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Enhanced Wind Turbine Emulation through Vector Controlled Induction Motor Drive Empowered by Fuzzy Logic Controller

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ABSTRACT

Thisprojectintroducesaninnovativeapproachtowindturbineemulationbyemployinga Vector ControlledInductionMotorDrive(VCIMD)systemenhancedwith a Fuzzy Logic Controller (FLC). Theproposedsystemaimstooptimizetheperformance and efficiency of wind energyconversion.Throughvectorcontrol,theinductionmotordriveispreciselymanipulatedto emulatethedynamiccharacteristics of wind turbines, allowing fora more accurate representation of real-worldconditions. The integration of a Fuzzy LogicController adds a layer of intelligence to thesystem, enabling adaptive control strategiestoenhanceoverallstabilityandresponse.ThissynergisticcombinationofVCIMDand FLCnotonlyfacilitatesefficientpowergenerationbutalsoensuresrobustperformance under varying wind conditions.The project explores the dynamic inter play between the se technologies, presenting acomprehensivesolutionforwindturbineemulationthatholdsgreatpromiseforadvancingre new able energy research and development. The findings from this study contribute to the on going efforts in optimizing wind energy systems forincreased reliabilityand sustainability.

Keywords:

One Degree of Freedom (1-DOF) and TwoDegree Of Freedom (2-DOF) control, windturbine, emulation, pre-filters, Fuzzy LogicController

Introduction

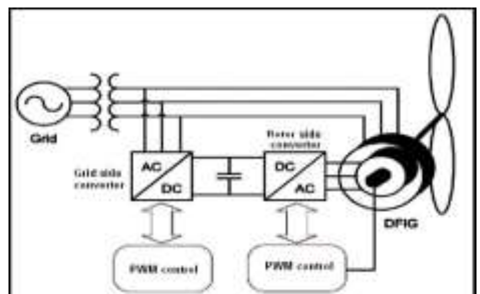
Theinstalledwindpowercapacityhas been increasing. In 2015, the installedcapacity was predicted to reach 765 GW by2020 [1]; this has already reached 597 GWby2019[4].Majorfactorsforthisimpressive growth rate are advancements inoffshore wind technology, reduction in costofsystemcomponents,andgovernmentincentive programs [1]. Compared to a set ofsmallwindturbines,asinglelargewindturbineofthesamecumulativecapacityreducesinstallation andmaintenancecosts[1], [5]. Hence, ratings of individual windturbines have been increasing over the years;12 MW wind turbine with a diameter of 105m is among the largest currently ; 20 MWturbines with diameters exceeding 150 m arebeingpredictedinnearfuture[1].

Generationofelectricpowerfromwind in an efficient and reliable manner andincompliancewithmoderngridcodesdemandsresearchanddevelopmentofadvancedcontrolstrategies.Windenergyindustryisalsoprovidingmassivejobopportunities,leadingtosignificanteconomic development [1]. It is, therefore,imperative that the operation and control ofwind energy conversion systems be taught toengineers to develop skilled man power forthefield.Hence,tofacilitateresearchand education,itisessentialtodevelopcontrolled test beds that can emulate large-inertiawindturbines(WT)usingsmall-inertia electric machines, without relying onthe availabiltyofwind.

A wind turbine can be emulated either usingaDCmotordrive[7]orasquirrelcageinduction motor (SCIM) drive [8]. AlthoughDC motors are favorable from the standpointof control, they are bulky and expensive, andrequirefrequentmaintenanceduetocommutators and brushes [9]. The generatorcouldbedoubly-fedinductiongenerator(DFIG),permanentmagnetsynchronousgenerator (PMSG), orany othergenerator,as deployed in the field. Around 50% of thegeneratorsemployedinwindenergyconversion systems are DFIGs [1], [2]. Themain factor for theirlarge marketshare isthe reduced power rating of the convertersemployed for their control, which results inreduced cost and improved efficiency [1]–[3]. Hence, the present workconsiders DFIGas the generator and and SCIM as the primemover,inthetestbed,forvalidatingtheproposed controllers. However, the proposedcontrol structures and controller designs areapplicabletoanytypeofmotorandgenerator.

