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Broj: 02/1-1709/1
Datum: 25.10.2023.

UNIVERZITET CRNE GORE

- Odbor za doktorske studije -

- Senatu -

O V D J E

U prilogu dostavljamo Odluku Vijeća Elektrotehničkog fakulteta sa sjednice od 19.10.2023. godine i obrazac **D2**, sa pratećom dokumentacijom, za kandidata MSc **Mihaila Miceva**, na dalji postupak.

D E K A N

Prof. dr Saša Mujović

ISPUNJENOST USLOVA DOKTORANDA

OPŠTI PODACI O DOKTORANDU			
Titula, ime, ime roditelja, prezime	MSc Mihailo Branko Micev		
Fakultet	Elektrotehnički fakultet		
Studijski program	Doktorske studije elektrotehnike		
Broj indeksa	2/20		
NAZIV DOKTORSKE DISERTACIJE			
Na službenom jeziku	Novi pristupi u identifikaciji i optimizaciji parametara glavnih komponenti sistema za regulaciju pobude sinhronih generatora		
Na engleskom jeziku	Novel approaches for identification and parameters optimization of main components of synchronous generators' excitation regulation		
Naučna oblast	Automatika i industrijska elektrotehnika		
MENTOR/MENTORI			
Prvi mentor	Doc. dr Martin Ćalasan	Elektrotehnički fakultet, Univerzitet Crne Gore, Podgorica, Crna Gora	Električne mašine i pogoni
Drugi mentor	Prof. dr Milovan Radulović	Elektrotehnički fakultet, Univerzitet Crne Gore, Podgorica, Crna Gora	Automatika
KOMISIJA ZA PREGLED I OCJENU DOKTORSKE DISERTACIJE			
Prof. dr Vladan Vujičić		Elektrotehnički fakultet, Univerzitet Crne Gore, Podgorica, Crna Gora	Energetska elektronika
Prof. dr Dušan Stipanović		The Grainger College of Engineering, University of Illinois Urbana-Champaign, Ilinois, Sjedinjene Američke Države	Sistemi automatskog upravljanja (Control systems)
Prof. dr Gojko Joksimović		Elektrotehnički fakultet, Univerzitet Crne Gore, Podgorica, Crna Gora	Električne mašine
Prof. dr Milovan Radulović		Elektrotehnički fakultet, Univerzitet Crne Gore, Podgorica, Crna Gora	Automatika
Doc. dr Martin Ćalasan		Elektrotehnički fakultet, Univerzitet Crne Gore, Podgorica, Crna Gora	Električne mašine i pogoni

Datum značajni za ocjenu doktorske disertacije	
Sjednica Senata na kojoj je data saglasnost na ocjenu teme i kandidata	15. 12. 2021. godine
Dostavljanja doktorske disertacije organizacionoj jedinici i saglasanost mentora	05. 10. 2023. godine
Sjednica Vijeća organizacione jedinice na kojoj je dat prijedlog za imenovanje komisija za pregled i ocjenu doktorske disertacije	19. 10. 2023. godine

ISPUNJENOST USLOVA DOKTORANDA

U skladu sa članom 38 pravila doktorskih studija kandidat je cjelokupna ili dio sopstvenih istraživanja vezanih za doktorsku disertaciju publikovao u časopisu sa **(SCI/SCIE)/(SSCI/A&HCI)** liste kao prvi autor.

Spisak radova doktoranda iz oblasti doktorskih studija koje je publikovao u časopisima sa SCI/SCIE liste:

1. M. Micev, M. Ćalasan, and D. Oliva, "Design and robustness analysis of an Automatic Voltage Regulator system controller by using Equilibrium Optimizer algorithm," *Comput. Electr. Eng.*, vol. 89, p. 106930, 2021, doi: 10.1016/j.compeleceng.2020.106930.

Link na rad:
https://www.sciencedirect.com/science/article/abs/pii/S0045790620307795?via%3Dihub
Informacija o IMPACT faktoru časopisa:
https://www.sciencedirect.com/journal/computers-and-electrical-engineering

2. M. Micev, M. Ćalasan, and D. Oliva, "Fractional order PID controller design for an AVR system using Chaotic Yellow Saddle Goatfish Algorithm," *Mathematics*, vol. 8, no. 7, 2020, doi: 10.3390/math8071182.

Link na rad: https://www.mdpi.com/2227-7390/8/7/1182
Informacija o IMPACT faktoru časopisa: https://www.mdpi.com/journal/mathematics

3. M. Micev, M. Ćalasan, Z. M. Ali, H. M. Hasanien, and S. H. E. Abdel Aleem, "Optimal design of automatic voltage regulation controller using hybrid simulated annealing – Manta ray foraging optimization algorithm," *Ain Shams Eng. J.*, vol. 12, no. 1, pp. 641–657, 2021, doi: 10.1016/j.asej.2020.07.010.

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https://www.sciencedirect.com/journal/ain-shams-engineering-journal

4. M. Micev, M. Calasan, D. S. Petrovic, Z. M. Ali, N. V. Quynh, and S. H. E. Abdel Aleem, "Field current waveform-based method for estimation of synchronous generator parameters using adaptive black widow optimization algorithm," *IEEE Access*, vol. 8, pp. 207537–207550, 2020, doi: 10.1109/ACCESS.2020.3037510.

Link na rad: https://ieeexplore.ieee.org/document/9256260
Informacija o IMPACT faktoru časopisa:
https://ieeexplore.ieee.org/xpl/RecentIssue.jsp?punumber=6287639

5. M. Micev, M. Calasan, S. H. E. A. Aleem, H. M. Hasanien, and D. S. Petrovic, "Two Novel Approaches for Identification of Synchronous Machine Parameters from Short-Circuit Current Waveform," *IEEE Trans. Ind. Electron.*, vol. 69, no. 6, pp. 5536–5546, 2022, doi: 10.1109/TIE.2021.3086715.

Link na rad: https://ieeexplore.ieee.org/document/9451573
Informacija o IMPACT faktoru časopisa:
https://ieeexplore.ieee.org/xpl/RecentIssue.jsp?punumber=41

6. M. Micev, M. Calasan, and M. Radulovic, "Full Synchronous Machine Parameters Identification Based on Field and Armature Current during the Short-Circuit," *IEEE Trans. Ind. Appl.*, vol. 57, no. 6, pp. 5959–5968, 2021, doi: 10.1109/TIA.2021.3112141.

Link na rad: https://ieeexplore.ieee.org/document/9536395
Informacija o IMPACT faktoru časopisa:
https://ieeexplore.ieee.org/xpl/RecentIssue.jsp?punumber=28

7. M. Micev, M. Ćalasan, D. Stipanović, and M. Radulović, "Modeling the relation between the AVR setpoint and the terminal voltage of the generator using artificial neural networks," *Eng. Appl. Artif. Intell.*, vol. 120, p. 105852, 2023, doi: 10.1016/j.engappai.2023.105852.

Link na rad: https://www.sciencedirect.com/science/article/abs/pii/S0952197623000362
Informacija o IMPACT faktoru časopisa:
https://www.sciencedirect.com/journal/engineering-applications-of-artificial-intelligence

8. M. Micev, M. Calasan, M. Radulovic, S. H. E. A. Aleem, H. M. Hasanien, and A. F. Zobaa, "Artificial Neural Network-Based Nonlinear Black-Box Modeling of Synchronous Generators," *IEEE Trans. Ind. Informatics*, vol. 19, no. 3, pp. 2826–2837, 2023, doi: 10.1109/TII.2022.3187740.

Link na rad: https://ieeexplore.ieee.org/document/9813409
Informacija o IMPACT faktoru časopisa:
https://ieeexplore.ieee.org/xpl/RecentIssue.jsp?punumber=9424

9. M. Micev, M. Ćalasan, and M. Radulović, "Optimal tuning of the novel voltage regulation controller considering the real model of the automatic voltage regulation system," *Heliyon*, vol. 9, no. 8, p. e18707, 2023, doi: 10.1016/j.heliyon.2023.e18707.

Link na rad: https://www.sciencedirect.com/science/article/pii/S2405844023059157
Informacija o IMPACT faktoru časopisa: https://www.sciencedirect.com/journal/heliyon

Obrazloženje mentora o korišćenju doktorske disertacije u publikovanim radovima

Doktorand MSc Mihailo Micev je svoja istraživanja na kojima je zasnovana doktorska disertacija predstavio kroz 9 radova na kojima je prvi autor, a koji su objavljeni u časopisima sa SCI/SCIE liste. Kumulativni IMPACT faktor svih časopisa u kojima su publikovani radovi kandidata iznosi **53**. Ključni rezultati koji su publikovani kroz pomenutih 9 radova, na kojima se bazira predmetna doktorska disertacija, obrazloženi su u nastavku:

Naučni rad "*Design and robustness analysis of an Automatic Voltage Regulator system controller by using Equilibrium Optimizer algorithm*" objavljen je u časopisu *Computers and Electrical Engineering*, čiji je IMPACT faktor 4.3, demonstrira optimalno dizajniranje idealnog PID regulatora korišćenjem poznatog EO algoritma, pri čemu je predložena nova kriterijumska funkcija. Predložena kriterijumska funkcija predstavlja modifikaciju poznatih kriterijumskih funkcija, sa ciljem poboljšanja rezultata publikovanih u dostupnoj literaturi.

U naučnom radu "*Fractional order PID controller design for an AVR system using Chaotic Yellow Saddle Goatfish Algorithm*", koji je publikovan u časopsi *Mathematics* sa IMPACT faktorom 2.4, predložen je novi hibridni C-YSGA algoritam, koji predstavlja spoj haotičnog i već postojećeg YSGA algoritma. Takođe, u ovom radu je predložena nova kriterijumska funkcija. Predloženi pristup je iskorišćen za određivanje optimalnih vrijednosti parametara FOPID regulatora.

U naučnom radu "*Optimal design of automatic voltage regulation controller using hybrid simulated annealing – Manta ray foraging optimization algorithm*", publikovanom u časopisu *Ain Shams Engineering Journal* (IMPACT faktor 6), predložen je novi hibridni metaheuristički algoritam za određivanje parametara različitih regulatora koji se koriste u sistemu za automatsku regulaciju pobude sinhronog generatora. Razmatrana je primjena nekih od najčešće korišćenih regulatora u literaturi: idealni PID, realni PID, FOPID i $PIDD^2$. Pokazano je da regulatori čiji su parametri određeni primjenom predloženog algoritma omogućavaju znatno kvalitetniji odziv sistema u poređenju sa drugim metodama iz literature.

U radu "*Field current waveform-based method for estimation of synchronous generator parameters using adaptive black widow optimization algorithm*", koji je objavljen u časopisu *IEEE Access* sa IMPACT faktorom 3.9, demonstriran je metod estimacije parametara sinhronog generatora koristeći približni analitički izraz za struju pobude u režimu kratkog spoja. Takođe, u cilju estimacije parametara predložena je modifikacija postojećeg BWO metaheurističkog algoritma, čime su poboljšane njegove performanse i ubrzana konvergencija. Eksperimentalna verifikacije predloženog metoda izvršena je na realnom sinhronom generatoru snage 109.6 MVA u hidroelektrani „Bajina Bašta".

Naučni rad "*Two Novel Approaches for Identification of Synchronous Machine Parameters from Short-Circuit Current Waveform*", koji je publikovan u časopisu *IEEE Transactions on Industrial Electronics* sa IMPACT faktorom 7.7, predložena su dva nova pristupa za estimaciju parametara sinhronog generatora. Za proces estimacije koristi se aproksimativni izraz za talasni oblik struje armature u režimu kratkog spoja, a ekstrakcija samih parametara izvršena je pomoću novog hibridnog metaheurističkog algoritma koji je predložen u ovom radu. Prvi pristup zasnovan je na „fitovanju" eksperimentalno snimljenih i analitički proračunatih talasnih oblika ukupne struje armature. Za razliku od toga, drugi pristup se bazira na dekompoziciji talasnog oblika struje armature na dvije komponente, i zatim odvojenim „fitovanjem" obije komponente.

U radu "*Full Synchronous Machine Parameters Identification Based on Field and Armature Current during the Short-Circuit*", objavljenom u časopisu *IEEE Transactions on Industry Applications* (IMPACT factor 4.4), za razliku od prethodno pomenutih radova koji koriste približne izraze za struje pobude i armature, koriste se egzaktni izrazi za struje, što omogućava estimaciju znatno većeg broja parametara samog generatora. Takođe, primjena tačnih izraza dovodi do znatno bolje, tačnije i preciznije estimacije parametara. Tačni izrazi su izvedeni pomoću inverzne Laplasove transformacije, a eksperimentalna validacija je, kao i u prethodna dva rada, izvedena na realnom generatoru iz hidroelektrane „Bajina Bašta".

Naučni rad pod nazivom "*Modeling the relation between the AVR setpoint and the terminal voltage of the generator using artificial neural networks*", objavljen u časopisu *Engineering Applications of Artificial Intelligence* sa IMPACT faktorom 8, predlaže modelovanje veze između referentne vrijednosti napona generatora i napona na krajevima generatora pomoću neuralnih mreža. Na taj način obuhvaćen je kompletan system za regulaciju pobude, uključujući sve dodatne funkcionalne blokove. Za obučavanje i validaciju neuralnih mreža korišćeni su eksperimentalno snimljeni odzivi napona, dobijeni sprovođenjem odgovarajućih testova na realnom sinhronom generatoru iz HE "Piva", čija je nominalna snaga 120 MVA.

U radu "*Artificial Neural Network-Based Nonlinear Black-Box Modeling of Synchronous Generators*", koji je publikovan u časopisu *IEEE Transactions on Industrial Informatics* sa IMPACT faktorom 12.3, predložen je novi način reprezentacije veze između napona pobude i izlaznog napona na krajevima sinhronog generatora koristeći neuralne mreže. Ulazni signal predstavljen je naponom pobude, dok je izlazni signal napon na krajevima generatora. U cilju adekvatnog obučavanja i validacije neuralne mreže, obavljena su eksperimentalna testiranja na generatoru snage 120 MVA u hidroelektrani „Piva" i snimljeni su talasni oblici napona pobude i napona na izlazu generatora pri različitim uslovima rada. Komparativna analiza je nedvosmisleno pokazala da je predloženi model baziran na neuralnim mrežama, znatno tačniji i precizniji u poređenju sa drugim parametarskim nelinearnim modelima koji su često korišćeni u literaturi.

U naučnom radu "*Optimal tuning of the novel voltage regulation controller considering the real model of the automatic voltage regulation system*", publikovanom u časopisu *Heliyon* sa IMPACT faktorom 4, predložen je novi tip regulatora za pobudne sisteme sinhronog generatora. Performanse predloženog regulatora testirane su korišćenjem simulacionog modela realnog sistema za regulaciju pobude, koji uključuje limitere i sve dodatne funkcionalne blokove. Optimizacija parametara predloženog regulatora sprovedena je primjenom predložene adaptivne modifikacije AVOA algoritma. Takođe, predložena je nova multiobjektivna kriterijumska funkcija, koja ima za cilj postizanje što kvalitetnijeg prelaznog procesa, kao i suzbijanje poremećaja i mjernih šumova.

