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HVDC TRANSMISSION LINE WITH RENEWABLE ENERGY (WIND GENERATION)

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Abstract:

Wind power generation has become an established alternative power source. Especially large wind farms in remote or offshore locations are appearing strongly. Their grid connection demands new transmission solutions as distances increase. A newly proposed voltage source converter (VSC) based HVDC transmission system looks promising compared to conventional AC and DC transmission systems. In order to transmit massive amount of power generated by remotely located power plant, especially offshore wind farms, and to balance the intermittent nature of renewable energy sources, the need for a strong high voltage transmission grid is anticipated. Due to limitation in AC power transmission the most likable choice for such a grid isa high voltage DC (HVDC) grid. This project deals with prospects for HVDC transmission line with renewable energy.

Keywords:HVDC, renewable energy, voltage source converters (VSCs).

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INTRODUCTION

With the increase in size and complexity of Power Systems, the problems associated withlong AC bulk power transmission like reactive power support, system stability etc have alsoincreased. A search for more efficient mode of transmission has led to the development of DCtransmission. High voltage DCtransmissionisahighpower electronicstechnologyusedinelectricpower systems.It is an efficient, economic and flexible method to transmit largeamountsofelectricalpoweroverlongdistancesbyoverheadtransmissionlinesorunderground/submarine cables.Factorssuchas improvedtransientstability,dynamicdampingof electricalsystemoscillationsandpossibilityto interconnecttwosystemsatdifferentfrequencies influencetheselectionofDCtransmissionoverAC transmission.TheHVDCtransmissionbasedon voltagesourceconverters(VSC)isacomparatively newtechnology, where the valves are built by IGBTs (Insulated Gate Bipolar Transistors) and PWM(Pulse WidthModulation)isusedtocreatethedesired voltagewaveformComparedtoconventionalline commutatedHVDCsystems.Theprincipal characteristicsofVSCtransmissionare that itneedsno externalvoltagesourceforcommutation,itcanindependently control the reactive power flow at each AC network and reactive power control isindependent ofactivepowercontrol.ThesefeaturesmakeVSC transmissiontechnologyveryattractivefor connectingweakACsystems,islandnetworks,and renewable sourcesintoamain grid[15].

The DC transmission requires conversion of power at its two ends. Conversion from AC to DCwill take place at the sending end rectifier station and conversion back to AC will take place atthe receiving end inverter station. The converters are static, using high power voltage sourceconverter (VSC) and the physical process of conversion is such that the same station can switchfrom rectifier toinverter bysimplecontrolaction,thusfacilitatingthe power reversal.

1.2. PROBLEMSTATEMENT

Powercanbetransmittedusingeitheralternatingcurrent(AC)ordirectcurrent(DC).All modern power systems use AC to generate and deliver electricity to customers throughtransmissionlinesandthenthroughdistributionlinestowhereitisneeded.Today,quiteafew windfarmsinthepowerrangeofseveralhundredmegawattsareunderplanning [13].InRwanda, the development of wind energy has not yet been given priority, because of the lack ofdetailed and reliable information on wind regimesand potential exploitation sites. However,sincedemand for electricity isgrowing and wearetrying to diversify our energy sources asmuch as possible the Government is currently exploring our national generation potential andpossibilitiesofwindenergydevelopment.Thisisparticularlyinterestingforourruralelectrificationobjectives,becausewindenergycanexploitedanddistributedonthespot,wherever the wind regime allows, and could thus distribute power to areas far from our nationalgrid[12].

Promising siteshoweverareoften situatedin remoteplacesor offshore,dueto betterwindconditions.Thisleadstoincreasingdistancesbetweenwindfarmsandsuitablegridconnection points. Unfortunately, AC cables inherently generate reactive power that limits themaximum permissible AC cable length. DC cables however are not affected by cable chargingcurrents and may be as long as needed. Thus, for increasing distances, HVDC transmission linebased on VSCs, also called VSC transmission, is a feasible and reliable solution compared totraditional AC transmission [13]. Many of the planned offshore wind farms will have a largepower and a considerable cable length to a receiving grid. The use of AC cables will be limitedbythephysicalnatureofthecables.Thecablecanberegardedasadistributedcapacitorwhichin AC will need constant recharging and at a given length, the critical length; this rechargingcurrent will be equal to the rated current for the cable. As a result there will not be any powertransmission. The classical way to increase transmission capacity is to increase the voltage, butthe reactive power increases with the square of the voltage, so the result is that the critical lengthwill be reduced with increased voltage and power. It is likely thatthose problems will beovercome with time, but HVDCtransmissions havedemonstratedinpractice that bulkpowerathighvoltage overlongdistancesispossible. And despite the relative high costs ofthe converter terminals, the line costs are lower than for AC, because HVDC only need twoconductors[14].

The technology now exists to use DC for bulk power transmission. AC electricity isconverted to DC electricity for transmission and then converted back to ACelectricityfordistributiontocustomersontheACpowergrid.Aconverterstationateachendofthelineis required to convert power from AC to DC and back so we can use the power in our homes, farmsand businesses. High voltage direct current (HVDC) transmission is widely recognized as beingadvantageous for long distance, bulk-power delivery, asynchronous interconnections and longsubmarine cable crossings. HVDC lines and cables are less expensive and have lower losses thanthose for 3-phase AC transmission. Higher power transfers are possible over longer distanceswith fewer lines with HVDC transmission than with AC transmission. Higher power transfers arepossible without distance limitation to HVDC cables systems using fewer cables than with ACcable systems.

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when connected to a multi-area interconnected power system is also examined in this work. The objective is to reach tolerable frequency deviation. The realm of Load Frequency Control has seen several attempts over the years, with the earliest being the use of flywheel governors of synchronous machines to control the frequency of a power system. However, this technique was found to be insufficient due to the significant time constant involved. Primary control alone is not enough for frequency control, and as a result, secondary controls are required. Secondary control entails managing the loading of different plants. However, classical controllers such as Integral, Proportional Integral (PI), and Proportional Integral Derivative (PID) are slow and do not make a significant impact on the system's response. The work presented in this report aims to enhance load frequency control in multi-area power systems by utilizing different techniques such as PID and Fuzzy logic controllers. The study compares the performance of these controllers for a three-area power system with thrnon-reheat thermal power units. The results demonstrate significant changes, including a decrease in overshoot/undershoot, reduced settling time, and improved frequency deviation performance. In conclusion, the primary objectives of load frequency control are to guarantee reliable and stable power supply by keeping the frequency of the power system within acceptable limits. The use of advanced control techniques such as PID and Fuzzy logic controllers can significantly improve load frequency control in multi-area power systems. As such, these techniques are an important consideration for power system engineers and operators looking to enhance their load frequency control capabilities.

1. Regulation of frequency
2. Maintaining the pre-scheduled power flow through the tie lines.
3. Equitable load sharing among the generating plants.

CHAPTERII:LITERATUREREVIEW

2.1.Windpowergeneration

Wind is the movement of air in response to pressure differences within the atmosphere.Pressuredifferences exert aforcewhichcauses airmasses tomovefrom aregionofhighpressure to one of low pressure. That movement is wind. Such pressure differences are causedprimarily by differential heating effects of the sun on the surface of the earth. Thus wind energycan be considered to be a form of solar energy**.** Wind flows from regions of higher pressure toregions of lowerpressure. Thelarger theatmosphericpressuregradient, thehigher thewindspeed and thus, the greater the wind power that can be captured from the wind by means of windenergy-convertingmachinery[1].

Air masses move because of the different thermal conditions of these masses. The motion of airmassescanbeaglobalphenomenon(i.e.thejetstream)aswellasaregionalandlocalphenomenon. The regional phenomenon is determined by orographic conditions (e.g. the surfacestructure of thearea) aswell asbyglobal phenomena[2].

2.1.2. Windturbines

Wind turbines produce electricity by using the power of the wind to drive an electricalgenerator. Wind passes over the blades, generating lift and exerting a turning force. The rotatingblades turn a shaft inside the nacelle, which goes into a gearbox. The gearbox increases therotational speed to that which is appropriate for the generator, which uses magnetic fields toconvert the rotational energy into electrical energy. A wind turbine extracts kinetic energy fromthe swept areaof theblades.

$$P_{air} = \frac{1}{2}\rho A v^3$$

Eq.(2.1)

Where:

ρ =airdensity(approximately1.225 kg.m^{-3})

A = swept areaof rotor, m^2

v =upwindfreewindspeed,m.s^{-1}.

Althoughtheaboveequationgivesthepoweravailableinthewindthepowertransferredtothewindturbinerotorisreduced bythepower coefficient,Cp:

$$C_p = \frac{P_{windtubine}}{P_{air}} \qquad \text{Eq.(2.2)}$$

$$P_{windturbine} = C_p P_{air} = C_p \times \frac{1}{2}\rho A v^3 \qquad \text{Eq.(2.3)}$$

Amaximumvalueof$C$pisdefinedbytheBetzlimit,whichstatesthataturbinecanneverextractmorethan 59.3% ofthepowerfrom an air stream.

In reality, wind turbine rotors have maximum Cp values in the range 25–45%.Itisalsoconventional to defineatip-speed ratio,λ, as:

$$\lambda = \frac{\varpi R}{v} \qquad \text{Eq.(2.4)}$$

Where:

ω=rotationalspeedofrotor

R= radiustotip of rotor

v =upwindfreewindspeed,m.s^{-1}.

