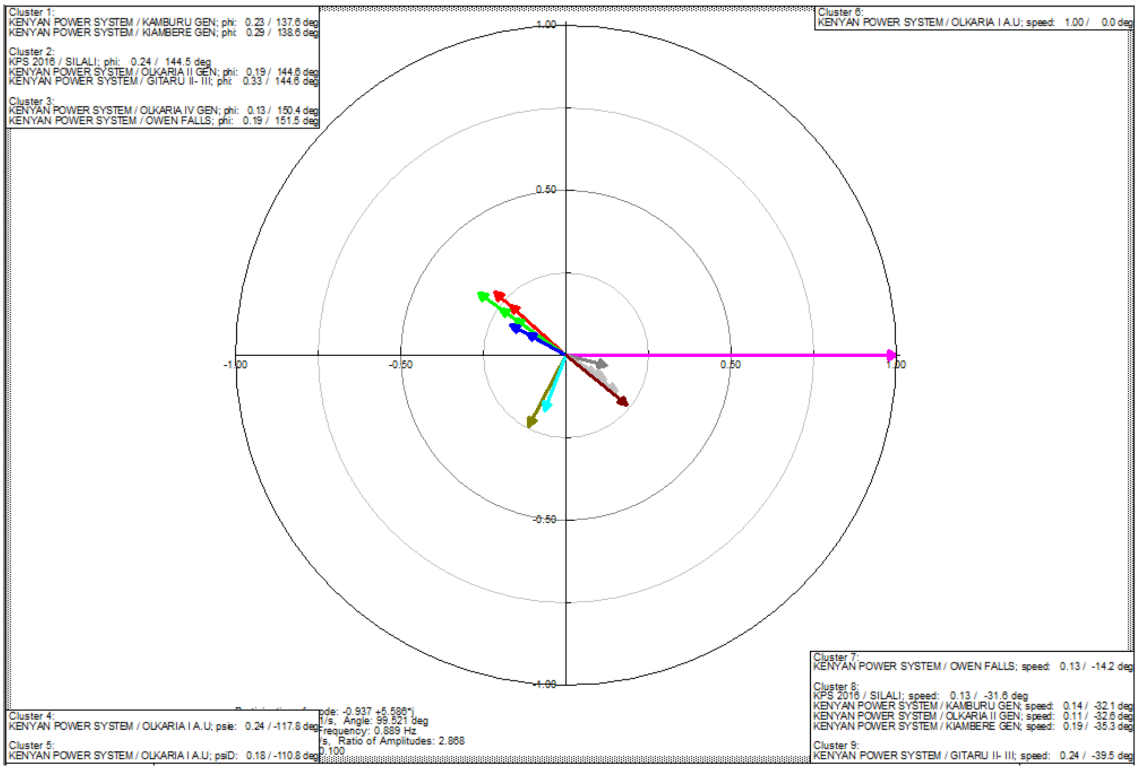


Figure 4.22: Modal Phasor plot of the Kenyan power system with an AVR and a PSS

V. Conclusion And Recommendations

This project analyses the impact of wind generation (20%) injection with excitation controllers on the small signal stability of the Kenyan Power System. The system was successfully modelled with the base case the system being identified as unstable.

The impact of the AVR and PSS on the Kenyan power system without integration of wind was also successfully studied. Based on the results and the discussion, it can be concluded that AVR to some degree affect the stability of a system negatively. The PSS was observed to negate the effect of the PSS on the system hence making the system stable.

When DFIGs were added into the system it was noted that they generally have a positive and negative impact on the inter area modes. This was corrected by use of AVR and PSS on the synchronous generators to add the damping in the system. The DFIG was noted to have a positive influence o the local area modes of oscillations through the improvement of damping when excitation systems were added.

5.1 LIMITATIONS

The data acquired was not complete in cases like transmission line data and generator data for new systems hence some approximations were made in this cases. The wind farms used were inbuilt in the software hence assumptions on wind speeds were made with analysis being done at maximum speeds. Some lines were also assumed to be of specific type since their information was missing.

5.2 RECOMMENDATIONS

In this project the specific technologies of wind and how they affect the small signal stability of the system was not investigated. The wind generators were not modeled in detail since analysis was done using the simplified DFIG in the software. Due to the latter the rotor side of the DFIG was directly connected to the grid hence the effect of the PWM and the series reactors was not investigated. The QR method was used in this analysis but the other methods have not been investigated to see how the system performs with them. This include the AESOP and Modified Arnoldi Method.

