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A novel type-2 fuzzy logic controller based hybrid micro grid with different renewable energy resources

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ABSTRACT— The increased demand and depletion of the fossil fuels for power generation led to the need forextracting powerfromthe renewable energyresources(RERs).The microgrids(MGs) aredesigned withthehelp of effective power extracted from renewable sources such as solar, wind, tidal, and geothermal. The adventofDCMGs overcomesthe conventionalACgrids.The hybridization ofthe AC andDCMGs will providemore advantages for various levels of consumers. This article proposes the design and modeling of a hybridDC/ACMGwiththeefficientuseofRERsanditcanreducenumerouspowerconversions.Thesolarenergyis extracted through photovoltaic (PV) panels meritoriously using interval type 2 fuzzy logic technique as themaximum power point tracking algorithm. The AC grid is designed using wind energy source and tidal energy.The permanent magnet synchronous generator is used as the wind turbine. Various control mechanisms areemployed in order to extract maximum power from the wind and tidal waves at varying conditions. Thesegenerated powers can supply the load and are connected to the utility grid. These are executed with the aid ofMATLAB/SIMULINKsoftware.

Index Terms— Hybrid DC/AC microgrid (MG), permanent magnet synchronous generator, power extraction, solarphotovoltaic(PV)energy,tidalenergy,windenergy.

I. INTRODUCTION

THEgeneratingsourcesclosetotheloadtakeadvan-tageofreducingtransmissionlossesandinpreventingnetwork congestion [1]. Different generating sources such aswind, solar,fuelcell,andtidaland energy storagedevicessuchasbatteryandflywheelareconnectedtoacommonnetwork which is saidto be known as microgrid (MG) [2].ThegrowthofDCloadsinthedistributionsidesuchaslight-emitting diode lights, electric vehicles, laptops, and unin-terrupted power supply makes a major concern about hybridAC/DC MG to reduce the complexity and power conversionstages.

AC, DC,and hybrid MGcontrol techniques are reviewedin [3]. A neural network control-based grid-connected hybridAC/DCMGispresentedin[4].Thewind,solar,fuelcell,andbatteriesareutilizedasageneratingandstoragesystem.Afault-tolerantsupervisorycontrollerisdesignedforisolated hybridAC/DCMGin[5],anditsatisfiesthepowerdemandin both AC and DC MG. The work in [6] presents the coor-dinatedcontrol strategyforisolatedwind–diesel hybrid MGto reduce the frequency deviation resulting from

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renewableenergy fluctuation and load variance. The topology of hybridAC/DCMGbasedontheconventional powernetwork andthe interconnection of the AC and DC networks are reviewedin[2].AbidirectionalresonantDCtransformerisimplementedin [7] to replace the conventional bulky transformer for busvoltage matching and the galvanic isolation in a hybrid MG.An architecture and control for multiple MGs with a hybridAC/DCconnectionisdesignedin[8].Adetailed modelof automatic centralized MG controller-based hybrid AC/DCMG is presented in [9]. The technologies, key drivers, andoutstandingissuesofMGarereviewedin[10]. Differentcontrolmethodsandcontrollersareusedformaximum power point tracking (MPPT) in solar photovoltaic(PV),wind,andtheotherrenewableenergy-based power-generatingsystems.Aradialbasisfunctionnetwork-basedMPPT control algorithm for a hybrid solar and wind energysystem is designed and analyzed in [11] for standalone andgrid-connected applications.Keyrouz andFakheredine [12]presentedthemachinelearningcontrol-basedMPPTforPV system under partial shading condition. The Perturb &Observe (P&O)-based fractional-order sliding-mode controllerfor MPPT of the PV system is designed in [13]. A decen-tralizeddynamicpower-sharingmethodforwind,PV, and