Dynamic emulation of linear and non-linearmechanical loads using two coupled SCIMsis explainedin [10]. Themethod describedin[8]estimatesthewindturbinetorquebased on wind speed and pitch angle, anddirectly feeds it as torque reference to theSCIM torque controller. Since the inertia ofthemotorusedforemulationisusuallymuchlessthanthatoftheWT,inertiacompensation is inevitable for precise windturbineemulation.Mostoftheemulationschemes, reported in literature, account forthe inertia difference by setting the torquereference through an additional loop termedinertiacompensationloop[7],[11]–[14].

Thetorquecompensationterm,produced by this loop, depends on combinedinertia andviscous friction of themotor-generator system (MGS); this also involvesdifferentiationofspeed,makingtheloophighlysensitivetonoise.Thedigitalimplementation of this emulation approachleads to stability issues, as reported in detailin. To mitigate this instability, a state spacebasedapproachhasbeenreportedin[13],thoughthishasnotbeenvalidatedexperimentally.Ahigherorderfilterisemployedin[14]tofilter thedeviatingcomponentofaccelerationresponse.Twoinertia compensation schemes described inignoretheviscousfrictiontermsofthe WTGSandemulator.Whilethisenablessimple proportional controllerdesign [15],steady state errors can beobservedin theexperimentalresultsinboththeschemes.The existing wind turbine emulation schemesuffersfromstabilityandparametersensitivityissues.Itbecomesunstableonemulating a WTGS having an inertia morethantwicethatoftheMGS.Thepresentworkfirstproposes1-DOFcontrolforinertiaemulationwhichisshowntobestableexperimentallyandalsohasmuchlower parameter sensitivity than the existingmethod. However, it requires feed-forwardcompensation of estimated generator torquetocancelthedisturbancetorque,owingto its



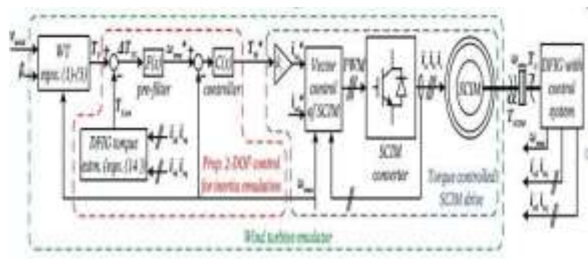
WindEnergyConversionSystempoordisturbancerejection capability.

The proposed 2-DOF control has very gooddisturbancerejectionandinsensitivitytoplantparameterinaccuracies.Twocontroldesignsforthe2-DOFstructureareexplainedindetail.Thispaper isanimprovedversionoftheconferencepaper, whereone2-DOFcontroldesignwasdescribed with simulation and experiments.Thisworkadditionallydiscusses1 -DOFcontrol andanother2-DOF control designmethod, along with extensive simulation andexperimentalresults,comparingalltheproposedmethods.

Literaturesurvey

T.HardyandW.Jewell;Inordertoprovidea testing environment for generator controlstrategies,awindturbineemulatorwasdeveloped. First, a mathematical model wasdevelopedforthea1.5MWwindturbinegenerator based on available modeling data.Using this data a function relating maximumpower output and wind speed was developedalong with a one-mass model of the turbine.The model was implemented in a softwaresimulation along with controllers for a DCmotoractingasthewindturbineandadynamometeracting as the generator. ThesoftwaresimulationwasimplementedinLabVIEW and read in a data file containinghigh sample rate (20 Hz) wind speed data,calculated the optimal power from that windspeed, and generated control signals for theDCmotoranddynamometer.Theeffectiveness of the controller was found bycalculatingthemean-squareerrorbetweentheoptimalpowercalculatedbythesimulationturbinemodelandtheactual powerproducedbytheDCmotor/dynamometer combination. Two 800second wind speed data files were used astestinputsfortheemulator:alow-speedlow-frequency wind profile and a turbulentorvarying-speedwindprofile.

