



Deustuko Unibertsitatea

## Doktorego Tesia

Energia Berriztagarri Sistemak

Modelatzeko eta Kontrolatzeko

Ekarpenak

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Deustuko Unibertsitatean Ingenieritzan Doktore titulua  
eskuratzeko aurkeztua Ingenieritza Fakultatean

Informazioaren Gizarterako eta Garapen Jasangarrirako  
Ingeniaritza programa

Hautagaia

Zuzendaria



## Eskerrak

*Gorka eta Diegori, beren aholkuengatik, beren lanagatik eta beti konstruktibo  
izateagatik*

*Ikerkuntza denbora partekatu dudanekin lankide guztiei*

*Unai, Iker, Virginia eta Deliciari, denbora lapurtu dietei tesi hau egiteko*

*Eskerrik asko denoi.*

*Jose Manuel Lopez Guede*



## Laburpena

Lan honetan landutako gai-ikerketaren helburua energia berriztagarrien arloan dagoen premia artatzea da. Gaur egun energia berriztagarrien arlo ezberdinetan lantzen ari da, non emaitza hobereana lortzeko beharrezkoa da osagai guztiak ondo, eta modu hobereanean, erabiltzea. Normalean arreta ipintzen da algoritmoetan edota kontrolagailuen diseinu-teknikak gehienezko potentzia puntua lortu ahal izateko, hurbilketak bere zatietatik modelaketa erabiliz. Hala ere, modelaketa errealista baten lan egiteak euren jokaeraren deskribapen zehatza edukitzeko aukera ematen digu. Sistemen eredu zehatzak erabiltzea oso garrantzitsua da simulazio egokiak egiteko eta errendimendua optimizatzeko. Energia berriztagarrien mundua hain zabala denez, tesi honek esparru fotovoltaikoa du ardatz; izan ere, eremu honek, munduan, bezero txikien artean, zabalpen gehiago dauka, beraz, tesiaren ekarpenak onuradun gehiago edukiko du. Hala ere, lortutako emaitzak beste energia-iturri berriztagarrietara zabal daitezke.

Tesi hau ekarpen bildumaren bidezko tesia da eta horregatik bere antolaketa zuzena da; izan ere bertako edukia JCR motako aldizkariren 3 argitalpenetan oinarritzen da.

Lehenengo artikuluari dagokionez, neurona-sare artifizialak eta datu-multzo handietan oinarritzen den modelatze prozesu sistematiko bat aurkezten dugu. Froga gisa, proposaturiko prozesua Mitsubishi Electric PV-TD185MF5 (185 Wp) modulu fotovoltaikoa modelatzeko erabili dugu. Artikuluan bi aurkikuntza nagusi agertzen dira. Lehena proposaturiko prozesu sistematikoak ongi funtzionatzen duela da, modu autonomoan  $I_{PV}$ -ren bi eredu zehatz lortzen baititu, neurketa-gailuen zehaztasuna gainditzen duten ereduak. Emaitzak duela gutxi-ko beste artikuluko garrantzitsuekin konparatu ditugu, gure prozesua lehiakorra dela baieztatuz, egungo emaitzak hobetzen baititu. Bigarrena ikasitako ereduak erabiliz, taula-formako datu-multzoen errepresentazio originalarekiko %99.5 espazio gehiago aurrez daitezkeela da.

Bigarren artikuluari dagokionez, PV modulu monokristalinoen eredu enpiriko eta zehatzak lortzearen arazo irekiari aurre egiten diogu, gainbegiratu gabeko prozesu sistematiko baten bidez. Horretarako, neurona-sare artifizialtan oinarritutako eredu dualak erabili ditugu. Bi eredu ezberdin probatu ditugu Atersa A-55 PV modulu batean. Bi urtaro-mailako eredu ezberdin lortu ditugu  $I_{PV}$ -rako. Lortutako zehaztasun horiek neurketa-gailuen zehaztasuna gainditzen dute, baita beste ikertzaileek plazaratutako emaitzak ere.