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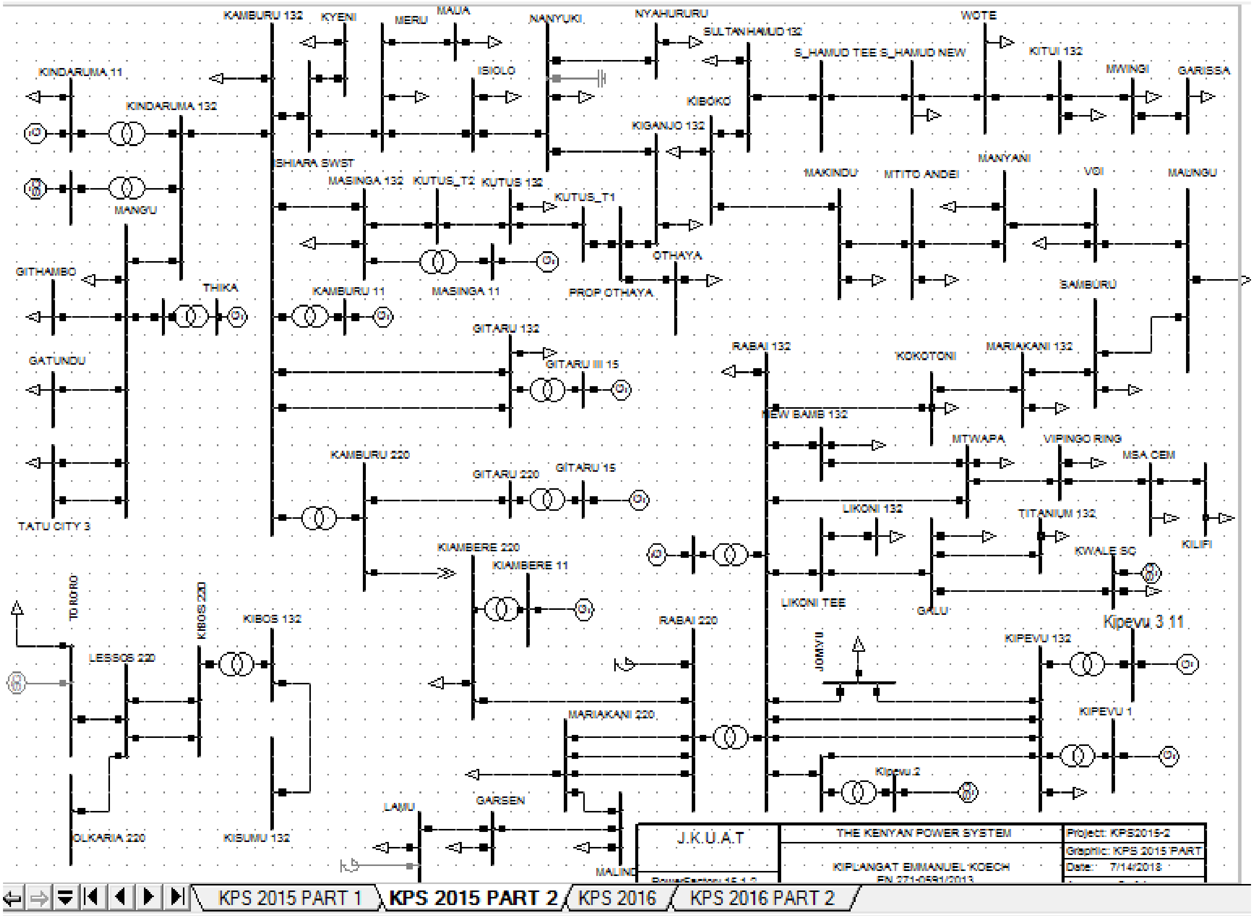
APPENDIX A-PROJECT TIME PLAN