Proposedcircuitdiagram



Block diagram of wind turbine emulatorwiththeproposed2-DOFcontrolfor inertiaemulator

WindTurbines

Clearly, wind energy is high on thegovernmentalandinstitutionalagenda.However, there are some stumblingblocksin the way of its widespread. Wind turbinescome with different topologies, architecturesanddesignfeatures.Someoptions windturbine topologiesareasfollows,

- Rotor axis orientation: horizontalorvertical;
- Rotorposition:upwindordownwindoftower ;
- Rotorspeed:fixedor variable;
- Hub:rigid,teetering,gimbaledorhingedblades;

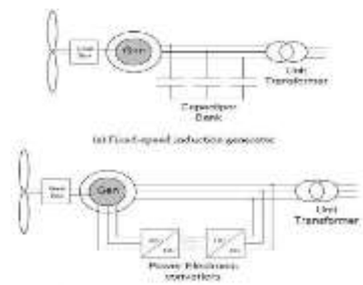
- Rigidity:stillorflexible;
- Numberofblades:one,two,threeorevenmore ;
- Power control: stall, pitch, yaw oraerodynamic surfaces;
- Yawcontrol:activeorfree.

Schematic of a wind turbine generation system

Windturbinesincludecriticalmechanicalcomponentssuchasturbineblades and rotors, drive train and generators.They costmore than 30%of total capitalexpenditureforoffshorewindproject.In general,windturbinesareintendedforrelatively inaccessiblesitesplacingsomeconstraints on the designsin a number ofways.Foroffshoreenvironments,thesitemay berealisticallyaccessedformaintenance once per year. As a result, faulttoleranceofthewindturbineisofimportanceforwindfarmdevelopment.

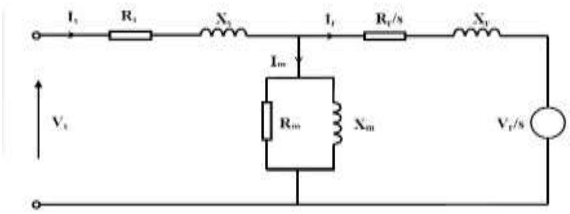
DFIG

TherotoroftheDFIGismechanically connected to the wind turbinethroughadrivetrainsystem,whichmaycontainhighandlowspeedshafts,bearings and a gearbox. The rotor is fed by the bi-directionalvoltage-sourceconverters.Thereby, the speed and torque of the DFIGcan be regulated by controlling the rotor sideconverter(RSC).AnotherfeatureisthatDFIGscanoperatebothsub-synchronousandsuper-synchronousconditions.Thestatoralwaystransferspowertothegridwhiletherotorcanhandlepowerinbothdirections.



The latter is due to the fact that the PWMconverters are capable of supplying voltageand current at different phase angles. In sub-synchronousoperation,therotorsideconverter acts as an inverter and the grid-side converter (GSC) as a rectifier. In thiscase, active power is flowingfrom the gridtotherotor.Undersuper-synchronouscondition,the

RSC operates as a rectifier and the GSC asan inverter. Consequently, active power isflowingfrom the stator as well as the rotortothepowergrid.



Per-phase equivalent circuit of the DFIG.