Azkenean, hirugarren artikuluari dagokionez, arlo horretan berebiziko garrantzita duen teknologia bat dakarkigu, hots, gehienezgo potentzia puntua-  
ren jarraipen algoritmoak (MPPT), haien implementazioa korrante zuzenetik  
korrante zuzenerako bihurtailuetan (DC-DC). Erakusgarri bezala, beste lan  
batzuetan ongi funtzionatu duen logika lausoan oinarritutako kontrolagailu bat  
modelatu dugu. Oso eredu zehatza lortu dugu. Eredu neural hauek abantaila  
handiak dituzte, esaterako, hutsegiteekiko tolerantzia handiagoa eta inplemen-  
tazio sinpleagoa. Gainera, logika lausoko kontrolagailu batek behar dituen  
elementu konplexu guztiak (fuzzifier, defuzzifier, inference engine eta knowledge  
base) ez dira beharrezkoak.

# Gaien Aurkibidea

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# Kapitulua 1

## Sarrera

Aurkezten den tesi honen sarrerak tesiaren informazio orokorra lantzen du. 1.1. atalak tesiaren motibazioa azaltzen du. 1.2. atalak lanaren ekarpenak laburbiltzen ditu. Tesi hau bermatzen duten agerkariak 1.3. atalean aurki ditzakegu. Bukatzeko, 1.4. atalak tesiaren egitura jasotzen du.

Kontuan eduki behar da tesi hau ekarpen bildumaren bidezko tesia da. Horregatik ataleko edukia zuzena da, bertako edukia JCR motako aldizkariaren 3 argitalpenetan oinarritzen delako.

### 1.1 Motibazioa

Tesi honetan landutako gai-ikerketaren helburua energia berriztagarrien arloan dagoen premia artatzea da. Gaur egun energia berriztagarrien arlo ezberdinetan lantzen ari da, non emaitza onena lortzeko beharrezkoa da osagai guztiak ondo, eta modu hoberenean, erabiltzea. Normalean arreta ipintzen da algoritmoetan edo kontrolagailuen diseinu-teknikak gehienezko potentzia puntua lortu ahal izateko, hurbilketak bere zatietatik modelaketa erabiliz. Hala ere, modelaketa errealista baten lan egiteak euren jokaeraren deskribapen zehatza edukitzeko aukera ematen digu. Arlo horri akademiak eta zientzia munduak ez diote arreta nahiko jartzen.

Energia berriztagarrien mundua hain zabala denez, tesi honek arlo fotovoltaikoan ipintzen du arreta; izan ere, eremu honek, munduan, bezero txikien artean, zabalpen gehiago dauka, beraz, tesiaren ekarpenak onuradun gehiago edukiko du.

Orokorrean, arlo honen aurrerapenen lehen onuraduna gizartea da, erregai fosila erabili barik energia berriztagarriak erabileraren ondorioz ingurumen hobekuntza dakarrelako. Jarrera hau defendatzeko ez da beharrezkoa argudio gehiagorik.

Beste aldetik, eta eskala askoz txikiagoan, gehien bat herrialde azpigaratuetan, badaude erkidego, herri edo herrigune batzuk bakarturik eta urrun daudenak, non ohiko harguneen bidez energia elektrikoa lortzea nahiko zaila den. Eskuarki onartua dago, ekonomia mailan, konpainia elektrikoek ez zaie la interesatzen biztanle gutxiko eta kilometro askotarako herrigunetako argi-hornidura, kontsumo-profila nahiko baxua delako. Energia berriztagarriekin zerikusia duten teknologien bitartez, herrigune hauek argindarra eskura ditzakete konpainia elektriken interesetara baldintzatuta egon barik, kasu gehienetan ez bailiete kontuan hartzen; besteetan, berriz, argindar - horniduraren eraikuntzan konponezinezko ingurumen hondamendiak sortzen dituztelako. Esan daiteke erratzeko beldur barik, energia fotovoltaiakoak energia berriztagarrien artean, merkeena dela (inbertsio gutxien behar duena).