Thetip-speedratio,λ,andthepowercoefficient,Cp,aredimensionlessandsocanbeusedto describetheperformanceof anysizeof wind turbinerotor.

Thepoweroutputofawindturbineatvariouswindspeedsisconventionallydescribedbyitspowercurve. Thepowercurvegivesthesteady-stateelectricalpoweroutputasafunctionofthewindspeedatthe hub height andisgenerallymeasured using10 min averagedata.

Anexampleofapowercurveisgiveninfigure2.1.

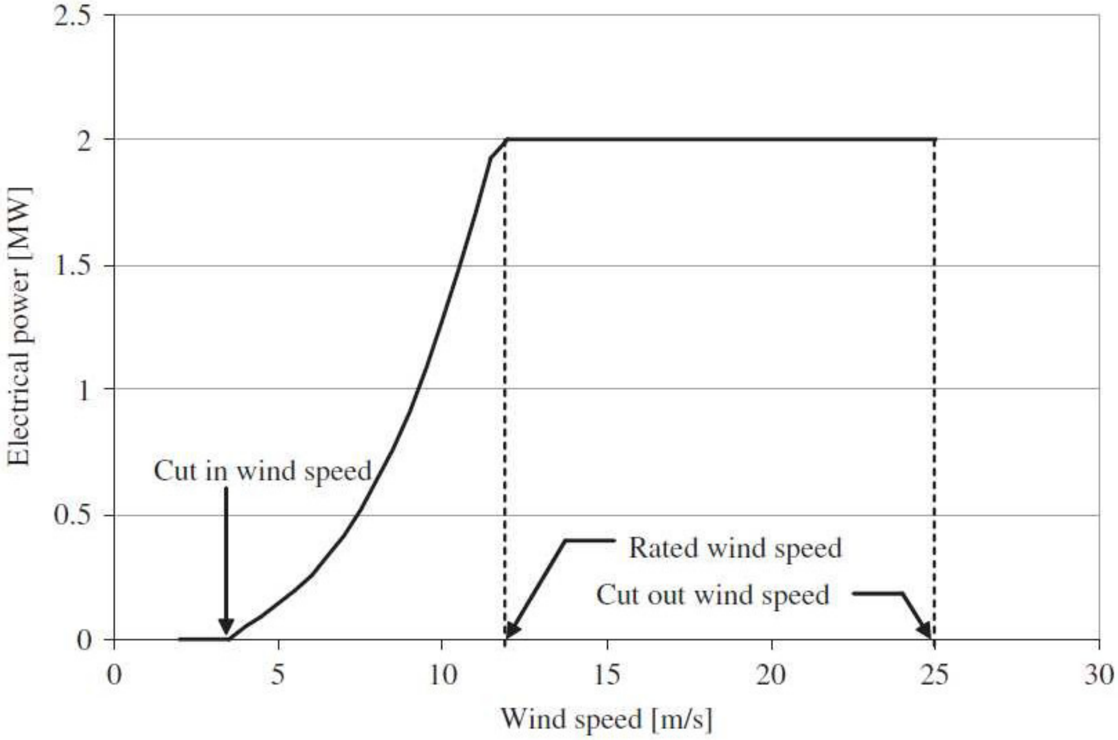

Figure 2.1: *Powercurve fora2MWwindturbine[3]*

The powercurvehasthreekeypointsonthevelocityscale:

- Cut-inwindspeed:Theminimumwindspeedatwhichthemachinewilldeliverusefulpower.
- Ratedwindspeed:Thewindspeedatwhichratedpowerisobtained(ratedpowerisgenerallythem aximumpower output oftheelectrical generator).
- Cut-outwindspeed:Themaximumwindspeedatwhichtheturbineisallowedtodeliverpower (usuallylimited byengineeringloadsand safetyconstraints).

Below the cut-in speed, of about 5ms^{-1}, the wind turbine remains shut down as the speed ofthe wind is too low for useful energy production. Then, once in operation, the power outputincreases following a broadly cubic relationship with wind speed (although modified by thevariationin*C*p) until rated wind speedisreached.

Above rated wind speed the aerodynamic rotor is arranged to limit the mechanical powerextracted from the wind and so reduce the mechanical loads on the drive train. Then at very highwindspeedstheturbineisshut down.

The choice of cut-in, rated and cut-out wind speed is made by the wind turbine designer who,for typical wind conditions, will try tobalance obtaining maximum energy extraction withcontrollingthemechanicalloads(and hence thecapitalcost) of the turbine.

- Cut-in wind speed:5m.s^{-1}, 0.6 Vm.
- Rated windspeed:12–14m.s^{-1},1.5–1.75Vm.
- Cut-out wind speed:25m.s^{-1}, 3Vm.

Powercurvesforexistingmachinescannormallybeobtainedfromtheturbinemanufacturer. They are found by field measurements, where an anemometer is placed on a mastreasonably close to the wind turbine, not on the turbine itself or to close to it, since the turbinemaycreateturbulenceandmakewind speedmeasurementsunreliable[3].

2.1.2.1. Horizontal-axiswindturbine

A horizontal-axis wind turbine is the most extensively used method for wind energyextraction [4]. The power rating varies from a few watts to megawatts on large grid-connectedwind turbines. In relation to the position of the rotor regarding the tower, the rotors are classifiedas leeward (rotor downstream the tower) or windward (rotorupstream the tower), this lastconfigurationbeingthemost widelyused.

These turbines consist of a rotor, a gearbox, and a generator. The group is completed withanacellethat includes the mechanisms,as well as a towerholding thewhole systemandhydraulic subsystems, electronic control devices, and electric infrastructure as it is shown inFig.2.2.

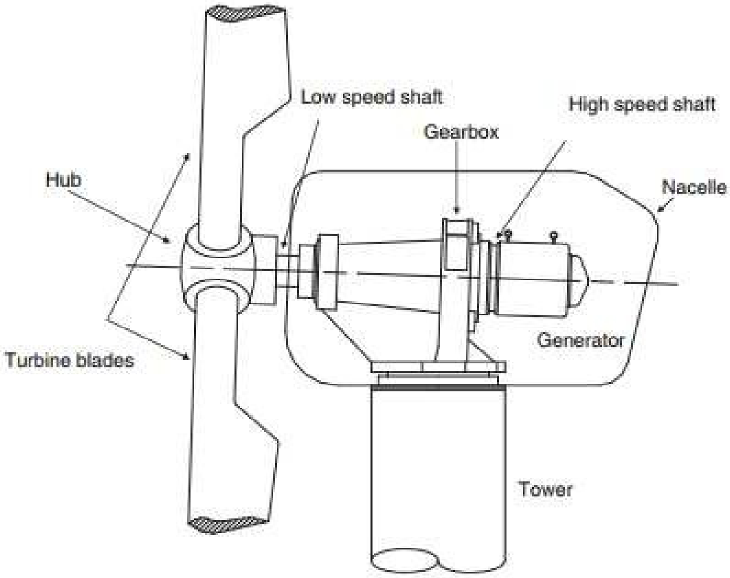

Figure2.2:*Viewofhorizontal-axiswindturbine[4]*

2.2. HVDCtransmission

The HVDC transmission system is a high power electronics technology used in electricpower systems mainly due to its capability of transmitting large amount of power over longdistances. Overhead lines or underground/submarine cables can be used as transmission path [9].The original motivation for the development of DC technology was transmission efficiency, asthe power loss of a DC line is lower than that of a corresponding AC line of the same powerrating. However, this required the use of HVDC and, therefore, the development of conversionswitches capable of withstanding high voltages. Substantial progress made in the ratings andreliabilityofthyristorvalveshasincreasedthecompetitivenessofHVDCschemes.DCtransmissionhas lower transmission losses andcost than equivalentAClines, butrequiresterminal equipment which adds to the cost and power losses. Thus traditionally, the DC optionhas been found economically viable only when the distance involved is long above 800km andthe amount of energyto betransferred large.

However, there are other factors that must be taken into consideration in the selection of anHVDC interconnection. An important factor in the economic comparison between AC and DCinterconnections is to determine whether synchronisation of the previously separate systems isfeasibleand economical.

Issuesaffectingthe feasibilityofthe interconnectioninclude:

- Whether the cable (in the case of a submarine interconnection) exceeds its capacity tocarry its own charging current (for sea cable interconnections with distances over 50 km,DCistheonlypractical solution);
- Whether the link is capable of maintaining synchronism of the two systems under all butextreme operatingconditions;
- Whetheritispracticaltoarrangegenerationandfrequencycontrolinthejointsystemona common basis;
- Whether the synchronous interconnection exceeds the fault levels of the interconnectedsystems.

All the above issues can be avoided when using the DC alternative, which offersthe followingadvantages:

- Lackoftechnical limitationsonthelengthof a submarinecable;
- Theinterconnectedsystemsdonotneedtooperateinsynchronism;
- Noincreaseintheshort-circuitcapacityis imposedontheACsystemsswitchgear
- Anypowertransfercanbesetindependentlyofimpedance,phaseangle,frequencyandvoltage;
- Thereceivingendofthelinkoperateslikeagenerator,i.e.itcansupplypoweraccordingtoanypre-specified criteria (load flow,frequencycontrol,voltageregulation,etc.);
- Theinterconnectioncanbeusedasafastsystem'sgenerationreservetobeableto providepowerimmediately;

TheDClinkcanbeoperatedtoimprovethestabilityofoneorbothACsystemsbymodulatingthe power in responsetothepower swing[10].