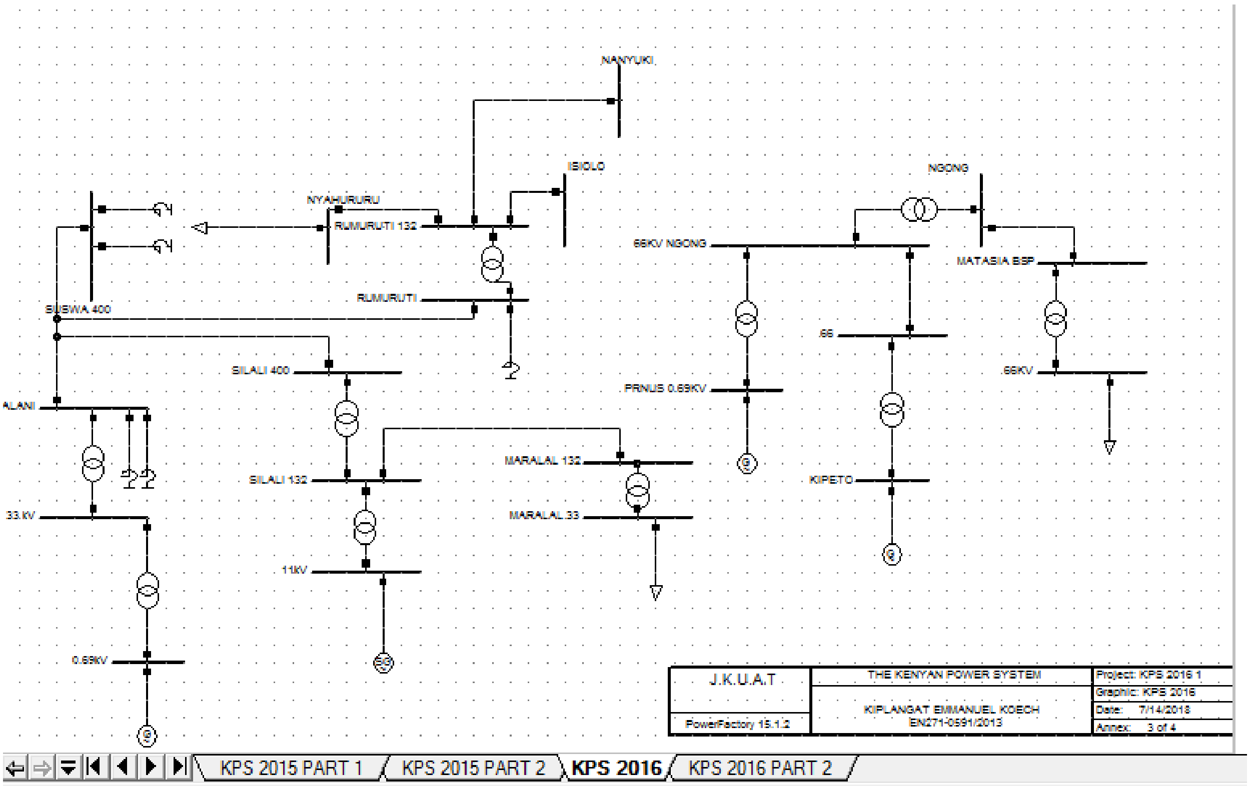
ACTIVITY		TIME FRAME								
		SEM 1					SEM 2			
		SEP	OCT	NOV	DEC		JAN	FEB	MAR	APR
1.	Project Research									
2.	Documentation									
3.	Abstract Submission & Approval									
4.	Proposal Writing									
5.	Mini Presentation									
6.	Data Collection									
7.	Simulation									
8.	Result Analysis									
9.	Final Presentation									

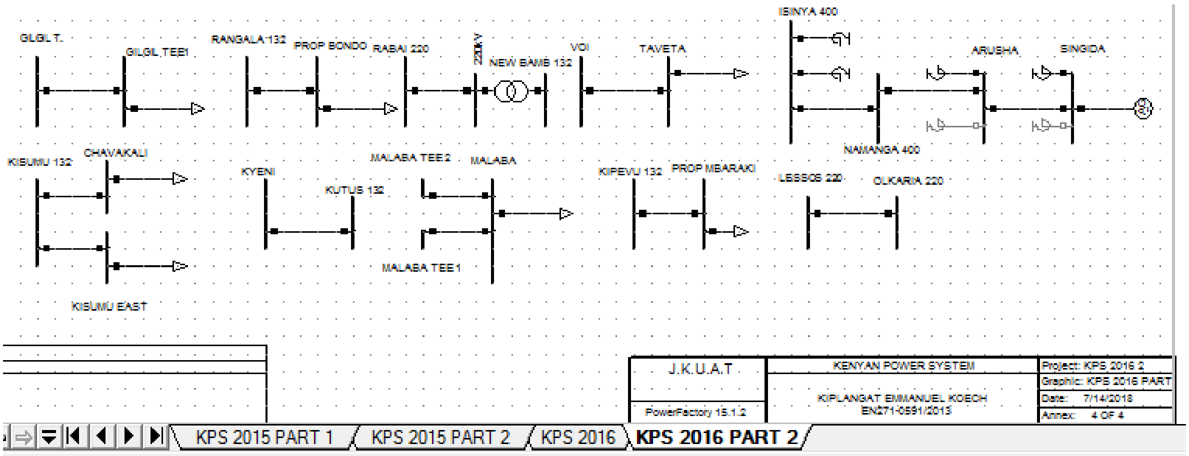
APPENDIX B- BUDGET

No	ACTIVITY	SUBTOTAL (Kshs)
1	Internet and Research	2000
2	Proposal printing, photocopying and binding	2000
3	Final project printing, photocopying and binding	3000
4	Miscellaneous expenses	2000
	TOTAL	9000

APPENDIX C- KENYAN POWER SYSTEM







Cynthia Cherema Mkabane. "Analysis of the Impact of Wind Power Generation on the Kenyan Power System's Small Signal Stability with Excitation Controllers for Conventional Generators." *IOSR Journal of Electrical and Electronics Engineering (IOSR-JEEE)*, 16(1), (2021): pp. 34-69.