ToanalyzetheDFIG’sperformance,italwaysneedstoadoptitsper-phaseequivalent circuit. From this figure, it can beseenthattheDFIG differsfromthe

conventional induction machine in the rotorcircuit where a voltage source is added toinjectvoltageintotherotorcircuit.Theactual d-q control of the DFIG is similar tothemagnitudeandphasecontroloftheinjected voltage in the circuit.Thematrixformofthe equationforthiscircuitis,

$$\begin{bmatrix} V_s \\ V_r / s \end{bmatrix} = \begin{bmatrix} R_s + j(X_s + X_m) & -jX_m \\ -jX_m & R_r / s + j(X_r \end{bmatrix}$$

TheinputpowerPincanbesummarized from the output power Pout andthetotallossPloss.Thelatterincludesstator conductor lossPcu1, rotor conductorlossPcu2,corelossPcore,wind-ageand frictionlossesPwfandstrayloadlossPstray. Among these losses, Pcu1is assumedtovary with thesquareof thestatorcurrentIs while Pcu2 varies with the square of therotor current Ir. The stray load loss could besplitintotwoparts:thefundamentalcomponent Pfun occurring at the stator sideandPharatthe rotor side.Thus PfunisproportionaltoIs2whilePharisproportionaltoIr2.Thetotallossisthengivenby,

$$P_{loss} = 3I_s^{\,2}(R_s + R_{fun}) + 3I_r^{\,2}(R_r{}' + R_{har}) + P_{core} + P_{wf}$$

TheefficiencyoftheDFIGis

$$\eta = \frac{P_{out}}{P_{in}} = \frac{3V_{out}\cos\varphi_r}{6I_s(R_s + R_{fun} + R_r{}' + R_{har}) + 3V_{out}\cos\varphi_r}$$

The efficiency can be expressed as afunctionoftheloadcurrentIsandthisfunctionis continuousandmonotonic.Consequently, the maximum efficiency canbefoundwhen,

$$\frac{\partial \eta}{\partial I_s} = 0$$

Thatis,theconditionofmaximumefficiencyfor DFIGsis,

$$P_{core} + P_{wf} = P_{cu1} + P_{cu2} + P_{stray}$$

InordertooptimizetheDFIGmachinedesign,its lossesandefficiencyneedtoderivenumerically orexperimentally.Anadditionalrefinementparameteristhemachine's operational point. The conditionofthemaximumefficiencyoccurrenceindicates:when theloaddependentlossesequalisetheload-invariantlosses,themachine efficiency peaks. In the design andoperation of DFIGs, it is beneficial to matchthe generator's characteristics with the site-specificwindspeedbymovingthismaximum efficiency point close to the ratedoroperationalload.Forcontrolpurposes,the DFIG mathematical model is based onthesynchronousreferenceframeasfollows,

$$\begin{cases} v_{sd} = r_s i_{sd} + \dfrac{d\psi_{sd}}{dt} - \omega_s \psi_{sq} \\ v_{sq} = r_s i_{sq} + \dfrac{d\psi_{sq}}{dt} + \omega_s \psi_{sd} \end{cases}$$

$$\begin{cases} v_{rd} = r_r i_{rd} + \dfrac{d\psi_{rd}}{dt} - (\omega_s - \omega_r)\psi_{rq} \\ v_{rq} = r_r i_{rq} + \dfrac{d\psi_{rq}}{dt} + (\omega_s - \omega_r)\psi_{rd} \end{cases}$$

$$\begin{cases} \psi_{sd} = (L_{ls} + L_m) i_{sd} + L_m i_{rd} \\ \psi_{sq} = (L_{ls} + L_m) i_{sq} + L_m i_{rq} \end{cases}$$

$$\begin{cases} \psi_{rd} = (L_{lr} + L_m) i_{rd} + L_m i_{sd} \\ \psi_{rq} = (L_{lr} + L_m) i_{rq} + L_m i_{sq} \end{cases}$$