2.2.1. HVDCtechnologies

2.2.1.1. RectifyingandInvertingComponents

The conversion of AC current to DC is known as rectification and from DC to AC asinversion.Early systems usedmercury-arcrectifiers,whichprovedunreliable. Thethyristorvalve was first used in HVDC systems in the1960s. Modern converters/inverters perform eitherfunction. The thyristor is a solid-state semiconductor device similar to the diode but with an extracontrolterminalthatisusedtoswitchthedeviceonata particularinstantduringtheACcycle.

The insulated-gate bipolar transistor (IGBT) is now also used for rectification and inversion.BecausethevoltagesinHVDCsystems,whicharearound500kVinsomecases,exceedthebreak downvoltagesofthesemiconductordevices,HVDCconvertersarebuiltusinglargenumbersof semiconductorsin series.

Thelow-voltagecontrolcircuitsusedtoswitchthethyristorsonandoffneedtobeisolatedfromthe highvoltagespresentonthetransmissionlines.Thisisusuallydone optically.

In a hybrid control system, the low-voltage control electronics send light pulses alongoptical fibers to the high-side control electronics. A direct light triggering system instead useslight pulses from the control electronics to switch light-triggered thyristors (LTTs). A completeswitching element is commonly referred to as a "valve," irrespective of its construction. Manyconverter stations are set up in such a way that they can act as both rectifiers and inverters. At theAC end, a set of transformers, often three separate single-phase transformers, isolate the stationfrom the AC supply, provide a local earth, and provide the correct eventual DC voltage. Theoutput of these transformers is connected to a bridge rectifier of a number of converter valves.The basic configuration uses six valves, connecting each of the three phases to each of the twoDC rails. However, with a phase change only every sixty degrees, considerable harmonics

(ACsignature)remain on theDC rails.

An enhancement of this configuration uses twelve valves (often known as a twelve-pulsesystem). The AC is split into two separate three-phase supplies before transformation. TwelvevalvesconnecteachofthetwosetsofthreephasestothetwoDCrails,resultinginathirtydegree phase difference between each of the sets of three phases, which considerably reducesharmonics. In addition to the conversion transformers and valvesets,various passiveresistiveandreactivecomponentshelpeliminateharmonicson theDCrails.

2.2.1.2. ACNetworkInterconnections

UsingthyristortechnologyonlysynchronizedACnetworkscanbedirectlyinterconnected those with the same frequency and that are in phase. However, many areaswishingtosharepowermayhaveunsynchronizednetworks.DClinksallowsuchunsynchronizedsystemstobeinterconnected.IGBT-basedHVDCsystemsfurtheraddthepossibilityof controllingACvoltageandreactivepower flow.

Power generation systems such as photovoltaic cells generate direct current. Basic wind andwaterturbinesgeneratealternatingcurrentatafrequencythatdependsonthespeedofthe driving fluid. In the first instance, high-voltage direct current is generated, which may be useddirectly for power transmission. The second instance represents an unsynchronized AC system,which may benefit from a DC interconnect. Either situation might benefit from the use of HVDCtransmissiondirectly fromthegenerating plant,particularly ifplantsarelocatedinremotelocations.

In general,anHVDCpowerlineinterconnectstwoACregionsofthepowergrid. ConverterstationsconvertingbetweenACandDCpowerareexpensive,however,andaconsiderable cost in power transmission. Above a certain break-even distance (about 31 miles forsubmarinecablesandperhaps375to500milesforoverheadcables),thelowercost oftheHVDCcableoutweighsthecostoftheconverterelectronics.Inaddition,asnotedabove,conversionelectronicspermitmanagingthepowergridbycontrollingthemagnitudeanddirectionofpowerflow.Thus, HVDClinkscanincreasethestabilityinthe transmissiongrid.

2.2.1.3. PolarityandEarthReturn

In a DC system, a constant potential difference exists between two rails. In a commonconfiguration,oneoftherailsisconnectedtotheEarth(earthed),establishingitatEarthpotential. Theotherrail,atapotentialhighaboveorbelowground,isconnectedtoatransmission line. The earthed rail at the source end of a DC circuit may or may not be connectedto the corresponding rail at the terminal end of the circuit by means of a second transmission lineconductor. A monopole transmission line refers to a transmission line without an accompanyingearthedconductor.

To complete the circuit, an earth current (known as a telluric current) flows between the earthedelectrodes at the two stations. Such a large earth current may have undesirable effects in manylocations,renderingmonopolesystemsunsuitable.Issuessurroundingearth-returncurrentsinclude:

- Extended metal objects, such as pipelines, may have a considerable current induced inthem, resulting in corrosion unless cathodic protection is employed; sparking and shockproblemscan occurif earthingisincomplete.
- If either of the earthed electrodes is near the sea, currents could flow through salt waterandcauseemissionoftoxicchlorinegasandmakethewaterneartheelectrodealkaline.
- The presence of a considerableearth current can generate an extensive DC magneticfield,whichcould affectnavigational compasses.

These effects may be mitigated to some degree by laying a second conductor at ground potentialalongside themonopolefor carryingtheearth current.

Bipolar transmission offers an alternative to monopolar transmission. In bipolar transmission, apair of conductors is used, each at a high potential with respect to ground, in opposite polarity.Bipolar transmission is more expensive than monopolar transmission because of the cost of thesecond line. While monopolar transmission with an earth return uses two conductors, the earthreturn,because it isat earthpotential,requiresminimalinsulation, reducingcost.

Thereareanumberofadvantagestobipolartransmissionthatcanmakeitanattractive option:

- Undernormalload,negligibleearth-currentflowsoccur,minimizingenvironmentalimpacts.
- Ifafaultdevelopsinoneline,currentcancontinuetoflowusingtheearthasareturnpath, operatingin monopolarmode.
- Atagivenpowerlevel,bipolarlinescarryonlyhalfthecurrentofmonopolarlines,asvoltage iseffectivelydoubled;thussmaller conductorscan beused.

2.2.1.4. PolarityandCoronaDischarge

Coronadischargeinvolvesthecreationofionsintheairaroundtransmissionlineconductors by the presence of a strong electromagnetic field. Corona discharge can cause powerloss,createaudibleandradio-frequencyinterference,generateozone,and leadto arcing.

While AC coronas are in the form of oscillating particles, coronas from HVDC lines produce aconstant "wind" of ions. With monopolar transmission, the choice of polarity of the energizedconductordeterminesthe polarityof the ionsmakingupthecorona discharge.

Negative coronas generate considerably more ozone than positive coronas, and generate it fartherdownwind of the power line. Thus, the use of a positive voltage reduces the ozone impacts ofmonopole HVDC power lines. On the other hand, as negative ions are used in home air ionizersand have purported health benefits, particularly in being responsible for condensing particulatematter,theuse of negativepotentialonmonopole linesmaybe considered.

2.2.1.5. TransmissionLinesandCables

For bulk power transmission over land, overhead transmission lines are most frequentlyused. These lines most often employ a bipolar configuration using two conductors with oppositepolarity.HVDCcablesarealsonormallyusedforsubmarinepowertransmission.Themost common types of cables are the solid and the oil-filled types. Solid cables have insulation thatconsists of paper tapes impregnated with high-viscosity oil. No length limitation exists for thistype,anddesignsareavailabletodayfordepthsofabout1,100yards.Oil-filledcableiscompletelyfilledwithlow-viscosityoilthatismaintainedunderpressure.Themaximumpractical length for this type of cable is limited to around 37 miles, due to the limitations of oilsystems.

Recent developments have produced a new type of HVDC cable, which is available for HVDCunderground or submarine power transmissions. This cable is made using extruded polyethyleneinsulation,andisusedinvoltagesourcedconverter (VSC)-basedHVDCsystems[5].

2.2.2. Thecomponents ofanHVDCtransmissionsystem

To assist the designers of transmission systems, the components that comprise the HVDCsystem, and the options available in these components, are presented. The three main elements ofanHVDCsystemare:theconverterstationatthetransmissionandreceivingends,thetransmissionmedium, andtheelectrodes.

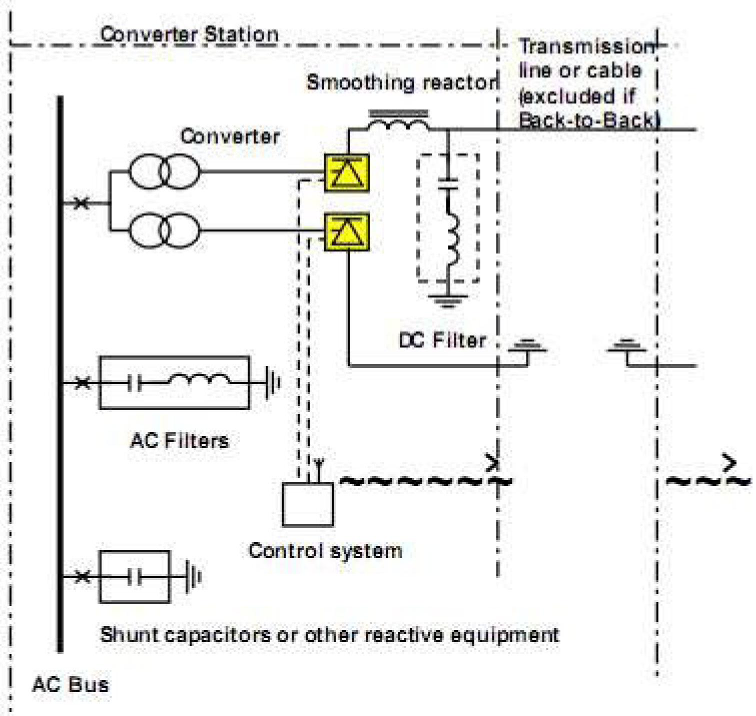

Fig2.3:*Theconverterstation[7]*

1.3. Objectives OBJECTIVESOFTHESTUDY

1.3.1. MAINOBJECTIVE

Themainobjectiveofthisstudy,“HVDCtransmissionlinewithrenewableenergy”istoestablishasystematic approachforimprovingenergytransmissionwithminimumlosses.