Datum i ovjera (pečat i potpis odgovorne osobe)	
U Podgorici, 25. 10. 2023. godine	MP DEKAN

Prilog dokumenta sadrži:

1. Potvrdu o predaji doktorske disertacije organizacionoj jedinici
2. Odluku o imenovanju komisije za pregled i ocjenu doktorske disertacije
3. Kopiju rada publikovanog u časopisu sa odgovarajuće liste
4. Biografiju i bibliografiju kandidata
5. Biografiju i bibliografiju članova komisije za pregled i ocjenu doktorske disertacije sa potvrdom o izboru u odgovarajuće akademsko zvanje i potvrdom da barem jedan član komisije nije u radnom odnosu na Univerzitetu Crne Gore

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Broj: 02-1574
Datum: 05.10.2023.

Na osnovu službene evidencije i dokumentacije Elektrotehničkog fakulteta u Podgorici, izdaje se

POTVRDA

MSc **Mihailo Micev**, student doktorskih studija na Elektrotehničkom fakultetu u Podgorici, dana 05.10.2023. godine dostavio je ovom Fakultetu doktorsku disertaciju pod nazivom: **„Novi pristupi u identifikaciji i optimizaciji parametara glavnih komponenti sistema za regulaciju pobude sinhronih generatora“**, na dalji postupak.

SEKRETAR

mr Valentina Lješević - Dedić

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Broj: 02/1-1709
Datum: 19.10.2023

Na osnovu člana 64 Statuta Univerziteta Crne Gore, u vezi sa članom 41 Pravila doktorskih studija, na predlog Komisije za doktorske studije, Vijeće Elektrotehničkog fakulteta u Podgorici, na sjednici od 19.10.2023. godine, donijelo je

O D L U K U

Predlaže se Komisija za ocjenu doktorske disertacije **„Novi pristupi u identifikaciji i optimizaciji parametara glavnih komponenti sistema za regulaciju pobude sinhronih generatora“** kandidata MSc **Mihaila Miceva,** u sastavu:

1. Dr Vladan Vujičić, redovni profesor Elektrotehničkog fakulteta Univerziteta Crne Gore,
2. Dr Dušan Stipanović, redovni profesor University of Illinois at Urbana-Champaign, Department of Industrial and Enterprise Systems Engineering, SAD,
3. Dr Gojko Joksimović, redovni profesor Elektrotehničkog fakulteta Univerziteta Crne Gore,
4. Dr Milovan Radulović, redovni profesor Elektrotehničkog fakulteta Univerziteta Crne Gore (komentor) i
5. Dr Martin Ćalasan, docent Elektrotehničkog fakulteta Univerziteta Crne Gore (mentor).

-VIJEĆE ELEKTROTEHNIČKOG FAKULTETA-

UNIVERZITET CRNE GORE
Elektrotehnički fakultet

D E K A N
Prof. dr Saša Mujović

Dostavljeno:
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- Odboru za doktorske studije,
- u dosije,
- a/a.

Spisak radova sa rezultatima iz doktorske disertacije:

- **Naučni časopisi na SCI/SCIE listi:**

1) M. Micev, M. Ćalasan, M. Radulović, S. H. E. A. Aleem, H. M. Hasanien and A. F. Zobaa, "Artificial Neural Network-Based Nonlinear Black-Box Modeling of Synchronous Generators," in IEEE Transactions on Industrial Informatics, vol. 19, no. 3, pp. 2826-2837, March 2023, doi: 10.1109/TII.2022.3187740.
2) Mihailo Micev, Martin Ćalasan, Dušan Stipanović, Milovan Radulović, „Modeling the relation between the AVR setpoint and the terminal voltage of the generator using artificial neural networks," Engineering Applications of Artificial Intelligence, Volume 120, 2023, 105852, ISSN 0952-1976, https://doi.org/10.1016/j.engappai.2023.105852.
3) M. Micev, M. Ćalasan, S. H. E. A. Aleem, H. M. Hasanien and D. S. Petrović, "Two Novel Approaches for Identification of Synchronous Machine Parameters From Short-Circuit Current Waveform," in *IEEE Transactions on Industrial Electronics*, vol. 69, no. 6, pp. 5536-5546, June 2022, doi: 10.1109/TIE.2021.3086715.
4) M. Micev, M. Ćalasan, D. S. Petrović, Z. M. Ali, N. V. Quynh and S. H. E. Abdel Aleem, "Field Current Waveform-Based Method for Estimation of Synchronous Generator Parameters Using Adaptive Black Widow Optimization Algorithm," in *IEEE Access*, vol. 8, pp. 207537-207550, 2020, doi: 10.1109/ACCESS.2020.3037510.
5) M. Micev, M. Ćalasan and M. Radulović, "Full Synchronous Machine Parameters Identification Based on Field and Armature Current During the Short-Circuit," in *IEEE Transactions on Industry Applications*, vol. 57, no. 6, pp. 5959-5968, Nov.-Dec. 2021, doi: 10.1109/TIA.2021.3112141.
6) M. Micev, M. Ćalasan, and D. Oliva, "Design and robustness analysis of an Automatic Voltage Regulator system controller by using Equilibrium Optimizer algorithm," *Comput. Electr. Eng.*, vol. 89, p. 106930, Jan. 2021, doi: 10.1016/J.COMPELECENG.2020.106930.
7) M. Micev, M. Ćalasan, Z. M. Ali, H. M. Hasanien, and S. H. E. Abdel Aleem, "Optimal design of automatic voltage regulation controller using hybrid simulated annealing – Manta ray foraging optimization algorithm," *Ain Shams Eng. J.*, vol. 12, no. 1, pp. 641–657, Mar. 2021, doi: 10.1016/J.ASEJ.2020.07.010.
8) Micev, M.; Ćalasan, M.; Oliva, D. Fractional Order PID Controller Design for an AVR System Using Chaotic Yellow Saddle Goatfish Algorithm. *Mathematics* **2020**, *8*, 1182. https://doi.org/10.3390/math8071182.
9) M. Micev, M. Ćalasan, and M. Radulović, "Optimal tuning of the novel voltage regulation controller considering the real model of the automatic voltage regulation system," *Heliyon*, vol. 9, no. 8, p. e18707, 2023, doi: 10.1016/j.heliyon.2023.e18707.

- Međunarodne konferencije:

1) M. Micev, M. Ćalasan and M. Radulović, "Identification of synchronous generator parameters from operating data during the short-circuit from no-load operation," *2021 20th International Symposium INFOTEH-JAHORINA (INFOTEH)*, 2021, pp. 1-6, doi: 10.1109/INFOTEH51037.2021.9400701.
2) M. Micev, M. Ćalasan i M. Radulović, " Modelovanje sistema za regulaciju pobude sinhronog generatora primjenom nelinearnog ARX modela," ETRAN 2021.
3) M. Micev, M. Ćalasan, M. Radulović, and V. Vujičić, "Parameter identification of different models of automatic voltage regulation system," in *2023 22nd International Symposium INFOTEH-JAHORINA (INFOTEH)*, 2023, pp. 1–6. doi: 10.1109/INFOTEH57020.2023.10094181.

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Two Novel Approaches for Identification of Synchronous Machine Parameters From Short-Circuit Current Waveform

Mihailo Micev, *Student Member, IEEE*, Martin Ćalasan, *Member, IEEE*, Shady H. E. Abdel Aleem, *Senior Member, IEEE*, Hany M. Hasanien, *Senior Member, IEEE*, and Dragan S. Petrović

***Abstract*—In this article, two novel approaches for identifying the synchronous generator (SG) parameters are presented. The proposed approaches use an experimentally obtained armature current during the short-circuit test as input data. Both approaches are simple, cost-effective, and practical since they do not require any additional equipment for signal generation nor applying any of the advanced control techniques. The first approach relies on fitting the analytical total armature current waveform with the experimental one, while the second approach relies on matching the observed waveform with an analytical waveform of asymmetrical and alternating components. Instead of traditional graphical methods typically used in standardized procedures, this article also proposes a novel hybrid metaheuristic algorithm to identify the SG's parameters. The experimental verification of the proposed methods is carried out on 100 MVA SG at the Bajina Basta hydropower plant in Serbia.**

***Index Terms*—Armature current, chaotic logistic mapping, equilibrium optimizer (EO) algorithm, parameter estimation, short-circuit, synchronous machine.**

I. Introduction

DIFFERENT studies related to the power grid analysis require reliable and precise models of each component of the power system. As it is well known, electrical energy production is carried out by electrical generators, among which the most recognized are synchronous generators (SGs) [1]. Obtaining the accurate model of SG is crucial for the stability analysis of the power system. Additionally, operation, planning studies, and testing of the power system dynamics in the transient period are based on computer models that require an accurate SG model. Small signal stability, fault protection, and sub-synchronous resonance are other important studies that require the knowledge of SG parameters. In accordance with the importance of estimating the generator parameters, many recent studies are dedicated to this topic. Numerous test methods have been presented in IEEE and IEC standards [2], [3]. Also, many authors have proposed novel methods for estimation of the SG parameters and exploring new modifications of the approaches to perform the tests. The proposed test methods can be classified in two ways. First, the methods can be divided into offline [3]–[10] and online methods [11]–[31]. The most popular offline methods presented in the literature are standstill frequency response (SSFR) test [3]–[5], sine cardinal (sinc) perturbation test [6], step voltage test [7], dc decay, and pseudorandom binary sequence (PRBS) test [8], [9] and chirp signal test [10]. The work in [6]–[10] proposed novel excitation signals (sinc, step, PRBS, and chirp), which were applied to the stator windings, while the field current and voltage signals, along with the stator current, were measured and used for the extraction of the generator parameters. The main drawbacks of the offline methods are the consequences caused by disconnecting the generator from the grid. The special types of offline methods are mandatory tests that can be carried out during the commissioning, overhaul, and revitalization of the generator [2], [3]. Among the most popular commissioning tests are the load rejection (LR) test [11]–[15] and the sudden short-circuit (SSC) test [16]–[18], which are also used in standardized procedures [2], [3]. The online methods are the ones that do not require the generator's disconnection from the grid. The usage of the operational data obtained by phasor measurement units to determine the parameters of the SG is demonstrated in [19]–[24]. The work in [25]–[28] proposed the methods for obtaining parameters by measuring stator and field voltages and currents during the generator's normal operation mode. The test method proposed in [29] is based not only on acquiring voltages and currents of the armature and field winding but also on measuring active and reactive power on the generator's terminals. An approach based on small current signal injection

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into the stator current, considering that the injected signal does not impact the generator's normal operation, is depicted in [30]. Furthermore, the generator's transient data during a remote line-to-line fault in the power system can be used to identify the generator's unknown parameters, as was demonstrated in [31]. The main drawback of most of the existing online methods is that they require the injection of different types of signals, which can significantly increase the cost of the setup due to the need for additional equipment. Furthermore, that makes the setup control techniques very complicated. Additionally, as highlighted in [32], many online methods require information about the load angle, which is not always possible to detect in practice.

The second classification of the test methods is on frequency response [3]–[5] and time response methods [6]–[31]. The main representative of frequency response methods is an SSFR test, which is also included in the IEEE standard. This test is composed of obtaining the generator's response when the stator is excited with the signals of various frequencies, which is time-consuming. Additionally, this test applies mainly to the thermal generator (with a round rotor), while there are specific difficulties when it is used to the generator with a high number of poles (hydro generators) [4]. Therefore, time response methods are found to be more popular compared with the frequency response methods.

Another important aspect of the test procedures is the method or algorithm used to extract the SG parameters. In the literature, a large variety of extraction methods are applied: least squares method was used in [10]–[12], [21], [25], and [29], metaheuristic algorithms were applied in [6], [7], [9], [18], [22], [30], and [31], while the dynamic state estimators based on Kalman filters were demonstrated in [19], [20], and [28]. The traditional graphical method was used in [15], an interior point was used in [13] and [24], and adaptive importance sampling along with Bayesian inference was applied in [23]. Some of the nonconvenient optimization tools are Knitro optimization solver, which was used in [16], nonlinear mapping and output error method [26], Hartley series [27], Levenberg–Marquardt [8], and numeric algorithm [17].

Regarding the SG parameters, it is also interesting to mention that the parameters change with age. The main reasons are overhauling and revitalizing the generator, which causes the change of the air-gap length. This further causes the change in direct and quadrature axis synchronous reactances X_d and X_q. Therefore, after each overhaul/revitalization, standard test procedures must be carried out again to determine the change in the generator's parameters.

This article deals with the SSC test method to determine the SG parameters. The drawback of the standardized SSC and LR tests is that the generator is stressed during these tests, i.e., potentially harmful to the machine at the rated voltage. The short-circuit test presented in this article is conducted at the reduced terminal voltage (20%, 30%, and 50% of the rated voltage) to avoid such potential machine damage. In line with the IEEE [2] and IEC standards [3], the graphical decomposition of the acquired armature current waveform is applied to get the generator's unknown parameters after performing the short-circuit test and obtaining the armature current waveform. Precisely, this technique consists of the manual construction of the envelopes of the armature current oscillogram. This procedure is manual, and it is, therefore, subject to human error. This article main contribution is the proposal of two novel techniques for determining the SG parameters. The first technique uses the armature current waveform during the short circuit. The second technique relies on the decomposition of the armature current on the asymmetrical and symmetrical components. This article also proposes a novel hybrid metaheuristic algorithm called the Chaotic equilibrium optimizer (C-EO) algorithm to overcome the graphical extraction method's disadvantages [33]. Additionally, the proposed C-EO algorithm is compared with other popular metaheuristic algorithms, and it proves the superiority in terms of convergence speed and the accuracy of the results.

The main advantage of the proposed methods is their applicability in both manufacturer's testing of the generator and testing in the power plant. Namely, they are straightforward, practical, and easy to implement since they do not require any additional equipment and testing procedures. Furthermore, during every overhaul or revitalization of the generator, conducting short-circuit and open-circuit tests are mandatory. Nevertheless, short-circuit test is described in IEEE and IEC standards, which highlights its importance, while none of the existing online methods is depicted nor described in the standards.

The rest of this article is organized as follows. The detailed description of the experiment set up in this article is presented in Section II. Afterward, a short overview of the SG model and armature current oscillograms and analytical expression is given in Section III. Section IV presents the novel hybrid metaheuristic algorithm proposed in this article, while the results are depicted in Section V. Finally, Section VI concludes this article.