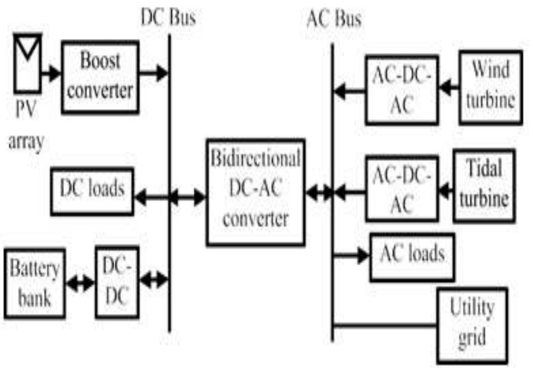

Fig.1.FundamentalschemeofahybridDC/ACMG.

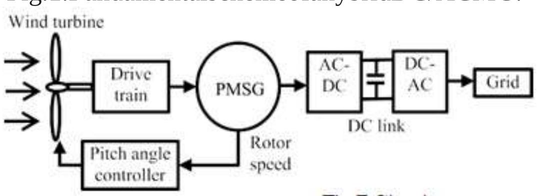

Fig.2.SchematicofPMSGWT.

B.ModelingofPVPanel

The PV model output mainly depends on the solar irradi-ationandtemperature [17].ThePVmodules areconnectedin series and parallel combinations to get the required poweroutput [18]. The number of PV modules to be connected inseries$N_s$canbedeterminedfrom

$$N_s = \frac{1}{2} \cdot \frac{V_{DC\,link}}{V_{MP}} \quad (1)$$

where $V_{DC\,link}$ is the DC link voltage and V_{MP} is the voltage at the maximum power point (MPP) of the PV module.

The PV string maximum power P_{string} connected in series is

$$P_{String} = N_S \cdot P_{MP} \quad (2)$$

$$P_{MP} = V_{MP} \cdot I_{MP} \quad (3)$$

The number of strings to be connected in parallel N_p is

$$N_p = \frac{P_t}{P_{String}} \quad (4)$$

where P_{MP} is the power at MPP, I_{MP} is the current at MPP,and P_t is the needed total power from the PV module.

C. Modeling of Wind Turbine Generator

The mechanical power that can be extracted from the WT is given in the following equation [20], [21]:

$$P_m = \frac{1}{2} \rho A_r C_p(\lambda, \beta) V_w^3. \quad (5)$$

II. SYSTEM MODELING AND CONFIGURATION

A.HybridDC/ACMicrogrid

Themechanicaltorqueoutput $T_m$isexpressedinthefollowingequation:

$$T_m = \frac{P_w}{\omega_m} = \frac{\frac{1}{2} \rho A_r C_p(\lambda, \beta) V^3}{\omega_m} \quad (6)$$

ThefundamentalschemeofahybridDC/ACMGisshowninFig.1.ItcomprisesDCgridandACgridinterlinked by a bidirectional DC/AC converter. The DC MG comprisesPVpanelsystemandabatterybankstoragesystem.TheDCloadsareconnected totheDCMGviaDCbus.TheAC MG comprises the wind turbine (WT) system and tidalturbinesystem.Thissystemistiedtotheutilitygrid. where ρisthe airdensity(kg/m^3),$A_r$represents theareaswept by the rotor, $C_p$is the power coefficient, $V_w$representsthe wind velocity (m/s), λ is the tip speed ratio, β is the pitchangle (deg), $\omega_R$is the angular velocity(rad/s), andR is thebladeradius(m).Fig.2showstheschematicofPMSGWT.

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Usingd–

$$\frac{di_d}{dt} = \frac{-R_s I_d + L_q \rho \omega_r i_q + V_d}{L_d} \quad (7)$$

$$\frac{di_q}{dt} = \frac{-R_s I_q - L_d \rho \omega_r i_d - p\lambda_a \omega_r + V_q}{L_q} \quad (8)$$

$$T_m = 0.75 p(\lambda_{sq} + (L_d - L_q) i_d i_q) \quad (9)$$

where $L_q$is the q-axis inductance, $L_d$is the d-axis inductance,$R_s$is the resistance of the stator windings, $i_q$is the q-axiscurrent,$i_d$isthed-axiscurrent,$V_q$istheq-axisvoltage,$V_d$is the d-axis voltage, ω is the angular velocity of the rotor,$\lambda_a$is the amplitude of flux induced, andp is the number ofpolepairs.