1.3.2. SPECIFICOBJECTIVES

Specific objectivesofthe studyare:

- Toknowhowelectricalenergycanbe transmittedatlongdistance withlowlosses.
- Toknowhowenergycan efficientlybetransmittedin Rwanda at longdistances.
- TohaveknowledgeonHVDCtransmissionlinewithrenewableenergy.

1.4. HYPOTHESIS

Thisworkfocusesonthefollowinghypothesis:“HVDCtransmissionlinewithrenewableenergy and will help to make a reliable transmission line, analysis and also make a good plan forthefuture”.

1.5. SCOPEOFTHERESEACH

Duetothelimitationoftimeandbudget,the studywillfocusonHVDCtransmissionlinewith renewable energy and see how HVDC transmission reduces the power losses in powersystem.

1.6. INTERRESTOFTHERESEACH

Once electric energy is transmitted by HVDC transmission, weget more advantages includingthe following:

- Transmissionofbigamountofpoweratlongdistanceswithlowerwastes.
- PowertransmissionandstabilizationbetweenunsynchronizedACdistributionsystems.
- Connectiongeneratingplantsremote frompowergrid.
- Connectionbetweencountrieswithdifferentcurrentfrequency/voltage.

1.7. METHODOLOGY

Methodology is a system of ways of doing, teaching or studying something. Also it is a meansnecessary by which onecan obtain the expected results within theframework of ascientificwork.That whythemethodologyofthisresearch will bein the followingway:

- Documentation
- SimulationwithSoftware:
- Matlab/Simulink

1.8. PROJECTLAYOUT

Thisresearchprojectwillbe organizedasfollow:

- ChapterI:Generalintroduction
- ChapterII:Theoreticalconceptsandliterature review
- ChapterIII:VSC-HVDCtransmissionlinewithrenewableenergy
- ChapterIV:Simulationandinterpretationofresults
- ChapterV:Conclusionandrecommendations
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- Appendix

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III.

response. The proportional component works on the difference between the desired value (set point) and the process variable (measured value) which is referred to as the Error term. The proportional gain (Kp) provides the ratio of output response to the error signal. The integral component produces an output by summing the error term over certain interval. The effect of the integral control is to drive the Steady-State error to zero. The derivative control affects the steady-state error of a system provided it deviates with time. The derivative part of the controller has no effect on the process if the steady-state error of a system has a time derivative of zero (i.e., if the steady-state error of the system is constant with respect to time). While the steady-state error evolves over time, a torque is created in such a way that it reduces the error magnitude in proportion to the rate of change of the error. [3]. The output of PID controller in time domain form is given by:

$$u(t) = Ke(t) + Ki\int_0^t e(t)dt + Kd\frac{de(t)}{dt} \qquad (5.1)$$

1. *Fuzzy Logic Controller*

Fuzzy Logic Controller is a system which is used to control the working of a physical system with the help of fuzzy logic [11]. The concept of fuzziness was founded by Prof. L.A. Zadeh in 1965. The generalized structure of a fuzzy logic controller (FLC), consists of three basic modules viz. the Fuzzification unit which is the input terminal. the inference engine built on the fuzzy logic control rule base, and the Defuzzification unit which is the output terminal, as shown in Figure 5.1

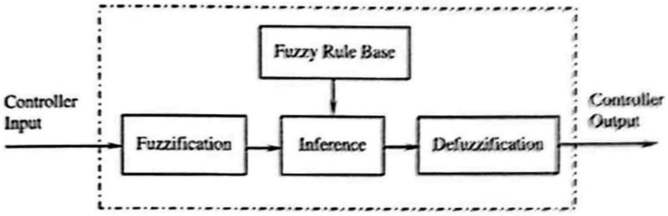


Figure 5.1: General structure of a fuzzy logic controller.

Fuzzification: Converts crisp values to fuzzy values using knowledge base. Knowledge base uses membership functions to define the input variables into fuzzy variables [15].

Fuzzy Inference System: It consists of fuzzy rule base which takes fuzzy variables as inputs and generate possible fuzzy outputs, given as input to defzuzifier.

• Defuzzification: The defuzzification module functions as a transformer to co- vert the controller outputs, which are produced by the control rule base in fuzzy terms, back to the crisp values that the plant can accept. It connects the control rule base and the physical plant to be controlled.

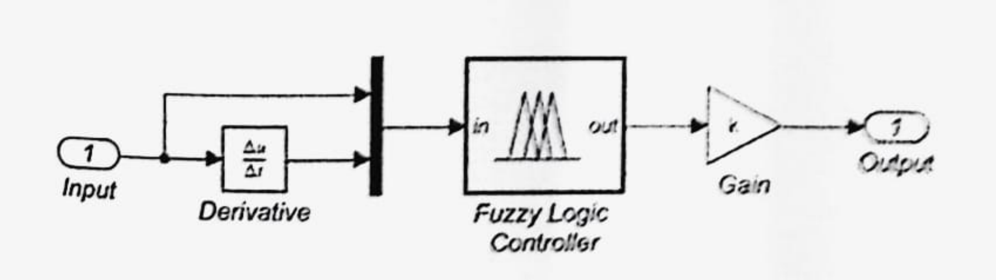


Figure 5.2: Fuzzy logic controller Simulink model

Figure 5.2 represents the Simulink model used to have the optimized value of PID controller. There are two inputs to the fuzzy block, one is the frequency deviation and other input is the rate of change of frequency. The corresponding member function plots of each input and the output are shown is Figures 5.3, 5.4 and 5.5

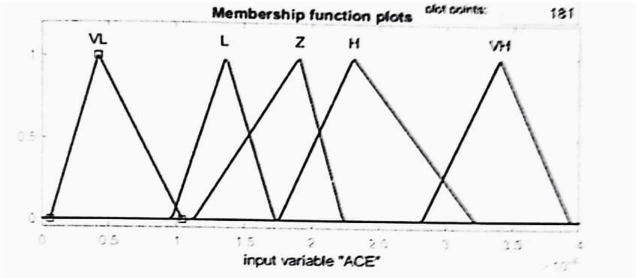


Figure 5.3: Fuzzy logic controller input 1.

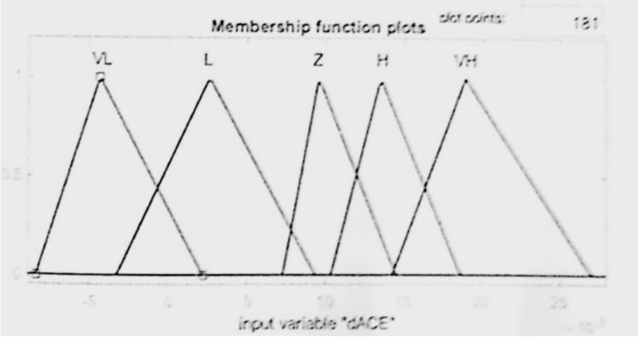


Figure 5.4: Fuzzy logic controller input 2.

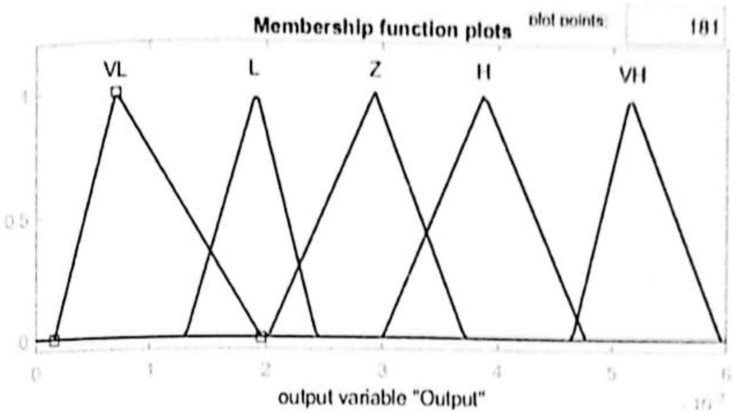


Figure 5.5: Fuzzy logic controller output.

Artificial Neural Network (ANN) tuned PID Controller

An artificial neural network (ANN) is a computational system that analyses and processes data in the same manner that the human brain does. However ANN is mostly required to perform one specific task at a one time. The ANN consists of input layer of source neuron, hidden layer and an output layer. The propagation of input signals proceeds layer by layer in a forward manner. The most common type of learning is error correction learning (ECL) in which the difference between the two outputs, known as the error, is calculated when the output of an ANN is compared to the expected output or target output value. Using the back propagation technique, at each training cycle the ECL algorithm intends to limit the error signal. The process continues until the desired threshold is achieved.