II. Parameter Identification Procedures

Typical construction of the SG, which consists of the three armature coils (a, b, and c), the field coil (f), and the damper coils (kd and kq), is shown in Fig. 1(a). The voltage equations for each winding can be derived, and the mathematical model related to the a–b–c frame is obtained. However, in this case, many of the inductances are time and rotor position functions. Hence, the armature variables (from the a–b–c frame) are transformed into the so-called d–q reference frame fixed to the field system to simplify the model. This approach is the most comprehensive method used to analyze and model the SG and is called Park's transformations. According to Park's practice, the synchronous machine is represented in a two-axis frame, consisting of a direct (d) and a quadrature (q) axis. The transformation of the frames is derived, taking into account that the currents in the d and q coils (i_d and i_q) would set up the same magnetomotive force as the currents in the actual windings of the generator (i_a, i_b, and i_c) [1]. Fig. 1(b) depicts the two-axis representation of the synchronous machine. The two-axis model of the synchronous machine is derived from the voltage equations for each winding from Fig. 1(b); thus

$$u_d = R_a i_d + \frac{d\psi_d}{dt} + \omega\psi_q \quad (1)$$

$$u_q = R_a i_q + \frac{d\psi_q}{dt} - \omega\psi_d \quad (2)$$

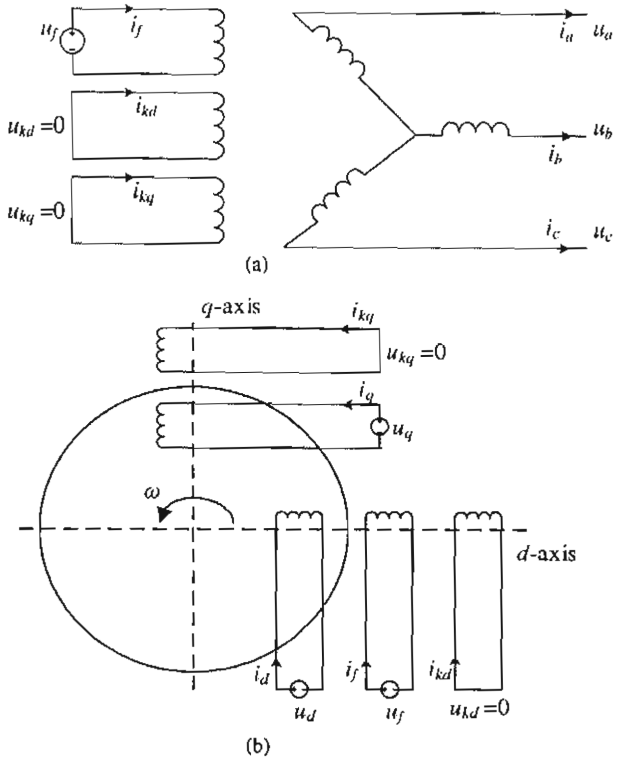

Fig. 1. Representation of the synchronous machine in (a) a–b–c frame. (b) d–q frame.

$$u_f = R_f i_f + \frac{d\psi_f}{dt} \tag{3}$$

$$u_{kd} = R_{kd} i_{kd} + \frac{d\psi_{kd}}{dt} = 0 \tag{4}$$

$$u_{kq} = R_{kq} i_{kq} + \frac{d\psi_{kq}}{dt} = 0. \tag{5}$$

In (1)–(5), u denotes the voltage, i denotes the current, R represents the resistance, ω and ψ denote the angular speed and flux linkage, respectively.

The subscripts d, a, q, f, kd, and kq refer to the direct axis, armature, quadrature axis, field, d-axis damper, and q-axis damper windings, respectively. The flux linkages of each winding can be calculated using (as

$$\psi_d = (L_{md} + L_a)\, i_d + L_{md} i_f + L_{md} i_{kd} \tag{6}$$

$$\psi_q = (L_{mq} + L_a)\, i_q + L_{mq} i_{kq} \tag{7}$$

$$\psi_f = (L_{md} + L_f)\, i_f + L_{md} i_d + L_{md} i_{kd} \tag{8}$$

$$\psi_{kd} = (L_{md} + L_{kd})\, i_{kd} + L_{md} i_f + L_{md} i_d \tag{9}$$

$$\psi_{kq} = (L_{mq} + L_{kq})\, i_{kq} + L_{mq} i_q. \tag{10}$$

In (6)–(10), the leakage inductance of the armature, field, d-axis damper, and q-axis damper windings are denoted with L_a, L_f, L_{kd}, and L_{kq}, respectively. Also, L_{md} and L_{mq} represent the mutual inductances between the windings on the d-axis and q-axis, respectively. Based on (1)–(10), the synchronous machine's equivalent circuit is drawn. The d-axis equivalent circuit of the synchronous machine is depicted in Fig. 2(a), while Fig. 2(b) corresponds to the q-axis equivalent circuit.

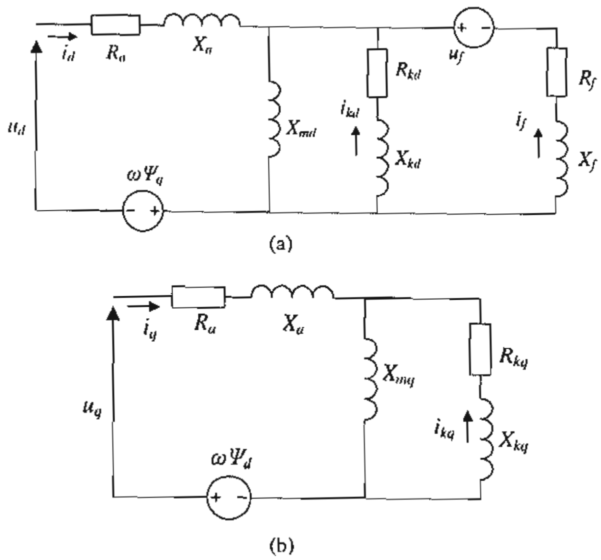

Fig. 2. Equivalent circuit of (a) d-axis and (b) q-axis.

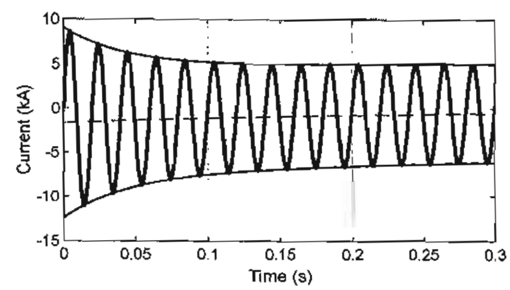

Fig. 3. Typical oscillogram of the armature current during the short-circuit test.

Further, the SSC test of an unloaded generator was carried out. The typical oscillogram of the armature current during the short-circuit test is depicted in Fig. 3.

The analytical expression for one phase's armature current during the short-circuit is derived in [1], and it is given as

$$i_a(t) = U_m \begin{bmatrix} \frac{1}{X_d} + \left(\frac{1}{X_d'} - \frac{1}{X_d}\right) e^{-\frac{t}{T_d'}} \\ + \left(\frac{1}{X_d''} - \frac{1}{X_d'}\right) e^{-\frac{t}{T_d''}} \end{bmatrix} \cos(\omega_0 t + \lambda)$$
$$- \frac{U_m}{2}\left(\frac{1}{X_d''} + \frac{1}{X_q''}\right) e^{-\frac{t}{T_a}} \cos(\lambda)$$
$$- \frac{U_m}{2}\left(\frac{1}{X_d''} - \frac{1}{X_q''}\right) e^{-\frac{t}{T_a}} \cos(2\omega_0 t + \lambda) \tag{11}$$

where U_m is the amplitude of the phase voltage before the short-circuit condition, t denotes time, ω_0 is the speed during the short-circuit test and is assumed to be constant and equal to the synchronous speed, and λ is the angle between phase A and direct axis when the short-circuit occurs. X_d is the direct-axis synchronous reactance, $X_d{}'$ is the direct-axis transient reactance,

$T_d{}'$ is the direct-axis transient short-circuit time constant, $T_d{}''$ is the direct-axis subtransient short-circuit time constant, T_a is the armature winding time constant, and $X_d{}''$ and $X_q{}''$ denote the d-axis and q-axis subtransient reactances.

Two novel approaches for the identification of SG parameters are proposed in this article. The first proposed approach is based on obtaining experimental armature current and the analytical waveform of the same current presented by (11). Namely, the generator's parameters are identified using the novel hybrid C-EO algorithm proposed in this article so that the normalized sum of squared errors (NSSE) between experimental and analytical current waveform is minimized. Defining such an objective function ensures that the curve fitting of analytical with the experimentally observed waveform will be the best possible. According to this, the objective function J_1, which the C-EO algorithm minimizes, is given by

$$J_1(\theta) = \frac{\sum_{k=1}^{N} \left(I_{a,\exp}(k) - I_{a,\text{sim}}(k)\right)^2}{\sum_{k=1}^{N} I_{a,\exp}(k)^2} \tag{12}$$

where $I_{a,\exp}$ and $I_{a,\text{sim}}$ denote the experimental and simulated armature currents, N is the number of measurements, and $\theta = \{X_d, X_d{}', X_d{}'', X_q{}'', T_d{}', T_d{}'', T_a\}$ is the vector of the estimated parameters. These parameters are significant because they are related to the parameters from the generator's equivalent circuits. Equations (13)–(19) represent the mentioned relations

$$X_d = X_{md} + X_a \tag{13}$$

$$X_d{}' = X_a + \frac{X_{md}X_f}{X_{md} + X_f} \tag{14}$$

$$X_d{}'' = X_a + \frac{X_{md}X_f X_{kd}}{X_{md}X_f + X_{md}X_{kd} + X_f X_{kd}} \tag{15}$$

$$X_q{}'' = X_a + \frac{X_{mq}X_{kq}}{X_{mq} + X_{kq}} \tag{16}$$

$$T_d{}' = \frac{1}{\omega_0 R_f}\left(X_f + \frac{X_{md}X_a}{X_{md} + X_a}\right) \tag{17}$$

$$T_d{}'' = \frac{1}{\omega_0 R_{kd}}\left(X_{kd} + \frac{X_{md}X_a X_f}{X_{md}X_a + X_{md}X_f + X_a X_f}\right) \tag{18}$$

$$T_a = \frac{X_a}{\omega_0 R_a}. \tag{19}$$

From the previously presented equations, it can be noted that the resistance R_f and reactance X_f of the field winding can be determined. It is essential from the perspective of automatic voltage regulation (AVR) algorithm design since the field winding parameters have a significant effect on the dynamic performance of the system.

The second approach is based on the decomposition of the armature current into the asymmetrical and alternating component. Namely, the experimentally obtained armature current can be easily divided into these two components. First, it is necessary to extract the envelope lines through the armature current waveform peaks, as shown in Fig. 3. Afterward, the dotted lines drawn half-way between the envelope curves represent the asymmetrical component of the armature current. The alternating component is obtained by deducting the asymmetrical component from the total armature current waveform. These components can be determined using the analytical expressions represented in (20) and (21) [1].

This article's second approach minimizes the NSSE between experimental and analytical results for both asymmetrical and alternating components simultaneously

$$I_{\text{asym}}(t) = -\frac{U_m}{2}\left(\frac{1}{X_d{}''} + \frac{1}{X_q{}''}\right) e^{-\frac{t}{T_a}} \cos(\lambda) \tag{20}$$

$$\begin{aligned} I_{\text{alt}}(t) &= U_m \left[\begin{array}{c} \frac{1}{X_d} + \left(\frac{1}{X_d{}'} - \frac{1}{X_d}\right) e^{-\frac{t}{T_d{}'}} \\ + \left(\frac{1}{X_d{}''} - \frac{1}{X_d{}'}\right) e^{-\frac{t}{T_d{}''}} \end{array}\right] \cos(\omega_0 t + \lambda) \\ &\quad - \frac{U_m}{2}\left(\frac{1}{X_d{}''} - \frac{1}{X_q{}''}\right) e^{-\frac{t}{T_a}} \cos(2\omega_0 t + \lambda). \end{aligned} \tag{21}$$

The objective function J_2 for the second approach for parameter identification is given as

$$\begin{aligned} &J_2(\theta) \\ &= \sum_{k=1}^{N} \left(I_{\text{asym,exp}}(k) - I_{\text{asym,sim}}(k)\right)^2 \Big/ \sum_{k=1}^{N} I_{\text{asym,exp}}(k)^2 \\ &+ \sum_{k=1}^{N} \left(I_{\text{alt,exp}}(k) - I_{\text{alt,sim}}(k)\right)^2 \Big/ \sum_{k=1}^{N} I_{\text{alt,exp}}(k)^2. \end{aligned} \tag{22}$$

III. C-EO Algorithm

In this section, short reviews on the existing equilibrium optimizer (EO) algorithm and the proposed hybrid C-EO algorithm are given in two separate sections.

A. EO algorithm

The EO algorithm belongs to the recently published metaheuristic algorithms, and it was initially presented in [34]. The common thing for all metaheuristic algorithms is that their original inspiration is found in nature. Each metaheuristic algorithm has its' own mathematical formulation and set of equations that lead to the optimal solution. This algorithm's base is found in the mass balance equation used in physics and chemistry. The EO algorithm population consists of N particles, where each particle's concentration represents the potential solution of the optimization problem. Before the first iteration of the algorithm, the population of the particles is randomly initialized

$$\vec{C}_i^{(0)} = \vec{C}_{\min} + \text{rand}_i\left(\vec{C}_{\max} - \vec{C}_{\min}\right) \tag{23}$$

where $\vec{C}_i^{(0)}$ stands for the initial concentration of the ith particle (i = 12, ..., N), $\vec{C}_{\min}$ and $\vec{C}_{\max}$ are lower and upper bound of the optimization variables, N stands for the number of the particles and rand_i is a random vector in the interval [0, 1]. For the problem of SG parameter identification, the concentration of ith particle is denoted as $\vec{C}_i$ and represents a vector of the unknown parameters. In every iteration, the concentration of ith particle is updated according to

$$\vec{C}_i(\text{ite}) = \vec{C}_{\text{eq}} + \left(\vec{C}_i(\text{ite}-1) - \vec{C}_{\text{eq}}\right) \cdot \vec{F} + \frac{\vec{G}}{\vec{\lambda}}\left(1 - \vec{F}\right) \quad (24)$$

where ite stands for the current iteration. The meaning of each term in (24) is expressed as follows.

1) $\vec{C}_{\text{eq}}$ stands for the randomly chosen particle from the equilibrium pool. An equilibrium pool is formed at the end of each iteration, and it consists of the four best particles from that iteration, i.e., of the four particles with the lowest objective function value.
2) The exponential term is denoted as $\vec{F}$ and is calculated using

$$\vec{F} = e^{-\vec{\lambda}(\vec{t}-\vec{t}_0)} \quad (25)$$

where λ is a vector of random numbers in the interval [01] called turnover rate. Vectors $\vec{t}$ and $\vec{t}_0$ depend on the current iteration and are calculated using (26) and (27). Thus

$$\vec{t} = \left(1 - \frac{\text{ite}}{\text{max\_ite}}\right)^{a_2 \frac{\text{ite}}{\text{max\_ite}}} \quad (26)$$

$$\vec{t}_0 = \frac{1}{\vec{\lambda}} \ln\left[-a_1 \cdot (1 - e^{-\vec{\lambda}t}) \cdot \text{sign}(\vec{r} - 0.5)\right] + \vec{t} \quad (27)$$

where max_ite represents the maximum number of iterations, and constants a_1 and a_2 are used to balance the global and local search. The expression $\text{sign}(\vec{r} - 0.5)$, controls the search direction, where $\vec{r}$ is a random vector in the interval [0, 1].