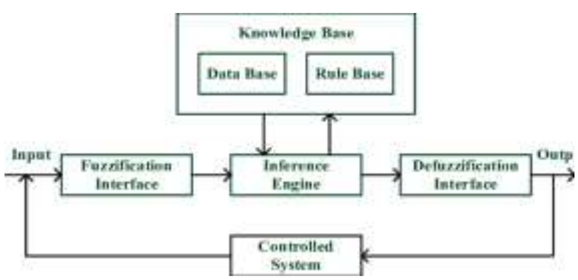
Wherersandrrarethestatorandrotorresistances in Ω, Lls and Llr are the statorand rotor leakageinductancesin H, Lm isthe magnetizing inductance in H. ωs is thesynchronous electrical speed in rad/sec. ωr isthe rotor electrical speed of the DFIG and itsrelation with rotor mechanical speed ωgisωr=Pωg,wherePispolepairs.Theelectromagnetic torqueisgivenby,

$$T_e = \frac{3}{2} P L_m (i_{sq} i_{rd} - i_{sd} i_{rq})$$

In DFIGs, active power is used to evaluatethepoweroutputandreactivepowerisr esponsible for its electrical behavior in thepowernetwork.TheDFIGrequiressomeam ounts of reactive power toestablishitsmagneticfield.Incaseofgrid-connectedsystems, the generator obtains the reactivepower from the grid itself. In case of isolatedsystemoperation,thereactivepowerne edsto be provided by external sources such ascapacitorsorbatteries.

ModelingOfFuzzyLogicBasedIn vectorControlOfInductionGeneratorInWecs

Thesimulinkblockgraphoffluffybasedaberran tvectorcontrolofacceptancegeneratorinwin denergychangeframework. The principal parts of the aboveSimulinkblockoutlineareVariablespee dand Variable Pitch Wind turbine, Enlistmentgenerator ,Aberrant vector regulator, Park'schangeandtwolevelcurrentcontrolledv oltagesourceinverter.

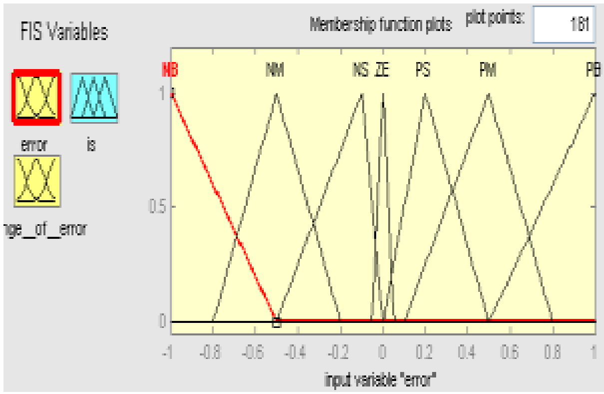


Fuzzylogiccontroller

FLCis a type of control system that usesfuzzylogictoreasonaboutuncertainorimpr ecise information. It is a type of expertsystemthatcanbeusedtocontrolawide rangeofsystems,includingindustrialprocesses ,consumerelectronics,androbotics.Fuzzylogi cisatypeofmathematical logic that allows for reasoningwith imprecise or uncertain information. Itwas introduced in the 1960s by LotfiZadeh,whorecognizedthatmanyreal-worldproblemsinvolveimpreciseanduncertai ninformation that cannot be easily modeledusing traditional logic. Fuzzy logic is basedon the concept of fuzzy sets, which are setsthat allow for partial membership, or degreesofmembership,ratherthanthetradition albinarysetmembership.

FLCsareparticularlyusefulinsystemswhere the inputs and outputs are not well-defined or are subject to change over time.FLCs can reason about the uncertainty andimprecision in the input signals and producecontrol actions thatare robust and adaptivetochangesintheenvironment.FLCsar eoftenusedincontrolsystemswheretraditional controlmethodsaredifficulttoimplementdueto thecomplexityofthesystem or the lack of precise mathematicalmodels.