Gainera, zenbat eta energia berriztagarri gehiago erabili, energi fosil gutxiagoaren beharra dago; horrek gutxiagotuko luke baliabide natural garrantzitsuengatik egoera deserosoak. Egoera hau garapen bidean dauden herrialdetan ematen ohi da; herrialde garatuak diren batzuei ere eragin arazi izan die. Adibide garbia herrialde edo gizarte orekatuak ez direnetan petrolio edota baliabide natural garrantzitsua (diamantea, coltana, eta abar) topatzea izaten da, horrek giza-desoreka sortzea ekar dezakeelako.

Azkenik, eta giza-onura ukaezin bezala, nahiz eta aurrekoek era naturalean izan, energia berriztagarri izateak, mundu mailan, gizartearentzat energia elektriko gehiago egotea dakar, beste baliabide motak erabili behar barik. Hau erabat interesgarria da, izan ere, munduko biztanleriak energia elektrikoaren kontsumoa gero eta handiago baitu.

Tesi honen ekarpen txikia, beste ildo antzeko tesienei gehituta, pertsonen eguneroko bizitzan ondorio onak dakartzalako.

## 1.2 Tesiaren ekarpenak

Tesi honetan argitaratutakoa JCR aldizkariaren bitartez, zientzia munduko elkarteetan onarpenaz aurkezten dira. Hona hemen, laburtuta, hauetako batzuk (argitalpenetan azalpen-garatuak aurki daitezke):

- Metodo teorikoetan oinarritutako elementu fotovoltaikoen modelaketa-tekniken egungo egoera
- Metodo teorikoetan oinarritutako modelaketa-emaizten egungo egoera
- Metodo enpirikoetan oinarritutako elementu fotovoltaikoen modelaketa-tekniken egungo egoera
- Metodo enpirikoetan oinarritutako modelaketa-emaizten egungo egoera
- Modulu fotovoltaikoen modelaketa-hurbilketa desberdinen proposamenak
- Tresneria zehatza eta egokia instalazio fotovoltaiko batetik benetako datuak ateratzeko prozesu baten diseinua
- Neurona-sareetan oinarritutako elementu fotovoltaikoen modelaketa prozesuaren planteamendu eta aurkezpen zehatza
- Datasets-en moldaketen bidez, modeloak lortzeko planteamendu eta aurkezpen zehatzak
- Neurona-sareetan oinarritutako modelo fotovoltaikoen emaizten diseinu esperimentalak
- Neurketa-tresneria baino zehatzagoak diren sare fotovoltaikoetan oinarritzen diren modeloen emaiztak
- Neurona-sareetan neuronaletan oinarritutako modelo fotovoltaikoen emaizten analisisa eta egungo egoeraren modeloarekin konparaketa
- Gehieneko potentzia-puntuen jarraipen-algoritmoen egungo egoera
- Lauso den kontrolagailuei modelaketa zehatza egitea sistema fotovoltaikoen gehieneko potentzia puntuen jarraipenari aplikatuta.

### 1.3 Argitalpenak

Tesi hau idatzi den bitartean, energia berriztagarriei buruzko argitalpen ezberdinak jaso dira, gehienak atzeritik jasoak. Jarraian, argitalpen guztiak zerrendatzen ditugu.

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### 1.3.5 Nazional biltzarretako argitalpenak

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## 1.4 Tesiaren egitura

Ekarpen bildumen bidez eginiko tesia denez, bertako egitura erraza eta zuzena da, JCR motako aldizkarian oinarritako 3 argitalpenak dira bere muina:

- Bigarren kapituluak, era eskematikoan, tesiaren helburuak adierazten ditu, izan ere, tesia baliosetan duen JCR aldizkariko 3 artikuluetan argi eta garbi azaltzen dira
- Hirugarren kapitulua, tesiaren lehenengo artikuluari dagokio. Artikulu hori “International Journal of Hydrogen Energy” izenez JCR motako aldizkarian argiratu zen, non panel fotovoltaikoen modelaketarako prozedura sistematikoaren lorpena planteatzen den
- Laugarren kapitulua, tesiaren bigarren artikuluari dagokio. Artikulu hori “International Journal of Hydrogen Energy” izenez JCR motako aldizkarian argiratu zen. Bertan, kristaldun motako panel fotovoltaikorako modulu dualaren emaitza adierazten da