3) The vector $\vec{G}$ stands for the generation rate, and it can be calculated using as

$$\vec{G} = \vec{G}_{\text{CP}}\left(\vec{C}_{\text{eq}} - \vec{\lambda}\vec{C}(\text{ite}-1)\right)\vec{F} \quad (28)$$

where $\vec{G}_{\text{CP}}$ denotes the generation rate control parameter. It depends on the vectors of random numbers $\vec{r}_1$ and $\vec{r}_2$ that range between [0, 1] and the generation probability (GP), which is the tuning parameter of the EO algorithm. Faramarzi *et al.*[34] suggested that GP's value set to 0.5 provides the best balance between the global and local search. Finally, the generation rate control parameter is determined using as

$$\vec{G}_{\text{CP}} = \begin{cases} 0.5\vec{r}_1, \vec{r}_2 \geq \text{GP} \\ 0, \vec{r}_2 < \text{GP} \end{cases}. \quad (29)$$

After the maximum number of iterations is reached, the particle with the lowest objective function value represents the optimal solution. For the optimization problem presented in this article, the optimal solution is a set of unknown SG parameters previously denoted as θ.

B. C-EO Algorithm

Due to the random numbers vector's presence, the initialization process described in (16) is random, which does not provide a good starting point in the optimization process. Since the metaheuristic algorithms are susceptible to the initial conditions, ensuring the right initial conditions may increase the algorithm's overall performance. The idea of embedding chaotic maps with the metaheuristic algorithm and examining the impact of many different chaotic maps on an algorithm's performance was presented in [35] and [36]. A comparative study demonstrated in [35] asserts that chaotic logistic maps are the best choice among all existing chaotic maps because of the better computational efficiency. Another reason is that the logistic mapping has a higher probability of generating values near 0 and 1, ensuring that this mapping can provide a faster local search. Logistic chaotic mapping is represented as

$$y_1 = \text{r and}$$
$$y_{i+1} = 4 \cdot y_i \cdot (1 - y_i), i = 1, 2, \ldots, N \quad (30)$$

where rand stands for the vector of random numbers between 0 and 1, finally, the proposed C-EO algorithm is obtained by replacing random vector rand_i with vector y obtained by logistic, chaotic mapping (30), in which the authors strengthen the conventional EO algorithm with a chaotic character.

IV. Experimental and Simulation Results

This section presents the results obtained by the proposed C-EO algorithm and the results obtained by other parameter identification procedures. A comparison of different identification methods is made to demonstrate the superiority of the SG parameter identification procedure proposed in this article. Furthermore, a comparative analysis of many metaheuristic algorithms is provided.

The parameters are identified from the short-circuit experimental tests when the terminal voltage is 50% of the nominal voltage. The duration of the test was 4.95 s. The short-circuit test was performed on the SG in a Serbian hydropower plant (HPP), therefore providing significant practical importance to the obtained results. The experiment was set, as suggested by IEEE standards [2]. The complete setup is depicted in Fig. 4. Also, the flowchart of the identification procedures is included.

Before the short-circuit occurs, the generator's field winding is fed by an AVR. The terminal voltage of the generator is controlled by setting the reference voltage for the AVR system. In this article, the terminal voltage of the generator, before the short-circuit condition, is kept as 50% of nominal voltage in the first case, 30% in the second case, and 20% in the third case. Afterward, the armature windings of the generator are short-circuited by simultaneously closing the three-phase breaker. Since the field voltage during the short-circuit must be constant, the AVR is removed, and a constant voltage source provides the needed excitation with low impedance. The datasheet of the SG is given in the Appendix.

For the purpose of a fair comparison, each of the applied metaheuristic algorithms must have the same settings. Therefore, the number of iterations is 50, and the size of the population is 30. The optimization variables for C-EO algorithm are the parameters of the generator $\theta = \{X_d, X_d', X_d'', X_q'', T_d', T_d'', T_a\}$. The objective function that needs to be chosen for applying C-EO algorithm is J_1 for the first approach and J_2 for the second approach. The search range of the parameters is ±10% of the values determined by the IEEE tests. The lower and upper bounds of the parameters are given in Table I.

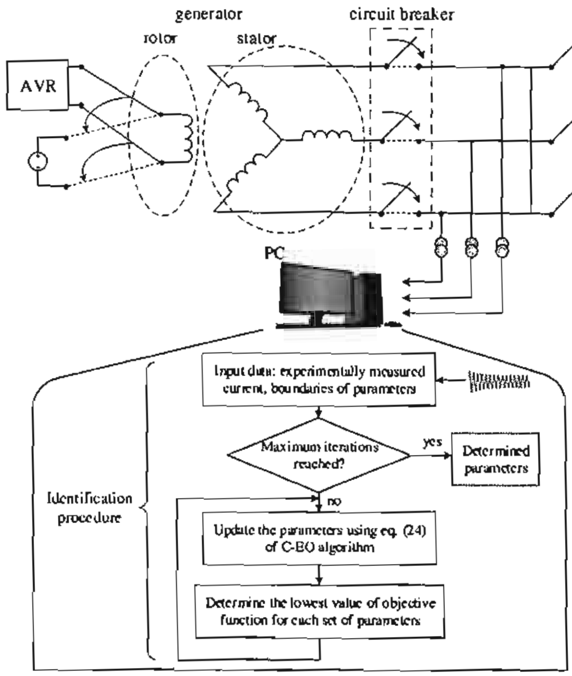

Fig. 4. Experimental setup.

TABLE I
LOWER AND UPPER BOUNDS OF THE PARAMETERS

Parameter	X_d (Ω)	X_d' (Ω)	X_d'' (Ω)	X_q'' (Ω)	T_d' (s)	T_d'' (s)	T_a (s)
Lower bound	1.926	0.669	0.377	0.377	2.07	0.041	0.236
Upper bound	2.37	0.818	0.4615	0.4615	2.541	0.051	0.2895

TABLE II
VALUES OF THE PARAMETERS DETERMINED BY DIFFERENT METHODS

Parameter	C-EO Approach 1	C-EO Approach 2	[18]	IEEE tests	VA Tech	Numeric [17]
X_d (Ω)	2.1573	2.3622	2.1518	2.1474	2.1005	NR**
X_d' (Ω)	0.6989	0.6949	0.7652	0.7441	0.7597	0.7489
X_d'' (Ω)	0.4605	0.4611	NR**	0.4192	0.4246	NR**
X_q'' (Ω)	0.4545	0.4611	NR**	0.4192*	0.4246*	NR**
T_d' (s)	2.1649	2.0790	2.1990	2.3100	2.0730	2.065
T_d'' (s)	0.0490	0.0485	0.0422	0.0466	0.0457	0.041
T_a (s)	0.2767	0.2893	0.2279	0.2630	NR**	0.248

* Parameter X_q'' was not determined by IEEE tests nor provided by VA Tech. However, in the literature, it can be found that both subtransient reactances are approximately identical, so it was adopted $X_q'' = X_d''$.

** NR stands for Not Reported. For carrying out the simulation, the values obtained by IEEE tests were adopted.

Precisely, the results obtained by the novel approaches presented in this article are compared with parameters measured using the standard IEEE test procedures [3], the parameters from the catalog data provided by the VA Tech company, with the method presented in [18], and with the numeric algorithm depicted in [17]. The values of the generator parameters obtained using different techniques are given in Table II.

According to [2] and [3], the saturated values of the reactances can be determined if the terminal voltage of the generator is set at the rated value during the short-circuit test. Alternatively, the parameters obtained for different values of the generator's voltage (up to 70% of the rated value) could be scaled to the values that correspond to the rated voltage. Since the short-circuit test at the rated voltage would be extremely dangerous for large power generators, such as the one considered for experiments in this article, the authors could not carry out such a test.

The detailed comparison of both approaches presented in this article with the other considered methods is shown in the following sections.

TABLE III
OBJECTIVE FUNCTION J_1 VALUE FOR DIFFERENT METHODS

Method	C-EO Approach 1	[18]	IEEE tests	VA Tech	Numeric [17]
J_1	0.0141	0.0190	0.0165	0.0180	0.0177

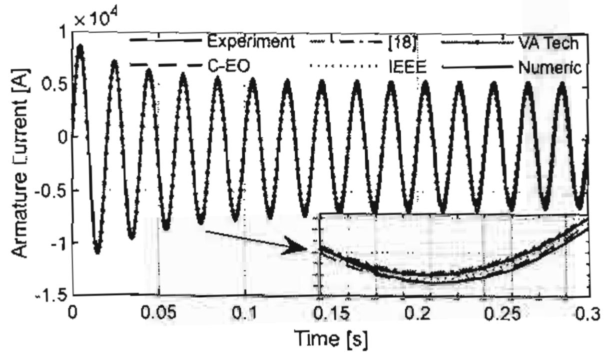

Fig. 5. Graphical comparison of experimental and analytical armature current waveform (at 50% of nominal voltage).

A. Approach 1—Total Armature Current Waveform

A comparison is made with the method presented in [18], as well as with the IEEE test methods and VA Tech parameters to demonstrate the accuracy of the parameters obtained by the first approach proposed in this article. Since the NSSEs between simulated and experimentally measured total armature current is denoted as objective function J_1, this function's values obtained using the different methods are given in Table III.

The lowest value of the objective function J_1 is obtained with the approach proposed in this article. Therefore, it means that the proposed approach's parameters ensure the best matching with the experimental results. Besides the numerical comparison given in Table III, the graphical comparison of the armature current experimentally observed waveform and the analytical waveform is given in Fig. 5.

Analytical waveforms of the armature current were obtained by applying the parameters determined by the methods from Table III. As mentioned before, the short-circuit test is carried out when the terminal voltage is reduced to 20% and 30% of the nominal to validate the results. In this case, Figs. 6 and 7 depict a fair comparison of experimental and analytical armature current waveforms. The same values of the generator parameters are applied to obtain the analytical waveforms.

Observing the presented figures shows that applying the SG parameters calculated using the C-EO algorithm ensures the best matching with the experimental results compared with other considered methods. Therefore, the proposed identification

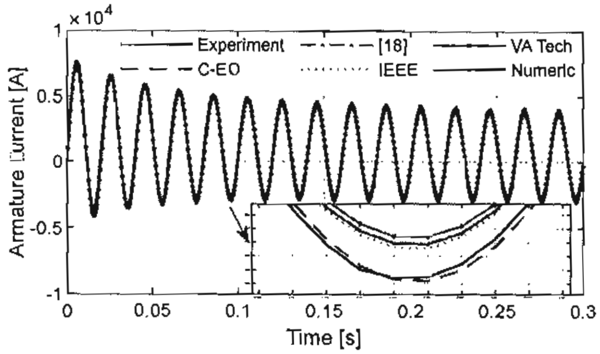

Fig. 6. Graphical comparison of experimental and analytical armature current waveform (at 30% of nominal voltage).

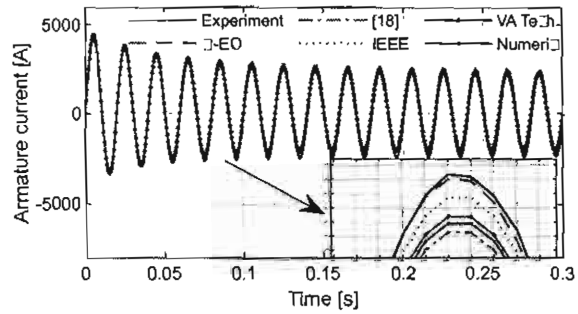

Fig. 7. Graphical comparison of experimental and analytical armature current waveform (at 20% of nominal voltage).

approach is proven to outperform other methods used to estimate the generator parameters.

Furthermore, it is demonstrated that even other popular computational intelligence methods can extract the generator parameters. Namely, some of the recent popular metaheuristic algorithms, such as the original EO algorithm, henry gas solubility optimization algorithm, marine predator algorithm (MPA), and differential evolution (DE) algorithm, were employed to estimate the parameters of the generator. All the algorithms, including the objective function, were enforced to have the same settings as the proposed C-EO algorithm to ensure the comparison is fair.

The C-EO algorithm's superiority over other popular metaheuristic techniques is depicted in Fig. 8, where the convergence curves of all considered algorithms are presented, in which the C-EO algorithm reached the optimal solution faster than the other considered algorithms.

B. Approach 2—Decomposition of the Armature Current

The C-EO algorithm presented in this article is used to extract the parameters that provide the best simulation results with experimental results. Like the first approach, the value of the objective function J_2 is calculated for the set of parameters obtained with the C-EO algorithm, IEEE tests, VA Tech catalog, the method demonstrated in [18], and the numeric algorithm from [17]. The calculated values of the function J_2 are given in Table IV.

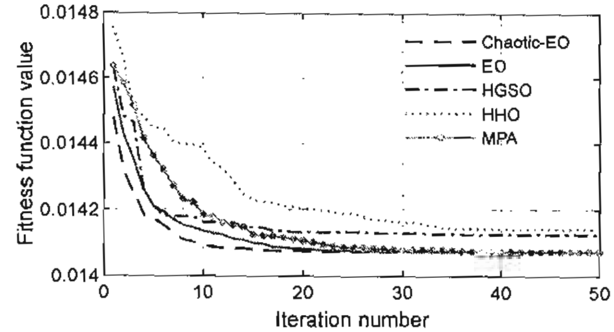

Fig. 8. Comparison of the convergence curve for different metaheuristic algorithms (for first approach).

TABLE IV
OBJECTIVE FUNCTION J_2 VALUE FOR DIFFERENT METHODS

Method	C-EO Approach 2	[18]	IEEE tests	VA Tech	Numeric [17]
J_2	0.0171	0.0317	0.0270	0.0266	0.0279

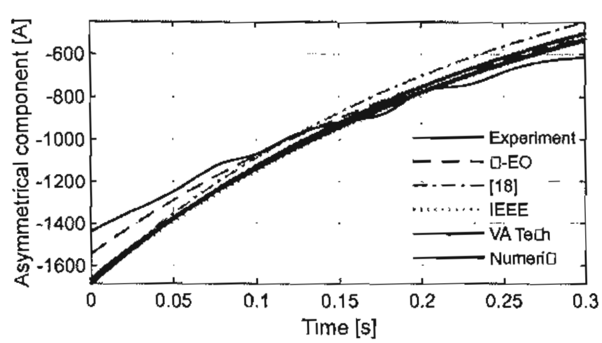

Fig. 9. Comparison of experimental and analytical asymmetrical component (at 50% of nominal voltage).

From the results presented, it is evident that even in the second considered approach, whose purpose is to provide the best fitting of asymmetrical and alternating components separately, this proposed method is superior compared with the other identification techniques from Table IV.

Additionally, to demonstrate the improvements made by introducing the novel approach, a graphical comparison of asymmetrical and alternating current waveforms is provided. Analytical waveforms obtained by applying parameters calculated using Table IV methods are compared with experimentally measured armature current components. Comparing the asymmetrical component obtained by different methods is provided in Fig. 9, while the alternating components are compared in Fig. 10. Before the short-circuit, the terminal voltage was set to 50% of the nominal for the results presented in these two figures.