D.ModelingofDriveTrain

In the two-mass model, the masses of the two disks are added. These two disks are connected by a shaft of equivalent stiffness [22]. The disk's mass moment of inertia J (kg · m²) is given by the following equation:

$$J = \frac{M D_d^2}{8} \quad (10)$$

where D_d is the disk diameter and M is the disk weight. The shaft stiffness K_s (N · m/rad) is determined by the following equation:

$$K = \frac{G\pi D_{sh}^4}{32L} \quad (11)$$

where D_{sh} is the diameter of the shaft, L is the length of the shaft, and G is the shear modulus. The two-mass model drive train is used in this article and it is modeled as follows:

$$J \frac{d\omega_g}{dt} = T_m - T_e - V_f \omega_g \quad (12)$$

where T_m is the WT mechanical torque, T_e is the electro-magnetic torque of generator, J is the rotating mass inertia constant, and ω_g is the angular speed of the rotor.

E. Modeling of Tidal Stream Energy Generation System Fig. 3 shows the block diagram of the tidal stream energy generation system (TSEGS). It consists of a horizontal axis tidal turbine (HATT) which captivates the kinetic energy (KE) of the tidal wave [23], [24]. The PMSG is used to convert it into electrical energy. The AC is converted into DC and transmitted to the land where DC–AC conversion is made and connected to the grid through a step-up transformer [25]. The density of water is 784 times greater than air. With small turbines at low tidal speeds, an enormous amount of power can be generated when compared with WT [26]. The HPTT will produce 4–5 times of power higher than the WT with an analogous turbine rating. The KE onto the tidal turbine

qreference,themodelofPMSGisgivenasfollows:
produces a total power [25] as given in the following equation:

$$P_{tidal} = \frac{1}{2} \rho \pi R^2 C_p(\lambda, \beta) V^3 \quad (13)$$

where ρ is the fluid density (kg/m 3), V is the tidal velocity (m/s), R is the radius of the blade (m), C p is the power coefficient, λ is the tip speed ratio, and β is the pitch angle (degree).

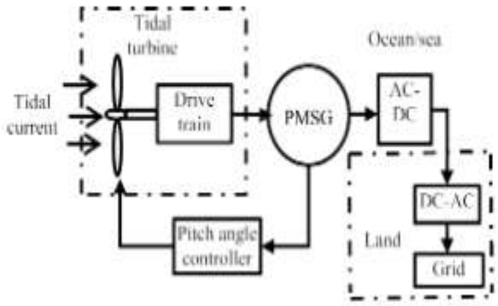

Fig.3.BlockdiagramoftheTSEGS.

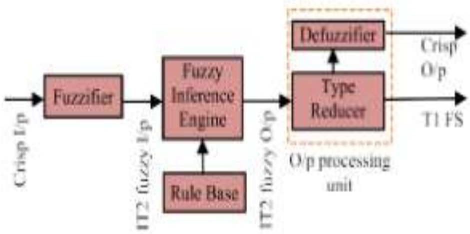

Fig.4.FlowdiagramofIT2FLC.

III. DESIGN OF THE HYBRID DC/AC MICRO GRID

The design structure of the hybrid DC/AC MG is segmented as DC MG and AC MG.

A.Design of DC Microgrid

The PV system contributes the necessary power to the DC MG. The next-generation thin-film solar cells are the conspicuous hope [18]. The CIGS solar cell which is very lightweight, thin, and flexible and has a very high absorption is used in this article for the design of PV array. The solar Frontier SF-170S panel, which has the highest efficiency of 19.9%, is used. In order to extract utmost and effective power from the PV system, the MPPT technique is used.