- Bosgarren kapitulua, tesiaren hirugarren artikuluari dagokio. Artikulu hori “Journal of Electronic Materials” izenez JCR motako aldizkarian argiratu zen. Bertan, lauso den kontrolagailu baten modelaketa azaltzen da, zein modulu fotovoltaikoen gehieneko potentzia puntuen jarraipenerako erabilia izan den
- Seigarren kapituluan, lortutako emaitzen laburpen orokorra eta izandako eztabaidak adierazten dira
- Azkenik, zazpigarren kapituluan, tesi honetan lortutako aurrerapenak eta lorpenei buruzko azken konklusioak agertzen dira



## Kapitulua 2

# Helburuak

Tesi honen helburu nagusia, energia berriztagarrien kontroletarako lagungarri diren modelo zehatzak lortzea izan da, bere erabilera ahalik eta hoberen izan dadila. Halere, arloaren zabalera kontuan izanda, ikerketaren muina, era orokorrean, sistema fotovoltaikoetan oinarritu da, beste teknologia berriztagarrien erabilera baliatuz ere.

Helburuak, tesi honek dituen argitalpen bakoitzean, zehaztasunez azalduta daude. Baina, laburtuta, honakoak adierazi ditzakegu:

1. Sistema fotovoltaikoen modelaketa-teknika desberdinei buruzko egungo egoera egin
2. Orain arte eginiko sistema fotovoltaiko-modelatuen emaitzei buruzko egungo egoera egin
3. Modelo-abstrakzio desberdinak planteatu
4. Sistema fotovoltaikoen modeloak lortzeko prozedura sistematikoa sortu
5. Prozedura sistematiko hau balidatu
6. Erreal sistema fotovoltaikoen datuak lortzeko prozedura sortu
7. Mitsubishi Electric PV-TDD185MFS modulo fotovoltaikorako modelo espezifikoa sortu
8. Altersa A-55 modulo fotovoltaikorako modelo espezifikoa sortu
9. Sistema fotovoltaikora aplikatuta dauden kontrolagailu lausoen modeloak lortu eta balidatu



## Kapitulua 3

# Sistema Fotovoltaikoen Modelatzea

### 3.1 Artikuluaren datu originalak aldizkarian

- Izenburua: Systematic modeling of photovoltaic modules based on artificial neural networks
- Egileak: J. M. Lopez-Guede, J. A. Ramos, E. Zulueta, U. Fernandez, F. Oterino
- Aldizkaria: Journal of Hydrogen Energy, 41(29), 12672-12687
- ISI JCR Impact Factor 2016: 3.582 (Q1)



## Kapitulua 4

# Sistema fotovoltaikoen modelatze duala

### 4.1 Artikuluaren datu originalak aldizkarian

- Izenburua: Dual model oriented modeling of monocrystalline PV modules based on artificial neuronal networks
- Egileak: J. M. Lopez-Guede, J. A. Ramos, E. Zulueta, U. Fernandez, G. Azkune
- Aldizkaria: Journal of Hydrogen Energy, 42(28), 18103-18120
- ISI JCR Impact Factor 2017: 4.229 (Q1)



## Kapitulua 5

# MPPT-rako kontrol neuronalak

### 5.1 Artikuluaren datu originalak aldizkarian

- Izenburua: Neural modeling of fuzzy controllers for maximum power point tracking in photovoltaic energy systems
- Egileak: J. M. Lopez-Guede, J. Ramos, N. Altın, S. Ozdemir, E. Kurt, G. Azkune
- Aldizkaria: Journal of Electronic Materials, 47(8), 4519-4532
- ISI JCR Impact Factor 2017: 1.566 (Q3)



## Kapitulua 6

# Emaitzen eta Eztabaidaren Laburpen Osoa

Kapitulu honetan tesiaren elaborazioan lortutako emaitzak aztertuko ditugu, egungo egoerarekin alderatuz. Tesi honen 1.3. atalean adierazitako zerrendan jasotako argitalpenetan jorratzen diren zenbakien kopurua eta barietatea kontuan hartuta, JCR motako 3 argitalpenek jasotzen dituztenak soilik aztertuko ditugu.