Furthermore, the previously calculated parameters are tested when the terminal voltage is reduced to 20% and 30%. The corresponding results are depicted in Figs. 11 and 13 for asymmetrical components and Figs. 12 and 14 for the alternating component. The graphical analysis of the plots is used to confirm the concluded remarks. The best matching of the short-circuit waveform components with experimentally obtained ones is ensured when

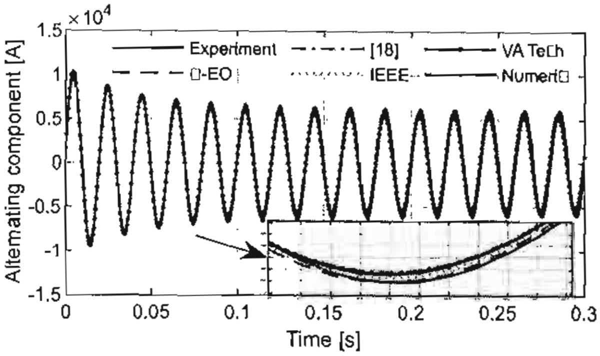

Fig. 10. Comparison of experimental and analytical alternating component (at 50% of nominal voltage).

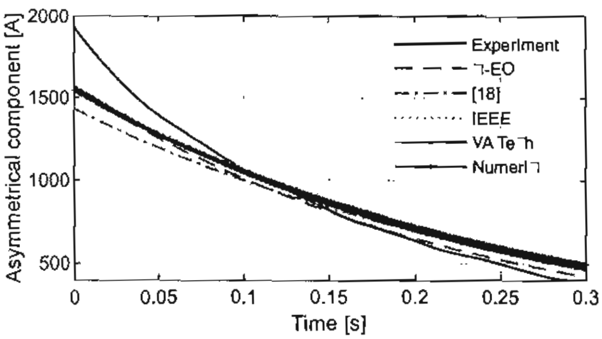

Fig. 11. Comparison of experimental and analytical asymmetrical component (at 30% of nominal voltage).

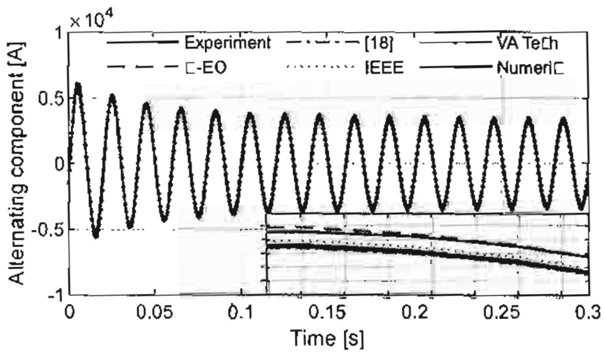

Fig. 12. Comparison of experimental and analytical alternating component (at 30% of nominal voltage).

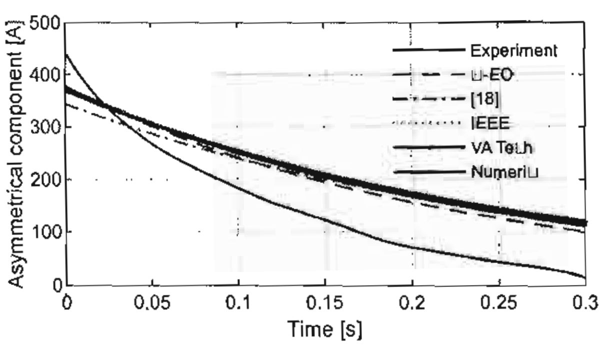

Fig. 13. Comparison of experimental and analytical asymmetrical component (at 20% of nominal voltage).

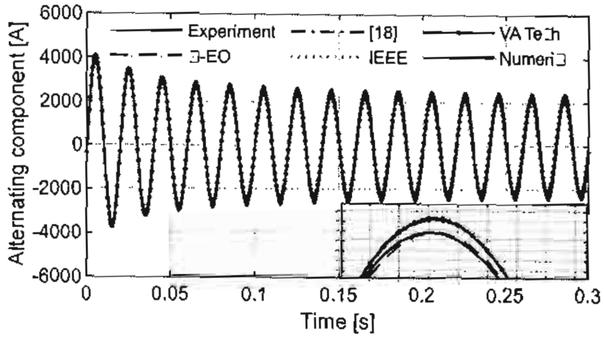

Fig. 14. Comparison of experimental and analytical alternating component (at 20% of nominal voltage).

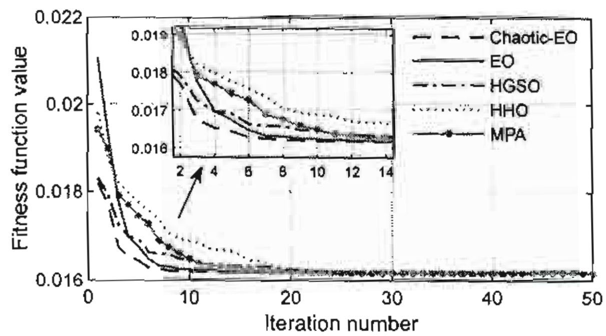

Fig. 15. Comparison of the convergence curve for different metaheuristic algorithms (for second identification approach).

the parameters are determined by the identification approach presented in this article.

Additionally, the second presented approach is also compared with other algorithms. The metaheuristic algorithms used for comparison are the same ones used for the first presented approach. Even in this case, where the objective function J_2 is minimized, the C-EO algorithm introduced in this article proves the superiority compared with other popular metaheuristic algorithms. The results are graphically depicted in the form of convergence curves, as shown in Fig. 15.

V. Conclusion

Two novel SG parameter identification approaches were presented. A hybrid metaheuristic method was proposed to replace the graphical method for extracting the parameters, which is very sensitive to human error. The proposed C-EO algorithm was compared with other popular metaheuristic techniques, and it showed superior performance in terms of convergence speed. With experimental verification, the short-circuit test was conducted on a real SG in a Serbian HPP plant. The results obtained validate the effectiveness of the proposed approaches using the proposed optimization method.

One possible direction is to include the effect of saturation in estimation procedures directly in future work. Precisely, the set of parameters could be determined for different voltage values that are significantly lower than the rated value. Furthermore, such a set of parameters could be extrapolated to the values that correspond to the rated voltage, which would adequately model the saturation's effect, particularly in large power generators.

Appendix

The photo of HPP Bajina Basta, located in Serbia, is given in Fig. 16.

Furthermore, the rotor and the stator of the studied generator are depicted in Fig. 17.

The key parameters of the generator, taken from the documentation, are given in Table V. The values of the generator's saturated and unsaturated reactances and time constants, provided by the manufacturer of the generator, are given in Table VI. Also, in this table, the tolerance limits for some parameters are provided. These limits result from the deal between the manufacturer and the end-user of the generator. They represent the allowed range of the deviation of the parameters after installation or revitalization of the generator. The manufacturer calculated these values using their own methodologies based on internal procedures.

TABLE V
KEY PARAMETERS OF THE GENERATOR

Parameter	Value	Parameter	Value
Stator outer diameter	9480 mm	Rated power	109.6 MVA
Stator inner diameter	8796 mm	Rated voltage	15.65 kV
Air-gap length	24.55~24.76 mm	Rated current	4043.3 A
Shaft diameter	970 mm	Power factor	0.95
Rotor hub diameter	1600 mm	Frequency	50 Hz
Stack height	1450 mm	Rated speed	136.4 min^{-1}
End-winding length	458 mm (top) 478 mm (bottom)	Overspeed	245 min^{-1}
Stator slot	462	Rated exc. voltage	288 V
Pole numbers	44	Rated exc. current	1251 A
Turns per phase	77	Insulation class	F
Current density	3.18 (stator) A/m^2 2.45 (rotor) A/m^2	Stator mass	150 t
		Rotor mass	310 t

TABLE VI
VALUES OF REACTANCES AND TIME CONSTANTS PROVIDED BY THE MANUFACTURER OF THE GENERATOR

Parameter	Value	Parameter	Value
X_d'' unsaturated (pu)	0.234 (-15%, +25%)	X_q unsaturated (pu)	0.7
X_d'' saturated (pu)	0.19 (-15%, +25%)	X_q' saturated (pu)	0.64
X_d' unsaturated (pu)	0.35 (±20%)	X_q'' saturated (pu)	0.19
X_d' saturated (pu)	0.32 (±20%)	T_{d0}' (s)	6.1
X_d unsaturated (pu)	0.95 (±10%)	T_{q0}' (s)	0.499
X_d saturated (pu)	0.84 (±10%)	T_d' (s)	2.15
X_0 saturated (pu)	0.128	T_d'' (s)	0.0471
Potier reactance X_p (pu)	0.22	T_a (s)	0.224

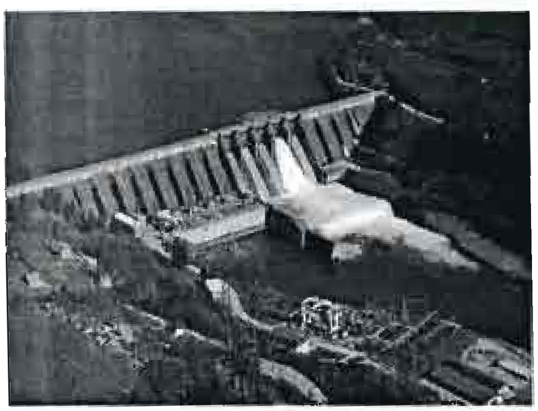

Fig. 16. Photo of HPP Bajina Basta in Serbia.

(a) (b)

Fig. 17. (a) Rotor. (b) stator of the studied generator.

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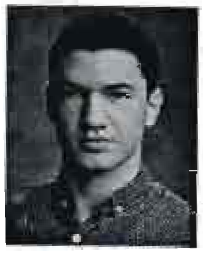

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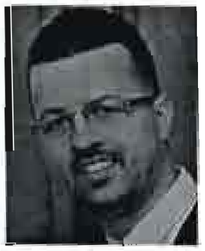

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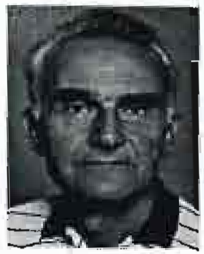

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Optimal design of automatic voltage regulation controller using hybrid simulated annealing – Manta ray foraging optimization algorithm

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ABSTRACT

This paper presents a hybrid metaheuristic method for optimal tuning of four different types of proportional-integral-derivative (PID) controller for an automatic voltage regulator (AVR) system. The method is based on the manta ray foraging optimization algorithm which is merged with the simulated annealing algorithm. Additionally, novel objective functions for the optimization of the controller's parameters are proposed. The performance of the obtained ideal PID, real PID, fractional-order PID, and PID with second-order derivative controllers is verified by carrying out a comparison with the controllers tuned by different algorithms presented in the literature. Results of the simulations validate that each type of controller tuned with the proposed SA–MRFO algorithm outperforms the controllers tuned by other algorithms. Further, a comparative analysis is carried out to determine the most suitable controller for application in AVR systems. The main advantage of the proposed algorithm is the significant increase in the convergence speed.

1. Introduction

An electric power system is a very complex network that consists of different electrical components, whose common goal is to supply, transfer, and use electric power. A typical power system consists of the generators that supply the electrical power, the transmission system, the distribution system, and the consumers. The quality of the electrical power supplied to the consumers is defined by two main parameters: the frequency and the voltage of each node in the whole power system. The control of the frequency is achieved through turbine regulation, which impacts the active power flow. On the other hand, the excitation control of the synchronous generator determines the reactive power flow, thereby defining the voltage level. According to this, two regulation contours in the power system can be defined: one is power–frequency (*P–f*) contour, which deals with the regulation of the frequency. The second is reactive power–voltage (*Q–U*) contour, which regulates the voltage level in the power system [1–4].

Among many voltage regulation devices, such as capacitor banks, tap-changing transformers, reactors, and so on, excitation control of the synchronous generator remains the most common way to keep the voltage level stable. The main part of the excitation system is the automatic voltage regulator (AVR), which consists of five main components: regulator, amplifier, exciter, generator, and sensor. The output of the generator is the terminal voltage, whose value is measured by a sensor. The measured voltage value is compared with the reference voltage to form the error signal. The regulator is realized as a microprocessor unit that uses the control law and the error signal to form the control signal. The role of an amplifier is to increase the power of the control signal and forward it to the exciter. Finally, the exciter defines the DC voltage level that will be applied to the field coil of the synchronous generator. In general, this article deals with the operation and control of the AVR system.

Despite the significant development of control theory and modern control techniques, the most-used regulator in AVR systems is

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still the proportional-integral-derivative (PID) regulator [5–22]. The ideal PID regulator comprises three parameters (K_p, K_i, and K_d), in which K_p, K_i, K_d denote the proportional, integral, and differential gains. However, a few studies consider the nonideal, or real PID regulator, in which the derivative action is filtered, as in references [19–22]. Besides the three mentioned parameters, the real PID regulator introduces another parameter that is called the filter coefficient (N). The performance can be further improved by adding fractional calculus into the PID regulator, obtaining the fractional-order PID regulator (FOPID) [23–30]. Tuning the FOPID implies determining values of five parameters: K_p, K_i, K_d, μ, and λ, where μ and λ denote the order of differentiation and integration, respectively. Additionally, recent studies consider another modification of the PID regulator, the so-called PID with second-order derivative, or PIDD^2 [6,31]. Compared to the conventional PID, this type of controller has one extra parameter, four in total: K_p, K_i, K_d, and K_{d2} (second-order derivative gain). In this article, the optimal design of the four controllers (ideal PID, real PID, FOPID, and PIDD^2) will be presented.

The optimal tuning of the controller is crucial to providing the desired voltage response of the AVR system. To that end, a large number of existing studies deal with determining the optimal values of the parameters. The most popular optimization methods are based on the usage of metaheuristic algorithms, among which the most popular are the genetic algorithm (GA) [11,13,24,27,29] and particle swarm optimization (PSO) [16,22,30]. Also, optimization can be based on other algorithms, such as improved kidney-inspired algorithm (IKA) [5], whale optimization algorithm (WOA) [6], cuckoo search (CS) [20,23], ant colony optimization (ACO) [9,19], teaching–learning-based optimization (TLBO) [8,21], many optimizing liaisons (MOL) [12], chaos optimization algorithm (COA) [15], symbiotic organisms search (SOS) [7], artificial bee colony (ABC) [14,26], local unimodal sampling (LUS) [8,10], harmony search algorithm (HSA) [8], velocity update relaxation PSO (VURPSO) and craziness PSO (CRPSO) [17], chaotic ant swarm (CAS) [18,28], multi-objective extremal optimization (MOEO) [25], and others. The existence of a large number of optimization methods indicates that the results obtained so far can be further improved.