B. Interval Type 2 Fuzzy Logic Controller MPPT TechniqueforPVSystem

Conventionally, P&O method is used as the MPPT tech-nique.TheT1FLCMPPTtechniqueisalsousedforthePVasacontribution fromartificialintelligence.However,theIT2FLC[27]

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worksmoreeffectivelyinhandlingtheimpre-cise data when compared with P&O and T1FLC. In T1FLC,themembershipvaluesaresingle,whilethemembershipfunctions of IT2FLC are intervals instead of a single value.TheMFsofIT2FLC has lower(L)and upper (U)regions.The IT2FLC has an additional step of type reduction (TR).This TR helps in reducing the IT2 fuzzy sets into IT1 fuzzysets.TheflowdiagramofIT2FLCisdepictedinFig.4.

The E and CE are divided into three fuzzy sets each. TheMFsofEandCEareshowninFig.5.TheEandCEMFsare chosen as trapezoidal MFs for providing accurate results.The MFs are depreciate (D), neutral (NT), and appreciate (A).Theoutput(D)isthedutycycleanditisgiventotheDC–DC converter. The output MFs are depreciate huge (DH),depreciate tiny (DT), NT, appreciate tiny (AT), and appreciatehuge(AH).TheIT2FLCusestherulebaseof TableI.

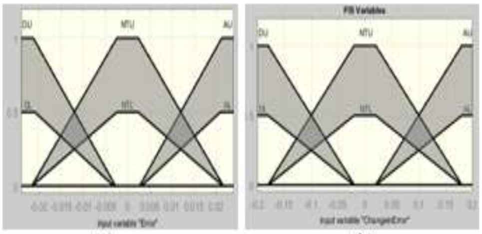
(a) (b)

Fig.5.MFsofIT2FLC.(a)Error.(b)Changeinerror.

TABLEI
RULEBASEFORTHEIT2FLCMPPT

E / CE	D	NT	A
D	DH	DT	NT
NT	DT	NT	AT
A	NT	AT	AH

The 270 V produced by the PV array is boosted to 500-VDCusingthisBoostconverter.Thedutycycleisautomaticallyvariedwiththehelpofthe MPPTstructure.Atotalloadof 30 kW is used in the DC MG. The 20-kW load is thepermanent residential load. At peak time, there is a load hikeof 10 kW. A 40-Ah Li-ion battery bank system is used tostore the power. When the power production is insufficient byPV arrangement, the battery bank supplies the residential load.Thebatterymodelisreferredin[19].

C. Design of AC Microgrid

A wind energy conversion system (WECS) consisting of a100-kW WT and a TSEGS of 50 kW forms the AC MG and isalso connected to the utility grid. It consists of a synchronousgenerator connected to an AC/DC converter, a DC link, and aDC/ACIGBT-basedpulsewidthmodulation(PWM)converter.The tip speed ratio is maintained at the optimum value. There-fore,thepowerextractioncoefficient$C_p$isalsoattheoptimumvalue. Speed regulator and pitch angle control techniques areused.Therefore,MPPistrackedcontinuously,andthepowerisproduced effectively and efficiently. The critical hospital loadof40kWiscoupledtotheACMG.Thepowerinterruptionfora few minutes can harm the patients' life. Failure of either ofthesystemdoesnotaffectthepowersuppliedtothehospital.