The input to the ANN is taken from the input terminal of PID controller and the weighted sum of the inputs is computed which is then passed to the activation function [14],[16] to get the desired output and is represented in the equation (5.2) and (5.3).

$$U_k = \sum_{j=1}^{p} wkjxj \quad (5.2)$$

where xj = Input Signal, Uk = Linear combiner Output, wkj = Synaptic Weights, Threshold, f = Activation function, Yk = Output signal of the neuron.

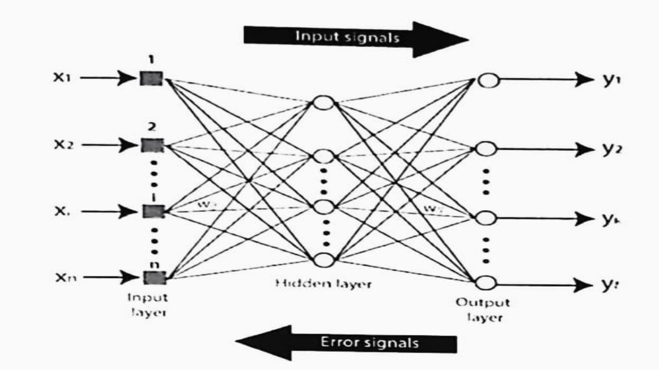


Figure 5.6: Architecture of radial basis function neural network

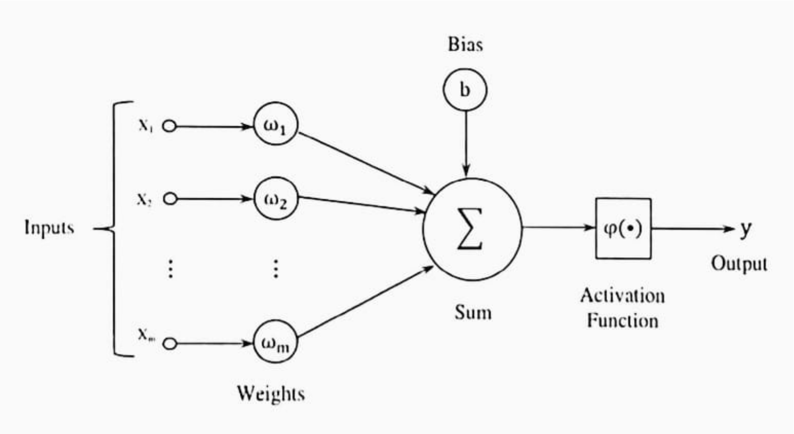


Figure 5.7: Typical artificial neural network.

The figure 5.6 and 5.7 represent the architecture of radial basis function neural network and the typical artificial neural network respectively.

Genetic Algorithm tuned PID Controller

Genetic algorithm is a search tool for finding the precise or nearly perfect resolution to optimization issues. The genetic algorithm is a type of evolutionary computation which employs mechanisms including inheritance, mutation, selection, and crossover that are based on the principles of evolutionary biology. Genetic Algorithm technique starts by selecting a population which refers to a set of solutions at an instantof searching process and on individual which refers to a single solution. Thus going from multiple solutions to a single solution which is optimal can be seen as going from population to individual. Each individual is characterized by a Set of chromosomes (which are binary coded or real coded in GA) and then Selection, Crossover, Mutation and Inversion is done to get the optimal solution [8], [13]. The flow chart of genetic algorithm is shown in Figure 5.8.

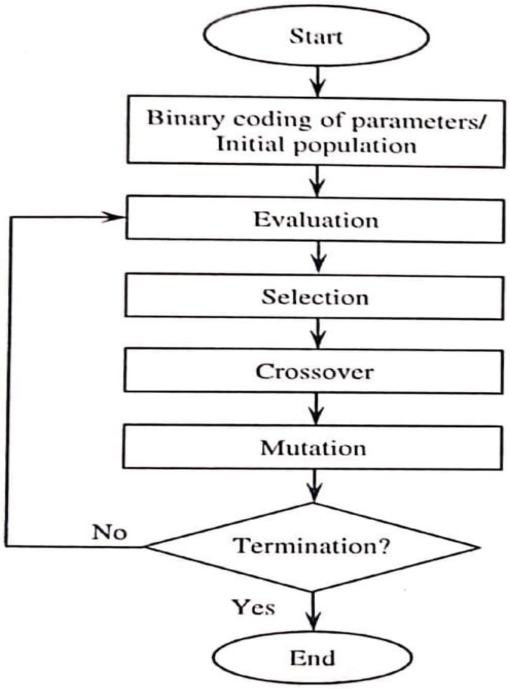


Figure 5.8: Flow chart for Genetic Algorithm.

Step-1: Formation of Chromosome- Coding and Decoding: The real system parameters are encoded into a binary string of the problem parameters in GA. Each string symbolizes a chromosome, with each chromosome describing one possible solution to the problem. A population of randomly generated elements is created after formation of encoded structure of chromosome [15]
Step-2: Genetic Operation-Crossover: Crossover or recombination operates on selected elements to build the new elements by combining the existing ones. The two elements swap their structures and results in creation of a new element containing the characteristics of their parents. During the crossover there is exchange of genetic information while production of new element. The process may be follow Single-Point, Multi-Point or Random-Point crossover.
Step-3: Genetic Operation-Mutation: Mutation averts the premature stopping of the algorithm in a local solution. Mutation works by changing a random bit value from 0 to 1 in a selected string having a low probability. During the process of reproduction and crossover there may be loss of some potentially useful genetic material, mutation provides a guarantee to recover the good genetic material.
Step-4: Termination of the GA: Genetic Algorithm is a probabilistic approach method, so it is difficult to specify any formal convergence criteria. The process terminates once the population has converged i.e., it does not produce any new element which is significantly different from the earlier generation. If the solution is not satisfactory the GA is restarted and a fresh search is initiated [11],[17].
For best performance, the integral time multiplied absolute error (ITAE) [7] is taken as the most common fitness function. In mathematical form, the error is expressed as:

$$ITAE = \int_0^t |f| \times t \times dt \qquad (5.4)$$

For a three control area power system, the ITAE criterion comprises the deviation
in frequency and the tie line power.

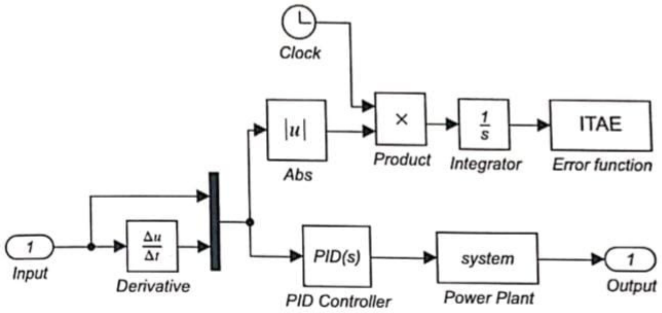


Figure 5.9: Genetic Algorithm tuned PID controller.

Figure 5.9 represents the simulink model of the genetic algorithm tuned PID Controller used for optimization of the PID controller with fitness function as ITAE given by (5.4)

Wind Energy Conversion System. (WECS)

With the increase in the consumption of energy and due to depletion of available conventional energy resources it has become imperative to harness the renewable sources of energy one among which is Wind Energy. As per the precursory statistics published by WWEA (World Wind Energy Association), the capacity of wind turbines has reached a record of 975GW in 2021 in the world market. The increased demand for electricity mandates the use of renewable energy sources such as the Wind Energy

Conversion System (WECS), which can be interfaced with the existing grid. Increased wind energy integration necessitated an intensive consideration of frequency regulation in the power system. The possibility of DFIG-based wind turbines to contribute to frequency support when integrated to a multi-area interconnected power system is also examined in this work. The objective is to reach tolerable frequency deviation. One of the possibilities is to operate the wind energy conversion system below the maximum available power as per the MPPT curve so as to keep some margin (5-10%) as reserve capacity required for frequency control. Secondly the inertia emulation by way of releasing the stored kinetic energy in the rotating mass of wind turbines also helps in mitigating the frequency deviation but for a shorter time. By that time the rest of the conventional system should respond to supply the additional power and if not possible then load shedding should be resorted to for avoiding the system collapse [15].

Wind Turbine

A wind turbine is a machinery that utilizes the kinetic energy from the wind to generate the electricity. A wind turbine blades revolve between 10 and 20 times per minute at a fixed or variable speed, depending on the technology employed. In order to maximize efficiency, the rotor speed varies in accordance to the wind speed. Wind energy is converted into electricity by a wind turbine using the aerodynamic force of the rotor blades [17].