This paper deals with the problem of tuning the parameters for all four mentioned types of PID controller—the ideal PID, the real PID, the FOPID, and the PIDD^2—unlike all previously published papers [5–31]. Toward that goal, the structure of an AVR proposed in the literature [5–31] is used. Furthermore, a novel hybrid algorithm is presented to optimize the parameters of the controllers. The hybrid algorithm presents the combination of the simulated annealing (SA) and the manta ray foraging optimization (MRFO) algorithms. The SA algorithm is used to define the initial population of the MRFO algorithm, which significantly increases the convergence speed. Each of the controllers tuned by the proposed SA–MRFO algorithm will be compared to the corresponding ones with parameters optimized by the other algorithms mentioned previously. The superiority of the application of the SA–MRFO algorithm for tuning the controllers is highlighted by carrying out a comparison in terms of step response quality, convergence speed, robustness, and disturbance rejection. Results of the simulations prove that each type of controller tuned with the proposed SA–MRFO algorithm outperforms the corresponding controllers tuned by other algorithms, in all of the previously mentioned performance tests. Additionally, a comparative analysis is carried out to examine which of the considered types of the controller is the most suitable for application in AVR systems. The tests demonstrate that the PIDD^2 controller, which is not common in the literature, outperforms the other kinds of PID controller.

The organization of this paper is as follows. A short overview of the composition of the AVR system is provided in Section 2. Section 3 presents a wide review of the literature that deals with the optimization of the different types of PID controllers. Then, a detailed description and the mathematical formulation of the proposed SA–MRFO algorithm are given in Section 4. Section 5 shows the results of the simulations that are carried out in this paper. Finally, conclusions are provided in Section 6.

2. Automatic voltage regulation system

The main role of an AVR system is to keep the voltage of the generator at a stable level under all operating conditions. Due to different disturbances in the system, certain oscillations of the voltage are likely to happen, which can threaten the stability of the power system. Therefore, the excitation system of the synchronous generator equipped with the AVR has the task of correcting the deviations of the terminal voltage. The structure of the AVR that is described in the previous section is depicted in Fig. 1.

Each of the components, except the controller, is presented by the first-order transfer function that consists of the unitless gain (K) values, and the time constant (T) values given in seconds. Typical values of these parameters, which are also considered in this work, are $K_A = 10$, $K_E = 1$, $K_G = 1$, $K_S = 1$, $T_A = 0.1$, $T_E = 0.4$, $T_G = 1$, and $T_S = 0.01$ [5–16,19–29,31], in which the suffix A denotes the amplifier, E denotes the exciter, G denotes the generator and S denotes the sensor. The controller is used to enhance the performance of an AVR system, especially in terms of the dynamic response of the voltage. This paper considers four types of PID controllers—the ideal PID, the real PID, the FOPID, and the PIDD^2—whose transfer functions and parameters are described as follows:

- Ideal PID controller has only three tuning parameters—K_p, K_i, and K_d—and its transfer function $C(s)$, in the s-domain, is:

$$C(s) = K_p + \frac{K_i}{s} + K_d s \tag{1}$$

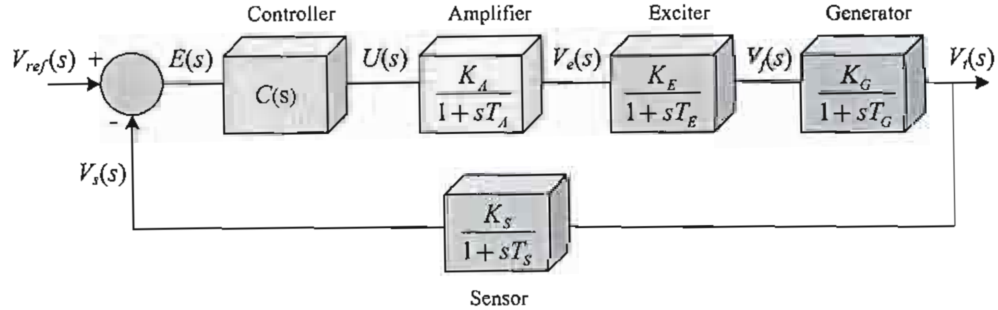

Fig. 1. The common structure of an AVR system.

Table 1
Review of the optimal parameters of the controllers.

Algorithm number	Reference	Year	K_p	K_i	K_d	K_{d2}	N	μ	λ
1	[5]	2019	1.0426	1.0093	0.5999	NA*	NA	NA	NA
2	[6]	2019	0.7847	0.9961	0.3061	NA	NA	NA	NA
3	[19]	2019	0.6392	0.4757	0.2159	NA	484.09	NA	NA
4			0.3120	0.2567	0.1503	NA	500.00	NA	NA
5			0.5463	0.3409	0.1485	NA	500.00	NA	NA
6	[20]	2018	0.6198	0.4165	0.2126	NA	1000.00	NA	NA
7	[7]	2018	0.5693	0.4097	0.1750	NA	NA	NA	NA
8	[8]	2018	0.9685	1.0000	0.8983	NA	NA	NA	NA
9			0.9519	0.9997	0.8994	NA	NA	NA	NA
10			0.86832	0.9325	0.9419	NA	NA	NA	NA
11	[9]	2017	0.6739	0.5951	0.2622	NA	NA	NA	NA
12			0.6348	0.4801	0.2267	NA	NA	NA	NA
13	[23]	2017	2.5490	0.1759	0.3904	NA	NA	1.3800	0.97
14			2.5150	0.1629	0.3888	NA	NA	1.3800	0.97
15			2.4676	0.3020	0.4230	NA	NA	1.3800	0.97
16	[21]	2016	0.5302	0.4001	0.1787	NA	175.26	NA	NA
17	[24]	2016	1.5338	0.6523	0.9722	NA	NA	1.2090	0.97
18	[22]	2015	0.7080	0.6560	0.2820	NA	1000.00	NA	NA
19	[25]	2015	2.9737	0.9089	0.5383	NA	NA	1.3462	1.15
20	[10]	2014	1.2012	0.9096	0.4593	NA	NA	NA	NA
21		2014	0.5878	0.4062	0.1843	NA	NA	NA	NA
22		2014	0.6022	0.3793	0.1841	NA	NA	NA	NA
23		2014	1.2930	0.9828	0.6303	NA	NA	NA	NA
24		2014	0.6190	0.4222	0.2058	NA	NA	NA	NA
25	[26]	2014	1.9605	0.4922	0.2355	NA	NA	1.4331	1.55
26	[31]	2014	2.7784	1.8521	0.9997	0.073	NA	NA	NA
27	[11]	2013	0.5600	0.5000	0.2000	NA	NA	NA	NA
28	[27]	2013	0.4080	0.3740	0.1773	NA	NA	1.3336	0.68
29			0.9632	0.3599	0.2816	NA	NA	1.8307	0.55
30			1.0376	0.3657	0.6546	NA	NA	1.8716	0.55
31	[12]	2012	0.5857	0.4189	0.1772	NA	NA	NA	NA
32			0.9931	0.7461	0.4249	NA	NA	NA	NA
33			0.9877	0.7780	0.5014	NA	NA	NA	NA
34			0.9544	0.9434	0.9909	NA	NA	NA	NA
35	[28]	2012	1.0537	0.4418	0.2510	NA	NA	1.1122	1.06
36			0.9315	0.4776	0.2536	NA	NA	1.0838	1.03
37	[29]	2012	0.9894	1.7628	0.3674	NA	NA	0.7051	0.95
38			0.8399	1.3359	0.3511	NA	NA	0.7107	0.9146
39			0.4667	0.9519	0.2967	NA	NA	0.2306	0.8872
40	[13]	2011	0.6823	0.6138	0.2678	NA	NA	NA	NA
41			0.6800	0.5221	0.2440	NA	NA	NA	NA
42			0.6727	0.4786	0.2298	NA	NA	NA	NA
43	[14]	2011	1.6524	0.4083	0.3654	NA	NA	NA	NA
44	[15]	2009	0.6710	0.5050	0.2640	NA	NA	NA	NA
45			0.6390	0.4770	0.2340	NA	NA	NA	NA
46			0.6480	0.4780	0.2410	NA	NA	NA	NA
47			0.6220	0.4530	0.2180	NA	NA	NA	NA
48			0.6590	0.4870	0.2540	NA	NA	NA	NA
49	[16]	2004	0.6568	0.5393	0.2458	NA	NA	NA	NA
50			0.6751	0.5980	0.2630	NA	NA	NA	NA
51			0.6570	0.5390	0.2458	NA	NA	NA	NA
52			0.6271	0.4652	0.2209	NA	NA	NA	NA
53			0.6477	0.5128	0.2375	NA	NA	NA	NA
54			0.6476	0.5216	0.2375	NA	NA	NA	NA

* NA = not applicable.

- Real PID controller is obtained by filtering the derivative action of the ideal PID controller with the filter coefficient N, and is presented by the following transfer function:

$$C(s) = K_p + \frac{K_i}{s} + K_d\left(\frac{N}{1+\frac{N}{s}}\right) \tag{2}$$

- FOPID controller allows the order of the derivative and the integral to be real numbers, so it is defined with five parameters—K_p, K_i, K_d, μ, and λ, and is presented as follows:

$$C(s) = K_p + \frac{K_i}{s^{\lambda}} + K_d s^{\mu} \tag{3}$$

- PIDD^2 controller, besides K_p, K_i, and K_d, has another parameter that represents second-order derivative gain—K_{d2}, and is presented as follows:

$$C(s) = K_p + \frac{K_i}{s} + K_d s + K_{d2} s^2 \tag{4}$$

3. Literature review

In order to highlight the contributions of this paper, firstly a detailed review of the existing studies is presented. To that end, Table 1 provides the optimal values of the parameters for the different types of PID controllers tuned by different algorithms presented in the literature.

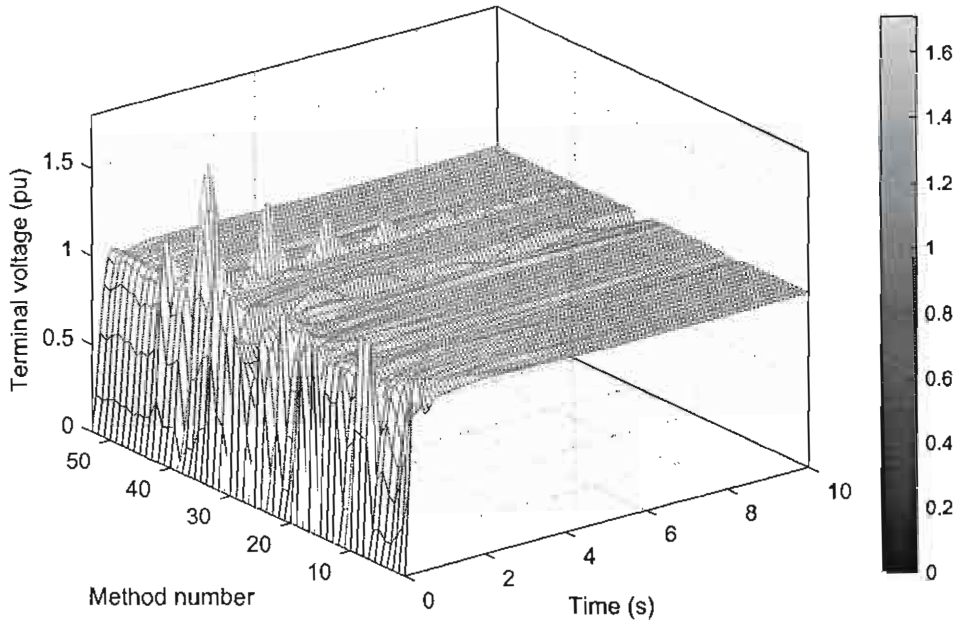

Fig. 2. Step responses obtained in the studies presented in Table 1.

Using those parameters, simulations were carried out to obtain step responses of the AVR system. A comparison of the step responses for each method from Table 1 is depicted in Fig. 2. All methods guarantee the null steady-state error. However, big differences in terms of overshoot, rise time, and settling time are more than evident.

It is well known from control theory that the dynamic response of the closed-loop system is characterized by the rise time (t_r), the settling time (t_s), and the overshoot (OS). For a complete review of the methods from Table 1, the transient response parameters obtained from corresponding step responses are presented in Appendix A. Their graphical representations are shown in Fig. 3. Moreover, Fig. 3(d) demonstrates the frequency of application of the different metaheuristic algorithms presented in Table 1.

The most essential step in designing a metaheuristic algorithm is the choice of the objective function. Earlier studies that have been considered as background for the current study that deals with the optimization of the PID controller for the AVR system proposed different objective functions. To make a proper overview of all these studies, Table 2 presents mathematical formulations of all objective functions used in the literature. In Table 2, e is the error signal (the difference between the reference voltage and the terminal voltage), t is the simulation time, V_f is the voltage of the generator field winding, ω_{gc} is the gain crossover frequency, u is the control signal (the output of the controller), e_{load} is the error signal when load disturbances are present, max_dv is the maximum point of the voltage signal derivative, P_m is the phase margin, and G_m is the gain margin.

4. Simulated annealing–manta ray foraging optimization algorithm

This paper presents a novel hybrid metaheuristic algorithm that is composed of two different types of existing algorithms, SA and MRFO. Metaheuristic algorithms can be divided into two categories—single solution-based algorithms and population-based algorithms [32]. Single solution-based algorithms, among which the most used is the SA algorithm, iteratively apply the generation and replacement procedures from the current single solution. On the other hand, MRFO represents the population-based algorithms, which start from an initial population, then iteratively apply the generation of a new population and the replacement of the current population. Thereby, the hybrid approach presented in this paper is based on an idea of merging the SA algorithm with evolutionary algorithms (EAs), which can be either collaborative or integrative merging [33]. Collaborative hybrid SA–EA can be teamwork collaborative, which means both algorithms work in parallel [34–37], or relay-collaborative, which means that the algorithms are executed one after the other [38–40]. The EA–SA algorithm presented in [38,39] firstly executes the EA, and afterward, each individual in the final population is optimized by the SA algorithm. The other version of the relay-collaborative hybrid algorithm is SA–EA, in which the SA algorithm is used to initialize the population of the EA algorithm [33,40]. On the other hand, in integrative hybrid metaheuristics, only a certain function of one algorithm is replaced by another algorithm [41–49].

This article considers the hybridization of the non-evolutionary MRFO algorithm [50,51], and the SA algorithm [52]. Although the MRFO algorithm does not belong to the group of evolutionary algorithms, it is still the algorithm that is based on the population of the solutions, which makes it a good candidate for merging with SA. The strategy that is used is teamwork relay-collaboration between the two mentioned algorithms, similar to SA–EA [33,40]. To be more precise, in this hybrid algorithm SA is used to initialize the population of the MRFO algorithm, obtaining a high-quality initial solution. In this way, it will be demonstrated that the convergence speed is significantly increased compared to the other algorithms used for solving the same optimization problem.

The original MRFO algorithm is based on the three intelligent foraging strategies of manta rays: chain foraging, cyclone foraging, and somersault foraging. Mathematical models of these foraging strategies, which are presented in Section 5, are used to form the MRFO algorithm [50,51].

Before the iteration process starts, the population of manta rays must be initialized. In the original MRFO algorithm [50], a population is randomly initialized in the search space. The hybrid SA–MRFO algorithm proposed in this paper uses the SA algorithm to initialize the population for the MRFO, similar to the SA–EA algorithm [33,40]. The aim of initialization using the SA algorithm is to increase the accuracy of the solution in the first iterations, which significantly contributes to the increase of the convergence speed.