D. Design of Bidirectional DC/AC Converter

Converters play an important role in the synchronizationprocess. The bidirectional DC/AC converter is an online con-verter which is common between the DC bus and the AC bus.It allows the bidirectional flow of power between DC bus andAC bus. It can work both as an inverter and as a rectifier.When there is a power deficit in the DC MG, the converterworks asarectifier andpower issupplied from theAC sideto the DC MG, thereby preventing the isolation of the loadsconnected to the DC bus. The voltage source control techniqueis used which has precise control over the magnitude, phase,and frequency of the voltage. The bypass diodes which areantiparalleltotheswitcheshelpinthecirculationofreactive

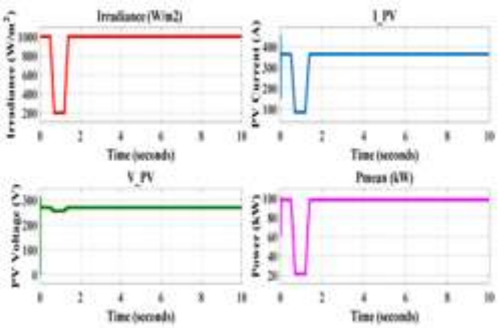

Fig.6.PVoutputusingIT2FLCMPPTatvaryingirradianceconditions.

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TABLEII
PERFORMANCE OF PVSYSTEM WITH VARIOUS MPPTTECHNIQUES

Parameters	P&O	T1FLC	IT2FLC
Output power at 1000 W/m²	90.95 kW	96.18 kW	98.29 kW
Output power at 200 W/m²	16.83 kW	20.85 kW	21.86 kW
Voltage and Current	Oscillating and Non-Uniform	Smooth and Uniform	Smooth and Uniform

power and in the flow of active power in both the directions.The sinusoidal pulsewidth modulation technique is used as theswitchingscheme.EvenifthewholeACMGfails,thehospitalload will be provided with uninterrupted supply of power fromtheDCMGviabidirectionalDC/ACconverter.

IV. SIMULATIONANDRESULTS

A. DC Microgrid

The CIGS solar PV array of 100 kW has an irradiationlevel of1000 W/m^{2}at0–0.5 s.At0.5s, the irradiationlevel decreases to 200 W/m^2. An average constant temperatureof 35 ˚C is maintained. Again at 1.2 s, the irradiation levelreaches1000W/m^2.

Fig.6showsthePVsystemoutputusingtheIT2FLCMPPTtechnique. From0.5 to1.6s,thebatterybank supplies theload as the power produced by the PV is insufficient to meetthe loadof 30 kW.After1.6 s,the PVagain suppliestheload.TableIIshowstheassessmentoftheperformanceofPVsystemwithvariousMPPTtechniques.

The above results prove that the PV system with IT2FLCMPPT technique produces utmost power than the P&O andT1FLC techniques. The power production under the minimumirradiation condition of 200 W/m^2 is comparatively higher inIT2FLCthantheothertechniques.

B. AC Microgrid

The AC MG is designed with RERs such as wind energyand tidal energy. PMSG outshines conventional WECS withdoubly fed induction generator (DFIG) by extracting morepower.PMSGhasreducedlossesasitdoesnotrequiregearboxand brushes. So, its weight is less, low losses, low noise, andless maintenance. PMSG is used in both the systems inorderto extract utmost power. A total load of 40 kW is connected totheACMG.Thehospitalloadof40kWiscoupledintheAC

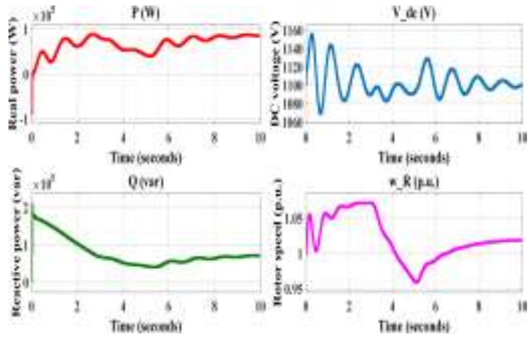

Fig.7.Activepower,reactivepower,DCvoltage,androtorspeedoftheWT.