### 1. artikulua: datu originalak aldizkarian

- Izenburua: Systematic modeling of photovoltaic modules based on artificial neural networks
- Egileak: J. M. Lopez-Guede, J. A. Ramos, E. Zulueta, U. Fernandez, F. Oterino
- Aldizkaria: Journal of Hydrogen Energy, 41(29), 12672-12687
- ISI JCR Impact Factor 2016: 3.582 (Q1)

### 2. artikulua: datu originalak aldizkarian

- Izenburua: Dual model oriented modeling of monocrystalline PV modules based on artificial neuronal networks
- Egileak: J. M. Lopez-Guede, J. A. Ramos, E. Zulueta, U. Fernandez, G. Azkune

34 KAPITULUA 6. EMAITZEN ETA EZTABAIDAREN LABURPEN OSOA

- Aldizkaria: Journal of Hydrogen Energy, 42(28), 18103-18120
- ISI JCR Impact Factor 2017: 4.229 (Q1)

**3. artikulua**ren datu originalak aldizkarian

- Izenburua: Neural modeling of fuzzy controllers for maximum power point tracking in photovoltaic energy systems
- Egileak: J. M. Lopez-Guede, J. Ramos, N. Altın, S. Ozdemir, E. Kurt, G. Azkune
- Aldizkaria: Journal of Electronic Materials, 47(8), 4519-4532
- ISI JCR Impact Factor 2017: 1.566 (Q3)

## Kapitulua 7

# Azken ondorioak

Kapitulu honetan tesi honetan garatutako lanaren azken ondorioak bilduko ditugu.

Berriro ere, tesi honetako 1.3. atalean jasotako argitalpenen kopuru eta barietatea ikusi ondoren, soilik frogatu daitezkeen JCR motako 3 argitalpenen ondorioetan zentratuko gara.

“Modulu fotovoltaikoak sistematikoki modelatzen neurona-sare artifizialen bidez” izenburua duen artikuluari dagokionez, gai nagusi bat aztertu dugu modelo global (ez partzialak) doiak sortzeko modulu fotovoltaikoen portaera elektrikoaren ikasketaz ari garenean: modelo zehatz hauek lortzeko prozedura sistematikorik eza; hau da, giza esku-hartze batere gabe. Arazo hau lantzeko gure ikuspegia izan da lau eredu proposatu eta deskribatzea, sare bidezko modulu fotovoltaiko baten portaera elektrikorako hurbilketa formulatzeko (hau da:  $M_1 = (V_{PH} - I_{PH})$ ,  $M_2 = (TG - V_{PH}I_{PH})$ ,  $M_3 = (TG - V_{PH}, TG - I_{PH})$  eta  $M_4 = (TGV_{PH} - I_{PH})$ ), eta prozedura sistematiko orokor bat ezartzea hurbilketa hauen neurona-ereduetan entrenatu eta horiek balidatzeko.

Prozedura sistematiko orokor hori egiaztatzeko, xeheki azaldu dugu erabili dugun diseinu esperimental, honako hauek aurkeztuta: modulu fotovoltaikoa (Mitsubishi Electric PV-TD185MF5, 185 Wp), zeinaren modelo zehatz bat lortu baita prozedura sistematiko orokorraren kontzeptu-proba gisa; magnitude nagusiak neurtzeko gailuak; eta prozedura sistematiko orokorraren deskribapen zabala. Prozedura hori aplikatzean 18 hilabetetan bildutako 63,000 laginek osatutako datu-multzo handi bati, doitasun handiko bi modelo lortu ziren (geruza ezkutatu bat duen neurona-sare bateko  $Perf_{test}$  0.045 A-ko RMSE da, eta bi geruza ezkutatu dituen sareko  $Perf_{test}$  0.042 A-ko RMSE da; bi kasuetan, neur-

gailuen doitasuna baino txikiagoa). Gainera, agerian gelditu da proposatzen den prozedura lehiakorra dela eta hobetu egiten dituela artearen egoeraren emaitzak, alderaketa egin daitekeen kasuetan.