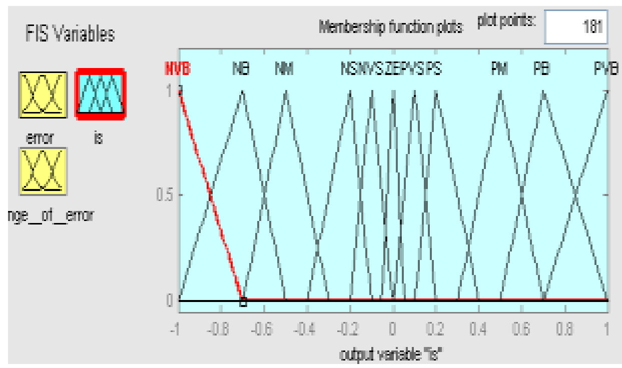
One of the key advantages of FLCs is thattheycanbeeasilyimplementedusingsoftwa reorhardware,makingthemapopularchoicefor real-worldcontrol applications.FLCshavebeen successfullyappliedinawiderangeofapplications,including automotive engineering, robotics,consumerelectronics,medicalequipment,trafficcontrol,andfinancialmodeling.



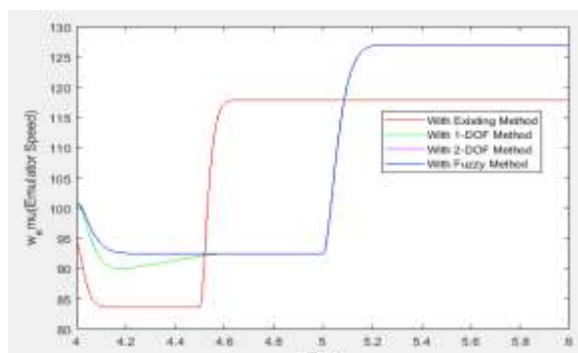
MemberFunctionsforError

In indirect vector controller block, it has subblockssuchasspeedcontroller(Fuzzycontroller),Tr_est,Iqs*,Ids*andωslcomputation blocks. The hysteresis currentcontrollerblockisusedtocontrolthecurrents.Theunitvectorcomputationblock, abc to syn and syn to abc conversionblocks are also used. Rule based fuzzy logiccontrollersareusefulwhenthesystemdynamics are not well known or when theycontainsignificantnon-linearities,suchastheun-steadywindcontainslargeturbulence.Fuzzylogiccontrollersapplyreasoning,similartohowhumanbeingsmake decisions, and thus the controller rulescontain expert knowledge of the system. Thedesign process for a fuzzy logic controllerconsistsof (i)determiningtheinputs,(ii)settinguptherules and(iii)designingamethodtoconvertthefuzzyresultofthe

rulesintooutputsignal,knownasdefuzzification. The inputs (Error &ChangeofError)andoutput(Ids*)oftheFuzzy Block are shown in Fig. 4, Fig. 5 and Fig. 6respectively.Triangularsymmetricalmembershipfunctionsaresuitablefortheinputandoutput,whichgivemoresensitivity especially asvariablesapproachto zero value. The width of variation can beadjusted accordingtothesystemparameters.



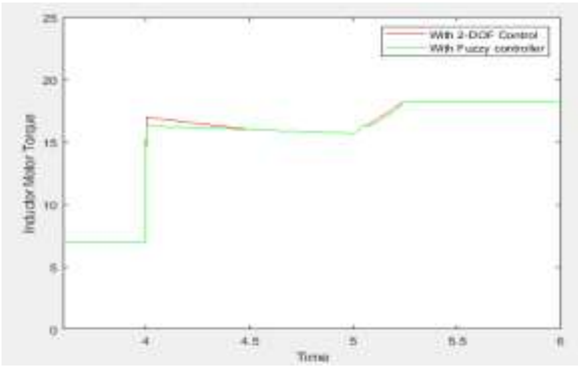
Simulationresults



FLCEmulator speed

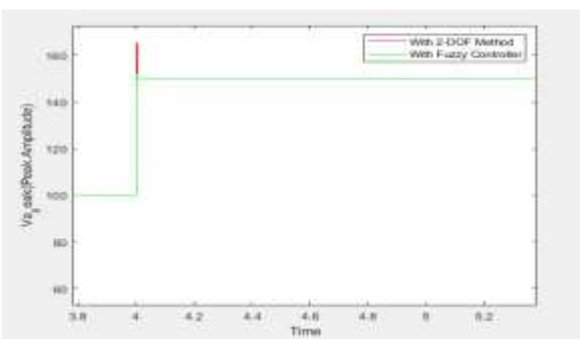
Simulation results of emu and act speed withExtensionasFuzzyLogiccontrollercompared with the Existing ,1 DOF ,2-DOFmethods.From the above graph on X-axiswehavetime(sec),andonY-axiswehaveEmulated&actualspeed.Herethe