Mechanical Drive Train Model

The rotating masses, gearbox, hub, connecting shafts, and generator inertia make up the drive train system of a wind turbine. A two-mass model of the drive train is depicted in Figure 6.1 and reflects the combined impact of the wind turbine and the generator. The turbine shaft and generator rotor shaft are flexibly joined via a gearbox and coupling [18]

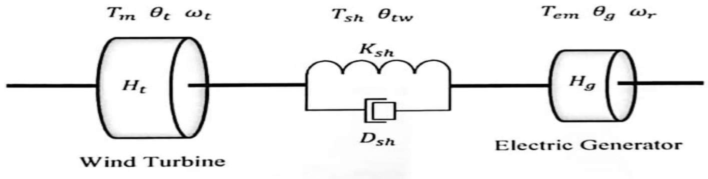


Figure 6.1: Drive train model Configuration

The equations governing the two-mass drive train model are given by:

$$2H_t \frac{dw_t}{dt} = T_m - T_{sh} \quad (6.1)$$

$$\frac{d\theta_{tw}}{dt} = w_t - w_r = w_t - (1 - s_r) \quad (6.2)$$

The power extracted from wind through a turbine is given by:

$$T_m = \frac{1}{2}\pi\rho C_p \delta R^3 V^3 \quad (6.3)$$

$$P_o = \frac{1}{2}\rho C_p A V^3 \quad (6.4)$$

The quantities wind speed, air density and the radius swept by the blades are not controllable. The performance coefficient Cp is the only variable which can be modified to maximize the energy production from the wind and the maximum turbine efficiency as determined by Betz's law is 59.3% due to geometry limits. Equation 6.9 represents the Tip Speed Ratio (7) which is equal to the ratio of turbine tip speed and the wind speed. WPG features differ greatly from those of traditional generators. Each WPG generates power differently depending on the local wind speed. As a result, accurate modeling of the WPG's operational state is necessary for the evaluation of this behavior. Using a plot of output power versus wind speed, a WTG "speed-power" curve is depicted in Figure 6.3 and can be used to estimate the power output of the machine.

Wind Turbine Power Curve

The power curve of wind turbine is a plot indicating the electrical power output as a function of wind speed as shown in Figure 6.2. For various wind speeds the power curve involves three specific points viz:

- Cut-in wind speed: The minimum wind speed at which the turbine begins to produce the output power.
- Rated wind speed: The speed of wind at which the turbine la capable of delivering the rated power.
- Cut-out wind speed: The highest wind speed that a turbine is permitted to use to generate the power.

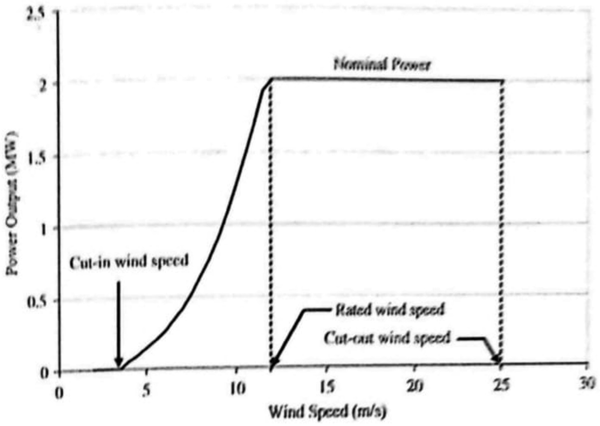


Figure 6.2: Wind turbine power curve for a 2MW machine.

When the wind speed is below the cut-in nearly 5m/s there is no power output. Above the cut-in wind speed, the power output increases with the wind speed in accordance to equation 6.7 till it gives the rated output and is limited via control action to reduce the mechanical load on the drive train. At the cut-out wind speed (approximately 25m/s), the rotor is then stalled, or permitted to hover at low speed for safety concern [18].

Variable Speed Wind Turbine

Depending upon the wind speed, the tip speed ratio for a particular wind turbine speed varies widely. The wind turbine power output can be maximized by running it at its maximum performance coefficient and can be achieved by modifying the tor speed to correspond to changes in wind speed. This is possible by adopting the variable speed DFIG technology. Numerous types of wind turbine technology have been created over the evolution of wind power and DFIG type WT is themost common form deployed in wind farms which have the advantages of minimal investment and flexible control [16]

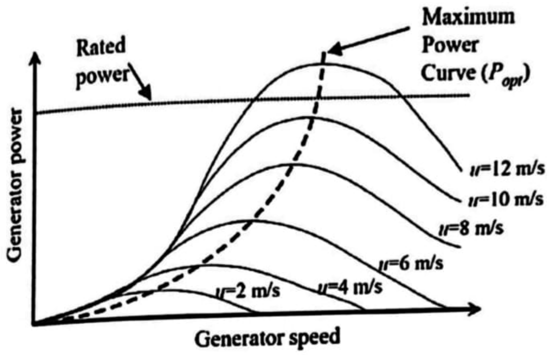


Figure 6.3: Power output of generator at various wind speeds

Doubly Fed Induction Generator

The classical configuration of a DFIG wind turbine is represented in Figure 6.4. DFIG type wind turbine generators are the most popular technology and have gained recognition across the globe. The converter and rotor winding are connected to a wond-rotor induction generator by slip rings. By applying an adjustable voltage to the rotor at the desired slip frequency, variable-speed operation is made possible. A DFIG's stator is often directly linked to the power grid, and regulated voltage source converters feed the rotor winding power back from the stator terminals.

Figure 6.4: DFIG wind turbine model.

A DFIG based wind turbine can transfer the electrical power to the network both through the converters and the stator of generator. In super-synchronous mode the rotor delivers the power to the network through the converters while in sub-synchronous mode the rotor absorbs power back from the network via the converters. Since the converters only provide the DFIG exciting current, their capacity is only about 20-25 percent of what the device is rated for. Further the feedback converters are built on insulated gate bipolar transistors (IGBT), the DFIG can be controlled in a variety of ways, and the controllers have a big -impact on the dynamic properties of the WT with DFIG. The active and reactive power flow to the grid from the stator of the DFIG directly controlled by the rotor side converter. The magnitude, phase angle and frequency injected into the rotor is controlled by voltage source controller. The three phase voltages at grid frequency is controlled in magnitude and phase by grid side converter which also regulates the DC link voltage and provides the grid with additional reactive power support.

RESULTS AND DISCUSSION

CHAPTERIV:SIMULATIONANDINTERPRETATIONOFRESULTS

A.

4.1. Introduction

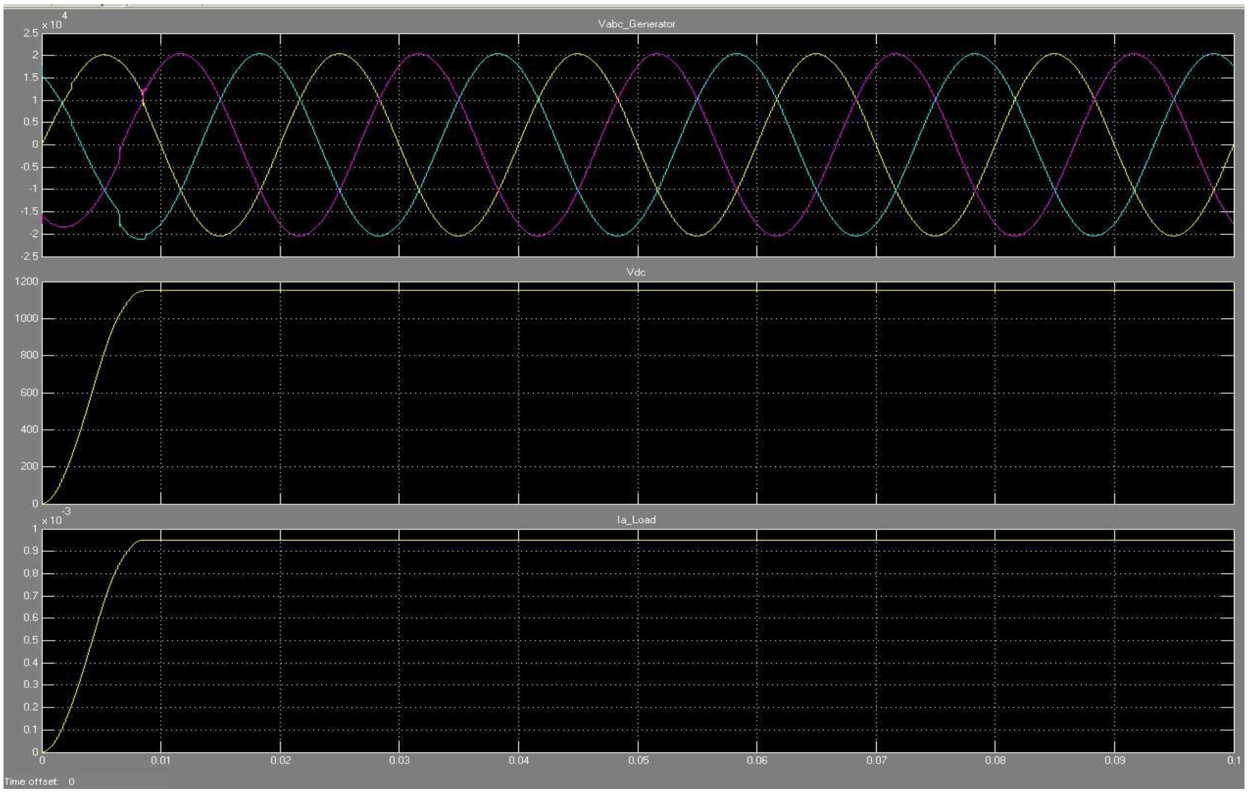
B. VoltageSourceConverterHVDC(VSC-HVDC)isaflexibleandefficientDCtransmissionanddistributiontechnologyusingfull-controlledswitchingdevicesandhighfrequency PWM modulation technology, and it is very promising in the fields such as the gridconnectionofrenewableenergy,theislandpowersupply,theurbanpowersupply,theinterconnectio n among synchronous grids and multi-terminal DC transmission. The converter istypically controlled through sinusoidal PWM. The rectifier is made by three arms diodes and theinverter is made by IGBT/diodes. The IGBT operates as a switch by operating between the activeregion and its cutoff region. The VSC based HVDC is forced commutated via control circuitsdriven by pulse-width modulation (PWM). In this chapter, the results forHVDC transmissionline usingvoltagesource converters,networkhasbeen shownbyusingMatlab Simulink.