“Dual model oriented modeling of monocrystalline PV modules based on artificial neuronal networks” izenburua duen artikuluari dagokionez, deskribatu egin ditugu bideragarrienak diren bi modelo espezifikazioen sarrera eta irteera, erabiliko direnak modulu fotovoltaiko monokristalinoaren portaera elektrikoa zehazki nolakoa izango den aurretiko. Gure ikuspegiaren bideragarritasuna erakusteko, xeheki azaldu dugu lan balidazio-atalaren konfigurazio esperimentala, Atersa A55 modulu fotovoltaiko monokristalinoak, neurtzeko gailuek eta prozedura sistematiko orokorraren deskribapen xeheak osatzen dutena.

Konfigurazio esperimental horren emaitza gisa, doitasun handiko modelook lortu ditugu, bai udarako bai negurako. Aurreko portaeraren hurbilketa egin dugu, RMSE= 0.201 mA errorearekin eta 33.554 mA-ko errore maximoarekin test datu-multzo baterako,  $M_2 = (TGV_{PH} - I_{PH})$  modeloaren abstrakziopean bi geruza ezkutu dituen neurona-sareaz. Aldiz, negurako modelook, doitasun handiagokoa, RMSE= 0.26 mA errorea eta 7.51 mA-ko errore maximoa du test datu-multzo batekin; kasu honetan,  $M_2 = (TGV_{PH} - I_{PH})$  modeloaren abstrakziopean geruza ezkutu bat duen neurona-sareaz. Ikasitako bi modeloen kasuan, honako hau atera dezakegu ondorio gisa: modulu fotovoltaiko monokristalino baten estaziorako modelook lortzeko erabili den prozedura sistematikoaren kontzeptu-probak erakutsi du egokia dela helburu honetarako, bi kasuetan errore maximoa txikiagoa delako neurgailuen doitasuna baino, eta gure emaitzek gainditu egiten dituzte egungo egoerarenak.

Amaitzeko, “Neural modeling of fuzzy controllers for maximum power point tracking in photovoltaic energy systems” izenburuarekin landu dugun azken lanari dagokionez, berrikusi egin dugu elementu fotovoltaikoen modelatuari buruzko egungo egoera, QBC eta MPPT algoritmoen moduko kontrolagailuak, den-denak material elektronikoetatik energia maximoa lortzea ahalbidetzen duten teknologiak.

Halaber, FLC diseinu espezifikoa bat gogoratu genuen, eta planteatu genuen hura nola modelatu neurona-sare bat erabilita, arrakasta izan zuen diseinu esperimental batez. Hala, FLC kontrolagailu espezifikoa baten modelo doi bat lortu zen, MSE errorea  $3.47 \times 10^{-6}$  delako eta errore maximoa  $16.32 \times 10^{-3}$  test datuetarako,  $R = 0.99992$  korrelazio-koefizientearekin test datu-multzorako. Horri esker, bihurgailuen implementazio askoz sinpleagoak egin daitezke, MPPT

algoritmoetan oinarrituak eta kontrolagailu difusoak erabilia, eta sistema orokorra sinpletzea eta hobetzea lortzen da, potentzia-produkzio bera lortzeko.

Oro har, tesi honetan burututako lana, energia berriztagarrien iturrietan erlazionaturiko teknologia zehatz bati (fotovoltaika) ezarritako modulazio eta kontrol tekniken erabileraren arrakasta bezala uler daiteke. Horrez gain, espreski adierazi dira, tesian jasotako teknikak eremu honekin zerikusia duten beste arlo batzuetan erabiltzeko beharrezko prozedurak.



## Kapitulua 8

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