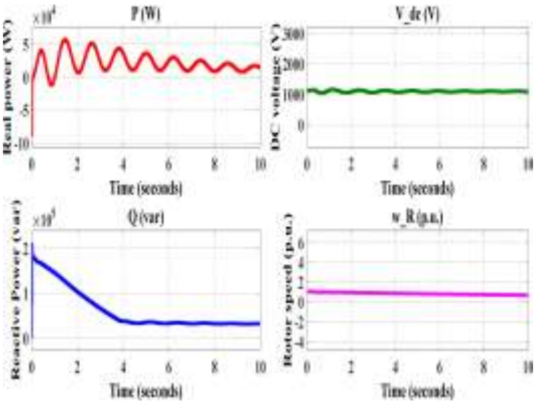

Fig.8.Activeandreactive power,DCvoltage,androtorspeedoftheTSEGS.

MG. The hospital load is a critical load where power supplyshould not be interrupted. This hybrid DC/AC MG is uniquefrom other MGs by providing uninterrupted power supply atany cause. When the WECS does not provide enough power,the TSEGS supply the power to the hospital and vice versa.The hospital load consumes 30-kW power and during peaktime,thereisahikeinpowerconsumptionby10k.

C. Wind Energy Conversion System

TheWECSconsistsofPMSGWTof100kW, whichproduces power at varying wind speed conditions. Based ontheyearlydata,therearevariationsinwindspeedfrom15to5 m/s. The simulation is carried out with varying wind speed.Fig. 7 shows the active power, reactive power, DCvoltage,androtorspeedoftheWT. The wind speed varies from 12 to 7 m/s at 3 s. In 5 s, thewindspeedagainchangesto12 m/s and accordingly,the power generation varies. The rotor speed decreases whenthewindspeeddecreases.Therefore,thepowergenerationalsoreduces. The WECS with PMSG produces 50-kW power evenwhenthewindspeedisreducedto7m/s.WhencomparedwithDFIG, thepower production ismore in

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WECSwith PMSG.It is evident from the simulation that WECS alone will be ableto supply hospital load when tidal stream energy conversionsystem(TSECS)isdisconnected.

D. Tidal Stream Energy Conversion System

HATTwiththegeneratorasPMSGisusedtoextractutmostpowerfromthetidalwaveswithhighefficiency.A50-kWTSEGSproducesthepowerat anaveragetidalspeedof2.5m/s.Fig.8showstheactive power, reactive power,DCvoltage,androtorspeedoftheTSEGS.

The rotor speed maintains constant 1 p.u. and the powergeneration is also constantly produced. The power productionin PV and WECS can be severely affected as it depends onvarying conditions of solar irradiation and wind speed. How-ever, the TSEGS depends on the gravitational force of the sunand moon. The power production from TSEGS is persistentwhich prevents the isolation of hospital load and residentialload via a bidirectional converter. This makes the proposedhybrid DC/AC MG unique as it ensures the prevention of loadisolationatanycausewiththeaidofTSEGS.

V. CONCLUSION

The deployment of DC loads requires the direct DC supplyto reduce the conversion losses. So, this article proposed theDC/AC hybrid MG with RERs. This system is designed andmodeled in the MATLAB/Simulink environment. The solarPVsystemandbatteriesareconnectedtotheDCgridandintheACgrid,windandtidalpowergenerationsystemsareconnected.Thebidirectionalconverterisemployedtoexchange powerfrom DCgridtoACgridandviceversa.An IT2FLC-based MPPT is proposed for the CIGS solar PVsystem. Moreover, the PMSG is used for both wind and tidalpowergeneration systemsduetoitsmerits.Theproposedsystemistheultimatesolutionfortheproblemsofisolationofloadsandpower production from nonexhaustible sources.It helps toprovide electricity even inremote, isolated areasandmeettheincreasedadventofDCloadswithminimallosses. With proper design, coordination between the DC andAC MGs and control over it can effectively utilize the powergenerated from the RERs. The mitigation of power qualityissuesthatarisesduetothecriticalandsensitivehospitalloadandcompensationofreactivepowerareconsideredasthefuturework.

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