4.2. Simulationstudyandinterpretation

C.

4.2.1. SimulationofAC-DCconverter

D. Thefigure,belowisthesimulationoffigure3.4whichisSimulinkmodelofdioderectifier.



E.

F.

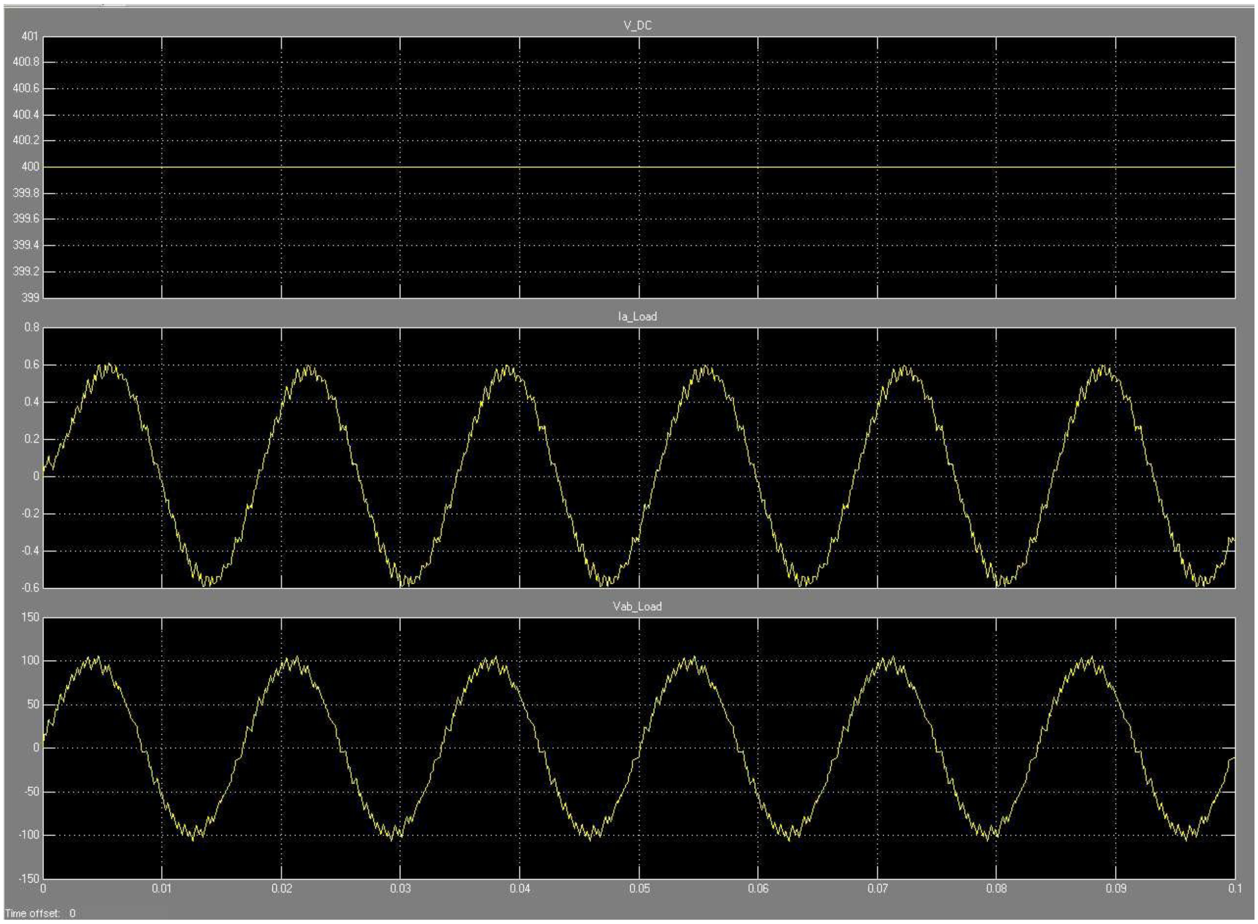
Fig4.1:*Phase togroudvoltagesofgenetatorterminals“Vabc”,voltage fromrectifier”Vdc” andcurrentfolowingin phase a”Ia”of seriesRLCloadwaveforms*

G.

H. As it is shown on fig 4.1, the output voltage of rectifier is DC voltage which is the input voltageto the inverter.As it is shown also on current folowing in phase a of series RLC load waveformthisshowsthat thecurrent isDC current.

4.2.2. SimulationofDC-ACconverter

I. Thefigure,belowisthesimulationoffigure3.7whichisDC-ACconvertermodelinSimulink.



J.

K.

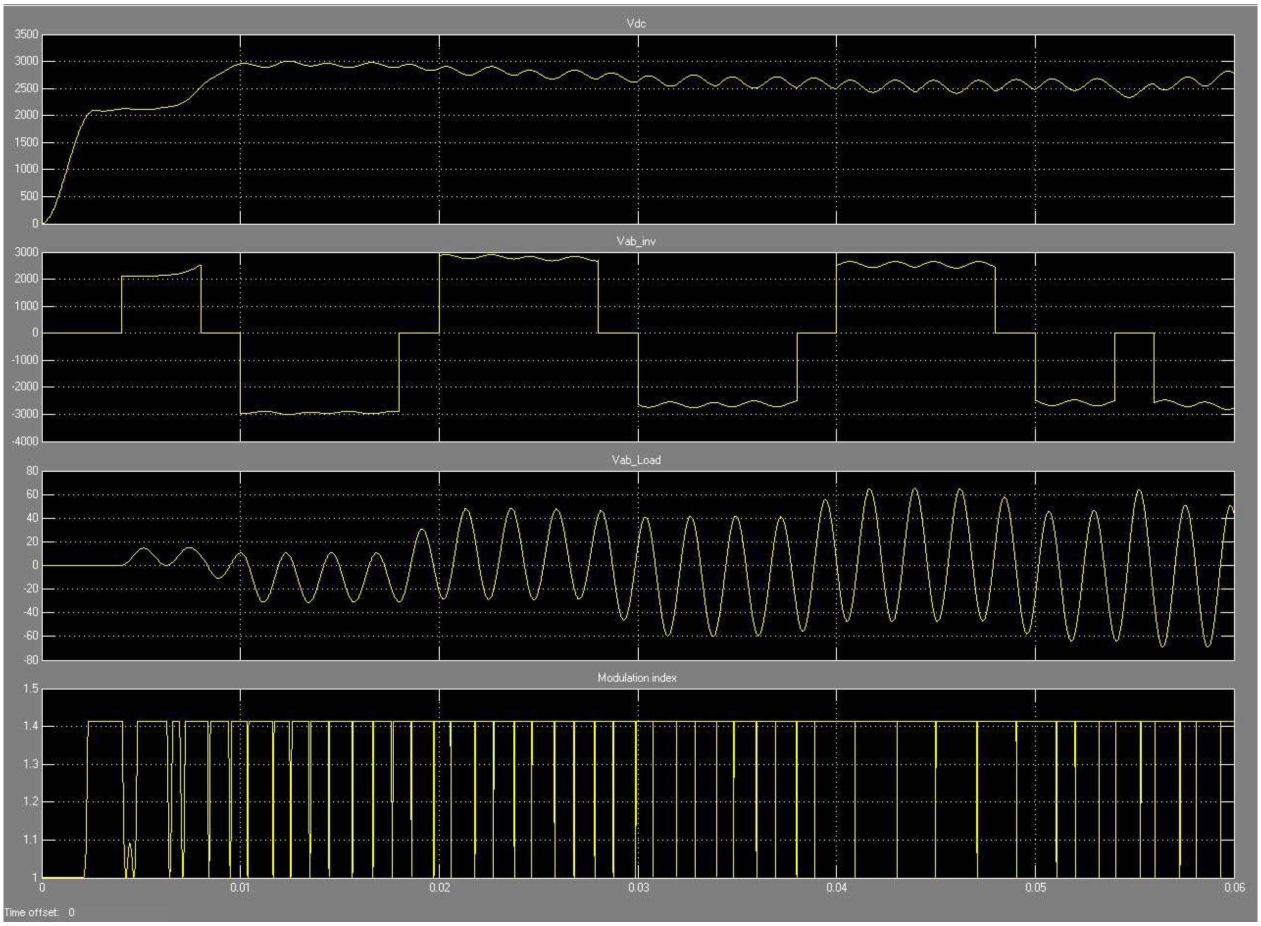
Fig 4.2: *DC voltage source "Vdc", current following in phase a of three-phase parallel RLCload "Ia" and the phase to phase voltage between phase a and b of three-phase parallel RLCload"Vab''waveforms*

L. As shown on the fig 4.2, the inverter power block changes DC voltage into a sinusoidal ACvoltage with constant amplitude and stable frequency. Again the current also is a sinusoidal ACcurrent.

4.2.3. SimulationresultsofWind-TurbineAsynchronousGeneratorwithAC-DC-ACconverter

4.2.3.1. Simulation of voltage of rectifier, phase to phase voltage between phase A and B tothe output of inverter, phase to phase voltage between phase A and B of the load2 andmodulationindex

M. The figure below is the simulation of figure3.8 which is Wind-Turbine AsynchronousGenerator with AC-DC-AC converter. That figure is for figure3.8, which is simulation of voltageof rectifier “V_dc”, phase to phase voltage between phase A and B “Vab” to the output ofinverter, phase to phase voltage between phase A and B “Vab_load”of load2 and modulationindex.