SA is a single-solution-based algorithm, which means it must be applied for each individual of the initial population. In the MRFO algorithm, we assume that a population P consists of m manta rays, $P = \{p_1, p_2, \ldots, p_m\}$, where p_i (i = 1, 2, ..., m) stands for the position of each individual. The initial population is defined using the SA algorithm which is given by the following pseudocode (see Algorithm 1), in which the objective function of the optimization problem is denoted by f:

Algorithm 1 (*Pseudocode of the SA algorithm*).

```
For each individual p_i
Enter the input data: k = 0, c_k = c_0, L_k = L_0
p_i = rand× (b^H − b^L) + b^L
Repeat
  For l = 0 to L_k
    Generate a solution p_j from the neighborhood of the
   current solution p_i
     If f(p_j) < f(p_i) then p_j becomes the current solution (p_i = p_j)
Else p_j becomes the current solution with the probability
  e^((f(i)−f(j))/c_k)
k = k + 1
Compute L_k and c_k
Until c_k ≅ 0
```

The parameters of SA algorithm c_k and L_k stand for the temperature and number of transitions, respectively, generated at iteration k. They are defined as explained in [52]. Also, *rand* presents a vector of random numbers between 0 and 1, while b^H and b^L represent the high boundary and the low boundary of the optimization variables, respectively. It is very important to highlight that each p_i is a vector that is composed of d variables that are being optimized.

After the initialization, the mentioned foraging strategies are applied to the whole population. Firstly, the chain foraging strategy is applied to each individual according to Eq. (5).

$$p_i^d(t+1) = \begin{cases} p_i^d(t) + r(p_{best}^d - p_i^d(t)) + \alpha(p_{best}^d - p_i^d(t)), i = 1 \\ p_i^d(t) + r(p_{i-1}^d - p_i^d(t)) + \alpha(p_{best}^d - p_i^d(t)), \forall i \in m, i \neq 1 \end{cases} \tag{5}$$

so that

$$\alpha = 2r\sqrt{|\log(r)|} \tag{6}$$

where $p_i^d(t)$ is the position of the ith individual at the iteration t in dth dimension, r is a random number between 0 and 1, α is the weight coefficient and p_{best} is the best individual found so far.

The second foraging strategy applied in the MRFO algorithm is cyclone foraging, which illustrates the spiral-shaped movement of the manta rays toward the food. The mathematical equation modeling the cyclone foraging can be formulated as:

$$p_i^d(t+1) = \begin{cases} p_{best}^d + r_1(p_{best}^d - p_i^d(t)) + \beta(p_{best}^d - p_i^d(t)), i = 1 \\ p_{best}^d + r_1(p_{i-1}^d - p_i^d(t)) + \beta(p_{best}^d - p_i^d(t)), \forall i \in m, i \neq 1 \end{cases} \tag{7}$$

so that

$$\beta = 2e^{r_1\left(\frac{t_{max}-t+1}{t_{max}}\right)} \sin(2\pi r_1) \tag{8}$$

where r_1 is a random number within the range of 0–1, t_{max} is the maximum number of iterations, and β is the weight coefficient. Eq. (7) illustrates the exploitation ability of the MRFO algorithm, or the ability to search the region around the current best solution. Despite this, every metaheuristic algorithm needs to have a good exploration ability, which provides the search of the whole search space, and not only around the current best solution. The mechanism which provides the exploration is:

$$p_i^d(t+1) = \begin{cases} p_{rand}^d + r_1(p_{rand}^d - p_i^d(t)) + \beta(p_{rand}^d - p_i^d(t)), i = 1 \\ p_{rand}^d + r_1(p_{i-1}^d - p_i^d(t)) + \beta(p_{rand}^d - p_i^d(t)), \forall i \in m, i \neq 1 \end{cases} \tag{9}$$

so that

$$p_{rand}^d = r_1\left(b^H - b^L\right) + b^L \tag{10}$$

Finally, the somersault foraging strategy is applied to obtain the final position of each individual, according to the following equation:

$$p_i^d(t+1) = p_i^d(t) + S(r_2 p_{best}^d - r_3 p_i^d(t)), \forall i \in m, i \neq 1 \tag{11}$$

where r_2 and r_3 stand for separate random number (unless by random chance) between 0 and 1, and S is the somersault factor that is equal to 2 [50]. After the somersault foraging is finished, the algorithm increases t by 1 and starts with the next iteration. Finally, the best individual p_{best}, which represents the individual whose fitness function has the lowest value, is the optimal solution to the optimization problem.

To describe the implementation of the proposed hybrid SA–MRFO algorithm, the pseudocode is given in Algorithm 2 as follows:

Algorithm 2 (*Pseudocode of SA–MRFO algorithm*).

```
Input data: t_max, m
Initialize the population of manta rays using the SA algorithm
Calculate the fitness value of each individual f(p_i) and obtain
  the best solution p_best
Set t = 1
While (t < t_max)
  For i = 1:m (for each individual)
    If (rand < 0.5) then apply the cyclone foraging
      If (t/t_max < rand) then apply the exploration mechanism
  according to (9)
      Else apply the exploitation mechanism that is given by
  (7)
    Else apply the chain foraging that is defined with (5)
  End For
  Compute the fitness of each individual, and update the best
  solution p_best
  For i = 1: m
    Apply the somersault foraging using (11)
  End For
  Compute the fitness of each individual, and update the best
  solution p_best
t = t + 1
End While
Return the global optimal solution p_best
```

5. Simulation results

This section presents the results obtained for the optimization of the different types of PID controller for the AVR system using the SA–MRFO algorithm proposed in this paper. Namely, in this paper, four types of PID controller for the AVR system are considered: ideal PID, real PID, FOPID, and PIDD^2. The parameters of the SA–MRFO algorithm are identical for the optimization process for

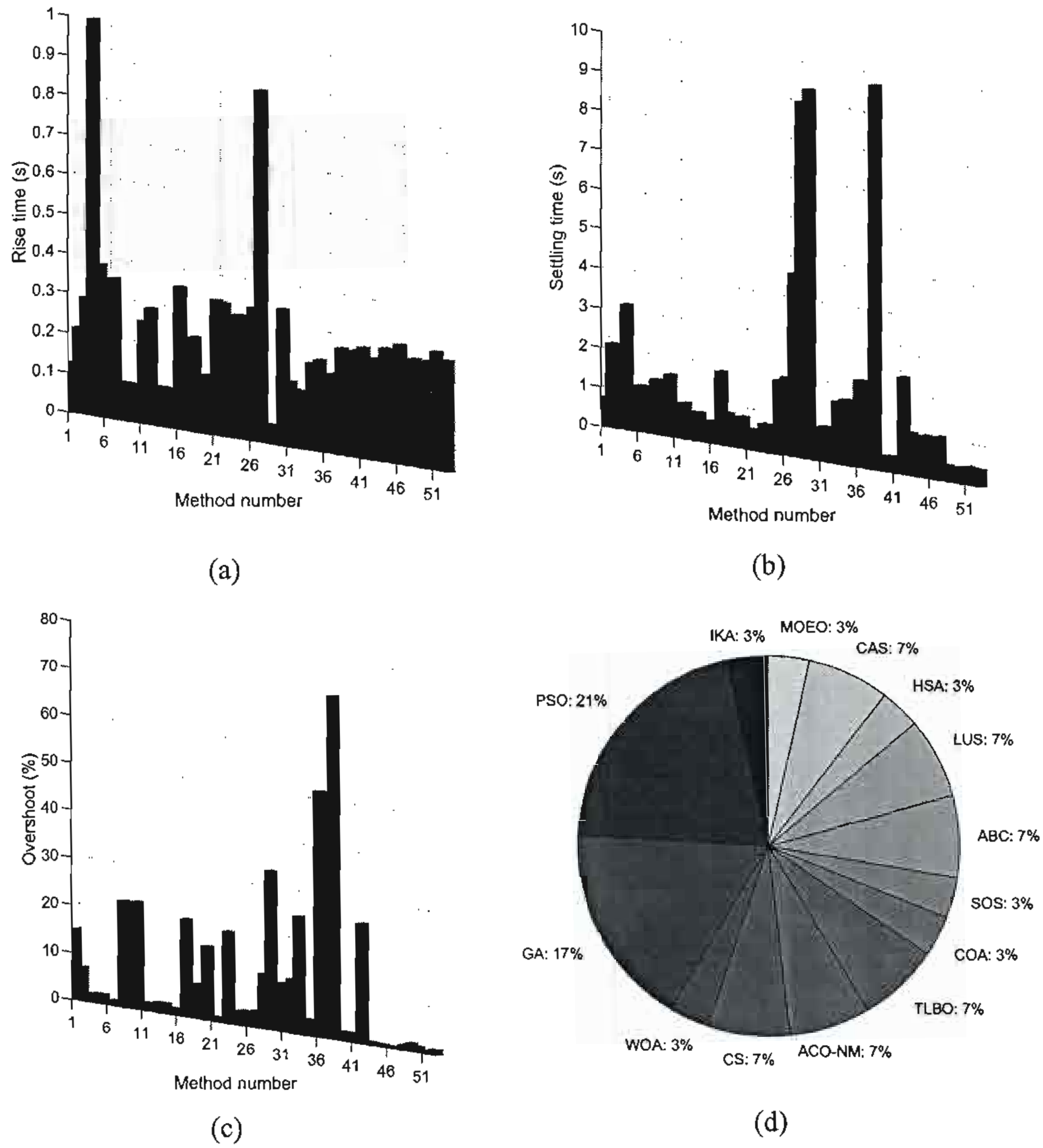

Fig. 3. The dynamic response obtained in the studies presented in Table 1: (a) rise time, (b) settling time, (c) overshoot, and (d) frequency of usage.

each controller—the maximum number of iterations is set to 50, and the size of the population is 30. All four types of controller tuned by the SA-MRFO algorithm are compared with the corresponding ones from the literature, in terms of convergence speed, step response quality, robustness, and disturbance rejection ability.

5.1. Optimization of the ideal PID controller

As can be seen from the transfer function of the ideal PID controller, given in Eq. (1), the optimization of this type of controller implies determining the optimal values of three parameters—K_p, K_i, and K_d. The lower bound for all three parameters is 0.1, and the upper bound is 1.0. The objective function (OF) that is used is given as follows:

$$OF = \left(1 - e^{-\beta}\right) \times \left(\frac{OS}{\alpha} + E_{SS}\right) + e^{-\beta}(t_s - t_r) \qquad (12)$$

where E_{SS} stands for the steady-state error, α and β are the coefficients whose values are 90 and 1, respectively. Using the proposed objective function, we made a compromise between overshoot and steady-state errors. The optimal values of ideal PID controller parameters obtained using the SA-MRFO algorithm are K_p = 0.6778, K_i = 0.3802, and K_d = 0.2663.

For comparison, among all the algorithms from Table 1 which deal with the ideal PID controller, three algorithms that provide the best results are chosen: PSO [16], MOL [12], and GA [11]. The main advantage of the hybrid SA-MRFO algorithm is the convergence speed, as can be seen in Fig. 4.

In Fig. 4, the convergence curve of the SA-MRFO algorithm is compared with the convergence curves of the mentioned three algorithms that are employed for PID parameter optimization, using the proposed OF given by (12). It is proven that the proposed algorithm reaches the optimal solution slightly faster than the other algorithms.

Table 2
Overview of the objective functions used in the literature.

Reference	Objective function (OF)
[12,26]	$IAE = \int \lvert e(t) \rvert dt$
[6,8,12]	$ISE = \int e^2(t)dt$
[12]	$ITAE = \int t \lvert e(t) \rvert dt$
[10,12,14]	$ITSE = \int te^2(t)dt$
[9,16,19,21,23,28]	$ZLG = (1 - e^{-\beta}) \times (OS + E_{SS}) + e^{-\beta}(t_s - t_r)$
[5]	$OF = \mu ITSE + ZLG$
[11]	$OF = w_1 OS + w_2 t_r + w_3 t_s + w_4 E_{SS}$
[20]	$OF = w_1 ITAE + w_2 OS + w_3 E_{SS} + w_4 t_s$
[17,24]	$OF = (w_1 OS)^2 + w_2 t_s^2 + \frac{w_3}{(max\_dv)^2}$
[15,18]	$OF = ITAE + wOS$
[19]	$OF = (1 - w)P_m + \omega_{gc}$
[19,30]	$OF = w_1 OS + w_2 t_r + w_3 t_s + w_4 E_{SS} + \int \left(w_5 \lvert e(t) \rvert + w_6 {V_f}^2(t) \right) dt + \frac{w_7}{P_m} + \frac{w_8}{G_m}$
[13]	$OF = \frac{e^{-\beta} t_r}{(1-e^{-\beta}) \times (1-t_r)} + e^{-\beta} OS + E_{SS}$
[22]	$OF = w_1 OS + w_2 t_r + w_3 t_s$
[7]	$OF = w_1 ITAE + w_2 N_{cp} + w_3 S_r$
[10]	$OF = \alpha_1 ITAE + \alpha_2 t_s + \alpha_3 OS$
[10]	$OF = \alpha_1 IAE + \alpha_2 t_s + \alpha_3 OS$
[10]	$OF = \alpha_1 ITSE + \alpha_2 t_s + \alpha_3 OS$
[10]	$OF = \alpha_1 ISE + \alpha_2 t_s + \alpha_3 OS$
[27]	$OF_1 = \omega_{gc}, OF_2 = P_m$
[29]	$OF_1 = te^2(t)dt, OF_2 = \int \Delta u^2(t)dt, OF_3 = \int te^2_{load}(t)dt$
[24]	$OF = w_1 OS + w_2 t_s + w_3 E_{SS} + w_4 \int \lvert e(t) \rvert dt + w_5 \int u^2(t)dt$
[25]	$OF_1 = IAE, OF_2 = 1000 \lvert E_{SS} \rvert, OF_3 = t_s$

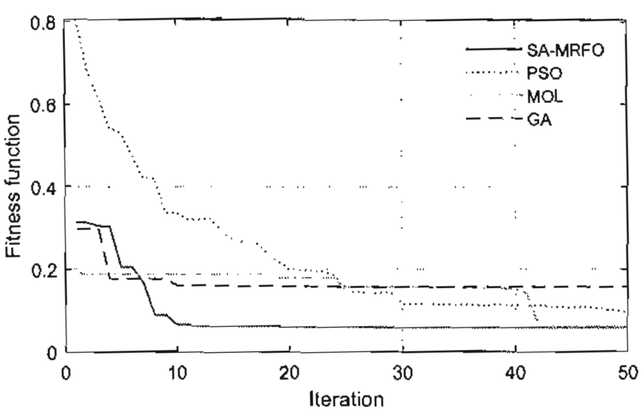

Fig. 4. Comparison of the convergence curves for optimization of the ideal PID.

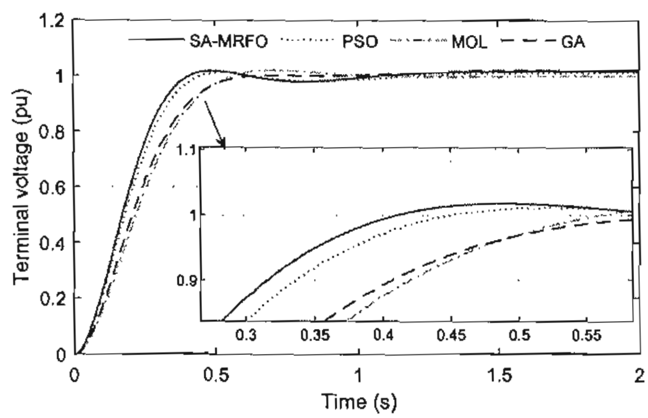

Fig. 5. Comparison of the step responses for the different ideal PID controllers.