emulatedspeedisbetterinFuzzy LogicControllerbycomparingwithotherscontrollersresults.



FLCTORQUE

SimulationresultsofTorqueswithExtensionas FuzzyLogiccontrollercompared with the 2-DOF control method.From the above graph on X-axis we havetime(sec),and on Y-axis we haveTorque.Herebycomparingwith2-DOFcontroller ,FuzzyLogicControllerhavebetterresults.



Flcsourcevoltage

Simulation results of Source Voltages withExtensionasFuzzyLogiccontrollercompared with the 2-DOF control method.From the above graph on X-axis we havetime(sec),and on Y-axis we haveSourceVoltages. Here by comparing with 2 -DOFcontroller,FuzzyLogicControllerhavebetterresultsbecausetheripplewhichiscreated at 150v ,4s it is eliminatedby theFuzzyLogicController

Conclusion

In conclusion, the "Enhanced Wind TurbineEmulationthroughVectorControlledInductionMotorDriveEmpoweredbyFuzzyLogicController"projecthassuccessfullydemonstratedtheefficacyofcombiningadvancedtechnologiestooptimizewindturbineperformance.Theintegrationofvector-controlledinductionmotor drive and a fuzzy logic controller hasproven to be a robust and efficient solutionfor enhancing wind turbine emulation. Thisapproachnotonlyimprovestheoverallefficiencyofenergyconversionbutalsoenhancesthesystem'sadaptabilitytovaryingwindconditions.Thefuzzylogiccontrollerplaysapivotal rolein ensuringreal-time adjustments, mitigating the impactof uncertainties, and optimizing the turbine'soutput.Throughmeticulousdesignandimplementation,theprojectnotonlycontributes to the renewable energy sector'stechnologicaladvancementsbutalsounderscoresthepotentialforintelligentcontrolsystemstorevolutionizethefield.Overall,thisprojectmarksasignificantstridetowardssustainable andintelligentenergysolutions,settingafoundationforfurtherinnovationsinwindturbinetechnology.

Futurescope

The"ImprovedBreezeTurbineImitatingthroughVectorControlledAcceptanceEngine Drive Enabled by Fluffy RationaleRegulator" project opens up a few roads forfutureinnovativework.Hereareafewpossiblefuturedegrees:

StreamliningandScaling:Furtherenhancement of the fluffy rationale regulatorboundariesandscalingtheframework forvarious breeze turbine sizes and types couldbeinvestigated.Thiswillupgradetheversatilityandrelevanceoftheproposedframeworktoamoreextensivescopeofwindenergyprojects.

High level Control Calculations: Examiningand carrying out further developed controlcalculations, for example, AI based or modelprescientcontrol,couldworkontheframework's capacity to adjust to dynamicnaturalcircumstancesandimproveingeneralexecution.

CombinationofEnergyStockpiling:Integrating energy stockpilingframeworks,like batteries, to store overabundance energyduring top breeze conditions and delivery itduringlow wind periods can work on thegeneral unwaveringquality andsoundnessofthebreezeenergyframework.

ContinuousObservingandDiagnostics:Fostering an exhaustive continuous checkingandindicative framework utilizing sensorsandinformationinvestigationcouldempowerproactiveupkeep,decreasefreetime, and improve the framework's generalunwaveringquality.