N.

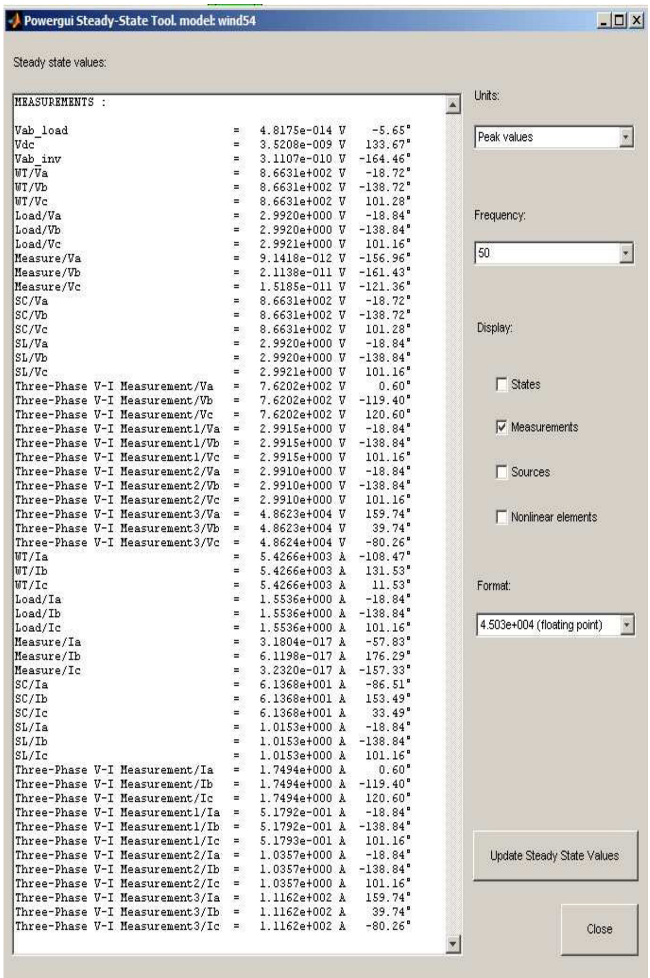
O.

Fig 4.3: *simulation of voltage of rectifier”Vdc”, phase to phase voltage between phase A and Bto the output of inverter “Vab_inv”, phase to phase voltage between phase A and B of the load2“Vab_Load2”and modulation index*

P. As it is shown on the figure 4.3, the AC voltage was converted into DC voltage by using arectifier and then returns into AC voltage by using an inverter. The inverter output voltage iscontrolled by controlling the inverter amplitude modulation index. To process the maximumpower by an inverter, the amplitude modulation index, M_a should be set at maximum valuewithout producing the unwanted harmonics distortion. The value of M_a is set less than 1 and inthe rangeof0.95 to produce thehighest ACoutput Voltage.

4.2.3.2. Measurementsshownbysimulation

Q. Thevaluesmesuredare shownhere below:



Steady state values:

```
MEASUREMENTS :

Vab_load                           =   4.8175e-014 V    -5.65°
Vdc                                =   3.5208e-009 V   133.67°
Vab_inv                            =   3.1107e-010 V  -164.46°
WT/Va                              =   8.6631e+002 V   -18.72°
WT/Vb                              =   8.6631e+002 V  -138.72°
WT/Vc                              =   8.6631e+002 V   101.28°
Load/Va                            =   2.9920e+000 V   -18.84°
Load/Vb                            =   2.9920e+000 V  -138.84°
Load/Vc                            =   2.9921e+000 V   101.16°
Measure/Va                         =   9.1418e-012 V  -156.96°
Measure/Vb                         =   2.1138e-011 V  -161.43°
Measure/Vc                         =   1.5185e-011 V  -121.36°
SC/Va                              =   8.6631e+002 V   -18.72°
SC/Vb                              =   8.6631e+002 V  -138.72°
SC/Vc                              =   8.6631e+002 V   101.28°
SL/Va                              =   2.9920e+000 V   -18.84°
SL/Vb                              =   2.9920e+000 V  -138.84°
SL/Vc                              =   2.9921e+000 V   101.16°
Three-Phase V-I Measurement/Va     =   7.6202e+002 V     0.60°
Three-Phase V-I Measurement/Vb     =   7.6202e+002 V  -119.40°
Three-Phase V-I Measurement/Vc     =   7.6202e+002 V   120.60°
Three-Phase V-I Measurement1/Va    =   2.9915e+000 V   -18.84°
Three-Phase V-I Measurement1/Vb    =   2.9915e+000 V  -138.84°
Three-Phase V-I Measurement1/Vc    =   2.9915e+000 V   101.16°
Three-Phase V-I Measurement2/Va    =   2.9910e+000 V   -18.84°
Three-Phase V-I Measurement2/Vb    =   2.9910e+000 V  -138.84°
Three-Phase V-I Measurement2/Vc    =   2.9910e+000 V   101.16°
Three-Phase V-I Measurement3/Va    =   4.8623e+004 V   159.74°
Three-Phase V-I Measurement3/Vb    =   4.8623e+004 V    39.74°
Three-Phase V-I Measurement3/Vc    =   4.8624e+004 V   -80.26°
WT/Ia                              =   5.4266e+003 A  -108.47°
WT/Ib                              =   5.4266e+003 A   131.53°
WT/Ic                              =   5.4266e+003 A    11.53°
Load/Ia                            =   1.5536e+000 A   -18.84°
Load/Ib                            =   1.5536e+000 A  -138.84°
Load/Ic                            =   1.5536e+000 A   101.16°
Measure/Ia                         =   3.1804e-017 A   -57.83°
Measure/Ib                         =   6.1198e-017 A   176.29°
Measure/Ic                         =   3.2320e-017 A  -157.33°
SC/Ia                              =   6.1368e+001 A   -86.51°
SC/Ib                              =   6.1368e+001 A   153.49°
SC/Ic                              =   6.1368e+001 A    33.49°
SL/Ia                              =   1.0153e+000 A   -18.84°
SL/Ib                              =   1.0153e+000 A  -138.84°
SL/Ic                              =   1.0153e+000 A   101.16°
Three-Phase V-I Measurement/Ia     =   1.7494e+000 A     0.60°
Three-Phase V-I Measurement/Ib     =   1.7494e+000 A  -119.40°
Three-Phase V-I Measurement/Ic     =   1.7494e+000 A   120.60°
Three-Phase V-I Measurement1/Ia    =   5.1792e-001 A   -18.84°
Three-Phase V-I Measurement1/Ib    =   5.1792e-001 A  -138.84°
Three-Phase V-I Measurement1/Ic    =   5.1793e-001 A   101.16°
Three-Phase V-I Measurement2/Ia    =   1.0357e+000 A   -18.84°
Three-Phase V-I Measurement2/Ib    =   1.0357e+000 A  -138.84°
Three-Phase V-I Measurement2/Ic    =   1.0357e+000 A   101.16°
Three-Phase V-I Measurement3/Ia    =   1.1162e+002 A   159.74°
Three-Phase V-I Measurement3/Ib    =   1.1162e+002 A    39.74°
Three-Phase V-I Measurement3/Ic    =   1.1162e+002 A   -80.26°
```

Units: Peak values

Frequency: 50

Display:

☐ States

☑ Measurements

☐ Sources

☐ Nonlinear elements

Format: 4.503e+004 (floating point)

R. *Fig4.4:Measurementsshownbysimulation*

CONCLUSION

The load frequency control performance analysis is done in this work for them non-reheat power system. The effect of different artificial intelligence based PID con trollers is tested to investigate the performance of the power system. The result of the different controllers used have been compared as shown in Table 7.2. It is noticed that a better Load Frequency Control performance has been achieved using Artificial Intelligence based controllers in comparison to the conventional PID controller The number of oscillations has reduced substantially. Significant improvement in overshoot, undershoot and lower settling time is attained using Genetic Algorithm and Neural Network based PID controller, but GA based PID controller has been found more efficient controller having better overall system response with overshoot(0.0054%), undershoot (0.09%) and lower settling time of 0.54 seconds Further, with the increased demand for electricity mandates the use of renewable energy sources such as the Wind Energy Conversion System (WECS), have beeninterfaced with the existing grid. With the increase in global capacity of wind turbines which has reached a record of 975GW in 2021 and its integration with the existing system, it has necessitated an intensive consideration of frequency regulation in the power system. The possibility of DFIG- based wind turbines to contribute in frequency regulation when connected to a multi-area interconnected power systemhas been simulated. For a three area interconnected power system, the A used controller and simultaneous integration of DP16 based wind turbine area has been examined by way of inertia emulation pose to send kinetic energy by way of reduction in speed to regulate the frequency. It is seen that there is increased system response by way of reduction in be settling time.

Future Scope

The future scope of this work is as follows

1. New AI based controllers including hybrid algorithms can be applied for further improved and optimized response,
2. Integration of other renewable energy sources for mitigating the frequency deviation.
3. Impact of RES on equivalent inertia of the power system along with incorporation of special protection schemes.
4. Incorporating Intelligent load shedding scheme to avoid blackout in extra cases.

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