MatrixJoiningandShrewdLatticeInnovations: Investigatingwaysofcoordinatingthebreezeturbineimitatingframework with brilliant lattice advances toempowereffectiveenergycirculation,requestreaction,andmatrixsecurityupgrades.

MixtureFrameworks:Exploringthecoordinationofdifferentenvironmentallyfriendlypowersources,forexample,sunlight based and wind, into a half and halfframework,andupgradingthecontrolprocedureforconcurrentactivity toboostenergy yield and unwavering quality.

CostDecreaseSystems:Exploringandcarrying out practical parts and materials tomake the framework all the more monetarilysuitableandavailableforboundlessreception.

Bydiggingintothesefutureextensions,specialistsandarchitectscanaddtothecontinuousdevelopmentofwindturbineinnovationandfurtherdevelopmenttheproficiency, dependability, andsupportabilityofenvironmentallyfriendlypowerframeworks.

References

[1] W. Li, K. Thirugnanam, W. Tushar, C.Yuen, K. T. Chew and S. Tai, “ImprovingtheOperationofSolarWaterHeatingSystems in Green Buildings via OptimizedControl Strategies,” IEEE Trans. IndustrialInformatics, vol. 14, no. 4, pp. 1646-1655,April2018.

[2] S.Sashidhar,V.GuruPrasadReddyand

B. G. Fernandes, “A Single-Stage SensorlessControlofaPV-BasedBore-WellSubmersibleBLDCMotor,”IEEEJournal of Emerging and Selected Topics in PowerElectronics,vol.7,no.2,pp.1173-1180,June 2019.

[3] S.MurshidandB.Singh,“Implementation of PMSM Drive for a SolarWaterPumpingSystem,”IEEETrans.IndustryApplications,vol.55,no.5,pp.4956-4964,Sept.-Oct.2019.

[4] E. T. Maddalena, C. G. d. S. Moraes, G.Bragança,L.G.Junior,R.B.GodoyandJ. O.P.Pinto,“A Battery-LessPhotovoltaicWater-PumpingSystemWithLowDecoupling Capacitance,” IEEETransactions on Industry Applications, vol.55, no.3,pp.2263-2271,May-June2019.

[5] D.Sera,L.Mathe,T.Kerekes,S.V.Spataru and R. Teodorescu, “On the Perturb-and-Observe and Incremental ConductanceMPPTMethodsforPVSystems,” IEEEJournal of Photovoltaics, vol. 3, no. 3, pp.1070-1078,July2013.

[6] M.A.Elgendy,B.Zahawi andD.J.Atkinson,“AssessmentofPerturband ObserveMPPTAlgorithmImplementationTechniques for PV Pumping Applications,”IEEE Trans. Sustainable Energy, vol. 3, no.1,pp.21-33,Jan.2012.

[7] M.KilliandS.Samanta,"ModifiedPerturb and Observe MPPT Algorithm forDrift Avoidance in Photovoltaic Systems,”IEEE Trans. Industrial Electronics, vol. 62,no.9,pp.5549-5559,Sept.2015.

[8] O. P. Pahari and B. Subudhi, "Integralslidingmode-improvedadaptiveMPPTcontrol scheme for suppressing grid currentharmonics for PV system,” IET Ren. PowerGen.,vol.12,no.16,pp.1904-1914,2018.

[9] K. Sundareswaran, V. Vigneshkumar, P.Sankar, S. P. Simon, P. SrinivasaRaoNayakand S. Palani, “Development of an ImprovedP&OAlgorithmAssistedThroughaColony of Foraging Ants for MPPT in PVSystem,” IEEE Trans. Industrial Informatics,vol.12,no.1,pp.187-200,Feb.2016.

[10] R.Antonello,M.Carraro,A.Costabeber,F.TinazziandM.Zigliotto,“Energy-Efficient Autonomous Solar Water-PumpingSystemforPermanent-MagnetSynchronousMotors,”IEEETrans.Industrial Electronics, vol. 64, no. 1, pp. 43-51,Jan.2017.