The quality of the tuned PID controller is measured by the step-response parameters of the closed-loop AVR system. To demonstrate the superiority of the proposed algorithm, step responses of the AVR system in which the PID controller is tuned by the different algorithms are computed and represented in Fig. 5. It can be seen that the PID controller optimized by the SA-MRFO algorithm provides a better step response than the other algorithms from the literature that deal with this topic.

Additionally, the parameters of the transient response (rise time, settling time, and overshoot) are calculated based on the previously shown step response of the AVR system and presented in Table 3. The lowest values of rise time and settling time, and the overshoot only slightly higher than the lowest, indicate the high quality of the step response of the AVR system when the PID controller is optimized by the SA-MRFO algorithm.

The behavior of the AVR system under off-nominal conditions is examined through the robustness analysis and the disturbance rejection test. Precisely, robustness analysis is carried out for the case of the change of the time constants T_A, T_E, T_G, and T_S from −50% to +50% of the nominal value, in the steps of 25%. In all the examined cases, the step response of the AVR system is computed and presented in Fig. 6.

Table 3
Comparison of the transient response parameters for the ideal PID controllers.

Algorithm	t_r (s)	t_s (s)	OS (%)
SA–MRFO	0.2540	0.382	1.799
PSO [16]	0.2719	0.411	1.165
MOL [12]	0.3431	0.515	1.955
GA [11]	0.3340	1.980	2.158

The results obtained from the robustness test indicate that the AVR system with the PID controller tuned by the SA–MRFO algorithm is robust to the considered variations in the parameters. Moreover, the transient response parameters do not considerably deviate compared to the nominal conditions, as can be seen in Table 4.

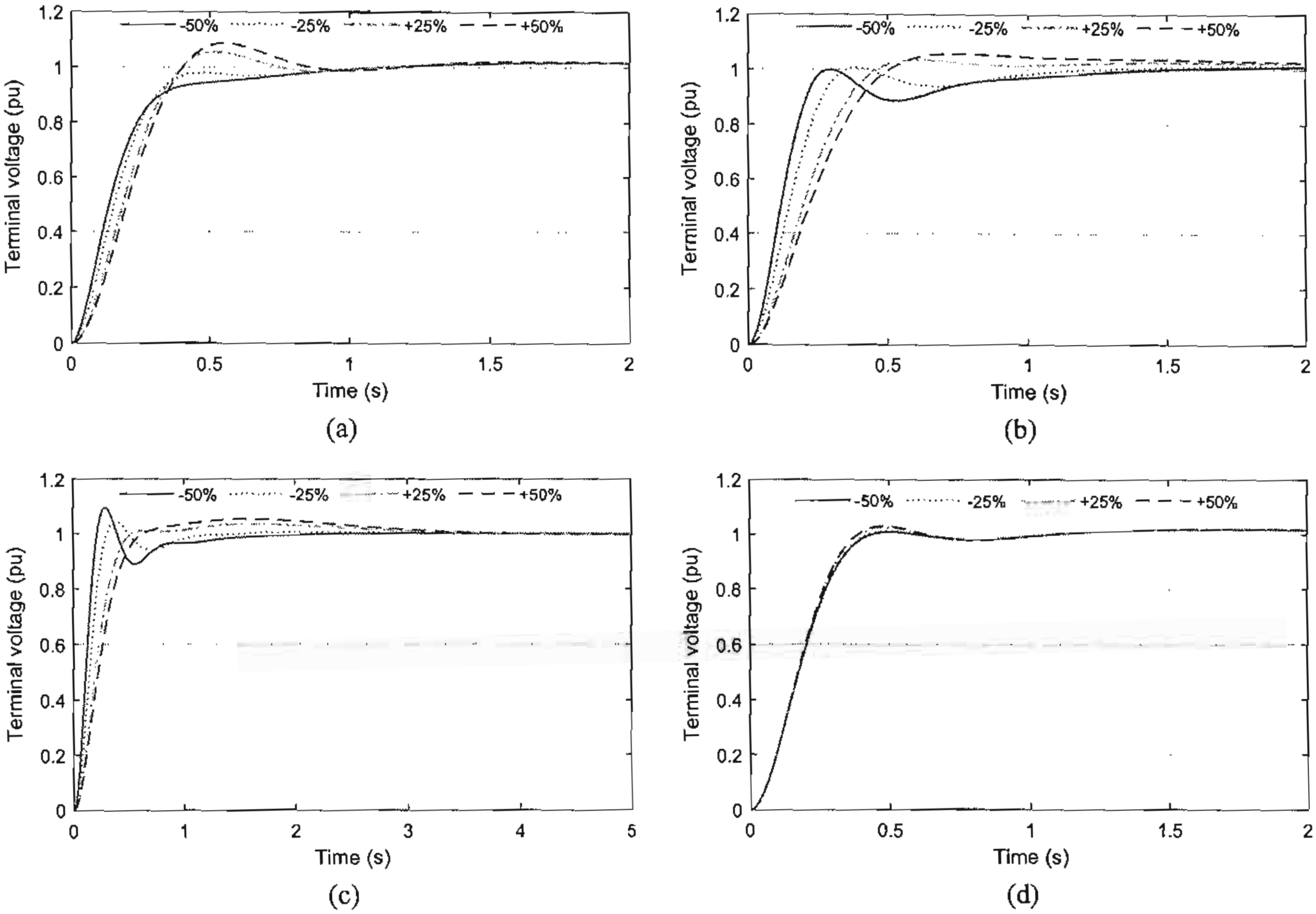

Fig. 6. The step response under the variation of the time constants from −50% to +50% of the nominal value: (a) variation of parameter T_A, (b) variation of parameter T_E, (c) variation of parameter T_G, and (d) variation of parameter T_S.

Table 4
Transient response for the robustness analysis of the ideal PID controller.

Parameter	Variation (%)	t_r (s)	t_s (s)	OS (%)
T_A	−50	0.2824	0.8512	1.6919
	−25	0.2549	0.8398	1.7442
	+25	0.2609	0.6764	5.3114
	+50	0.2690	1.8037	8.3913
T_E	−50	0.1665	1.1391	1.1137
	−25	0.2122	0.9699	1.3629
	+25	0.2932	2.0922	3.5740
	+50	0.3292	2.2381	5.8169
T_G	−50	0.1450	1.3292	9.3365
	−25	0.1984	0.9857	4.3950
	+25	0.3121	2.5294	3.4753
	+50	0.3708	2.8362	5.3403
T_S	−50	0.2628	0.3991	1.7907
	−25	0.2587	0.3895	1.7941
	+25	0.2509	0.8315	2.3344
	+50	0.2470	0.8494	2.8962

Moreover, the ability of the proposed controllers to reject different kinds of disturbances is investigated. The control signal and load disturbances are considered as shown in Fig. 7.

The control signal disturbance is modeled as a step signal with an amplitude of 1.0 pu, which lasts from t = 2 s to t = 8 s. A comparison of the PID controller tuned by the proposed SA-MRFO algorithm and the other considered algorithms is given in Fig. 8 (a), in which the step responses in the case of the described control signal disturbance are depicted. Similar to the control signal disturbance, the load disturbance is modeled as a step signal in the interval from t = 2.0 s to t = 3.5 s. The step responses that correspond to this type of disturbance are presented in Fig. 8(b). The SA-MRFO algorithm is compared to the same algorithms as in the previous parts of the ideal PID controller optimization. Based on the previously presented results, it can be concluded that all of the considered algorithms provide stabilizing of the voltage at

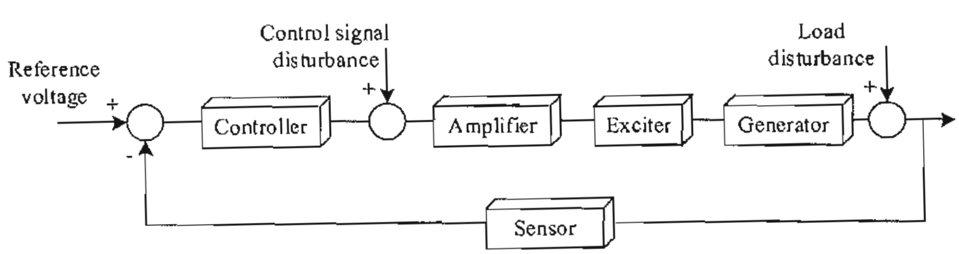

Fig. 7. The block diagram of the AVR that includes the disturbances.

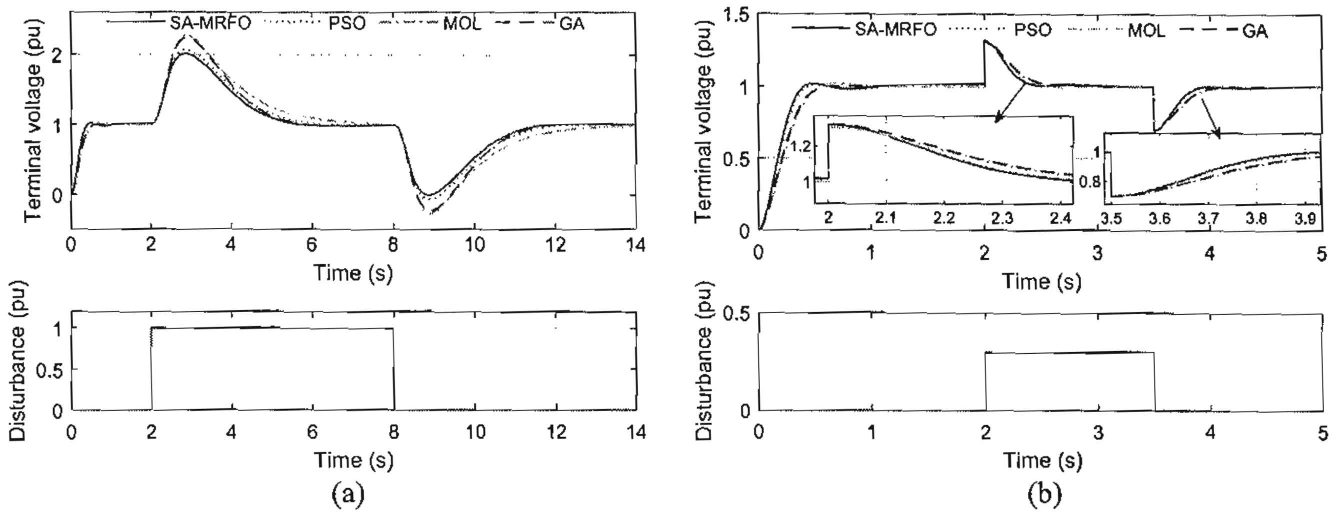

Fig. 8. Step response of the AVR controlled using the ideal PID controller with disturbances included (a) Control signal disturbance and (b) Load disturbance.

the nominal level, but the PID controller optimized by the SA–MRFO algorithm outperforms the others in the speed of the response.

5.2. Optimization of the real PID controller

According to the transfer function of the real PID controller, which is given by Eq. (2), the optimization process of the real PID controller must consider the additional parameter N.

In other words, the number of the design variables, in this case, is equal to 4. Lower and upper bounds of the gains K_p, K_i, and K_d are the same as in the case of the ideal PID, while the bounds of the parameter N are set to be 200 and 1000. The objective function used for the optimization of the real PID controller is identical to the one used for the optimization of the ideal PID controller. Thus, using the SA–MRFO algorithm the obtained optimal values for the real PID controller parameters are K_p = 0.6672, K_i = 0.5938, K_d = 0.2599, and N = 863.2453.

The performance of the proposed SA–MRFO algorithm for the optimization of the real PID controller is compared with the other algorithms from Table 1 that deal with the same problem. Precisely, the algorithms to be used for the comparison are CS [20], TLBO [21], and PSO [22]. In order to depict their convergence speed, each of the previously mentioned algorithms is employed for the optimal tuning of the real PID controller using the same settings as the proposed SA–MRFO algorithm. As is obvious from Fig. 9, the hybrid algorithm presented in this paper converges to the optimal solution significantly faster than the other algorithms from the literature that deal with the same problem.

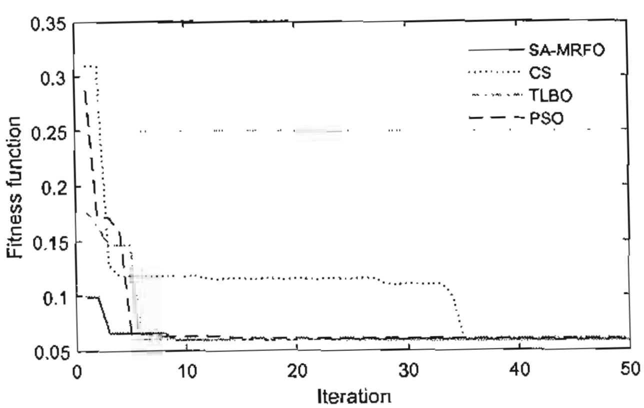

Fig. 9. Comparison of the convergence curves for optimization of the real PID.

The results presented in references [20–22] are also used for the comparison in terms of the step response quality. The real PID controller optimized by the SA–MRFO algorithm provides a step response of significantly higher quality than the same controller optimized by using the previously mentioned algorithms. The detailed comparison is provided by the step response plots and the transient response parameters, depicted in Fig. 10 and Table 5, respectively.

Furthermore, the results of the robustness analysis of the AVR system with the real PID controller tuned by SA–MRFO algorithm

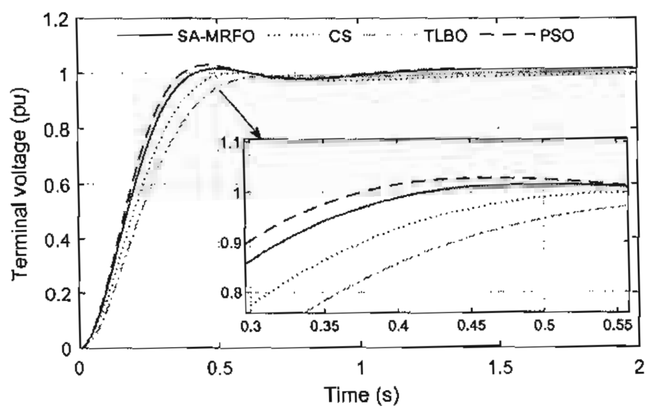

Fig. 10. Comparison of the step responses for the different real PID controllers.

Table 5
Comparison of the transient response parameters for the real PID controllers.

Algorithm	t_r (s)	t_s (s)	OS (%)
SA–MRFO	0.2576	0.3871	1.7283
CS [20]	0.3055	1.1743	0.1216
TLBO [21]	0.3571	0.5833	0.6166
PSO [22]	0.2378	0.8303	2.9905

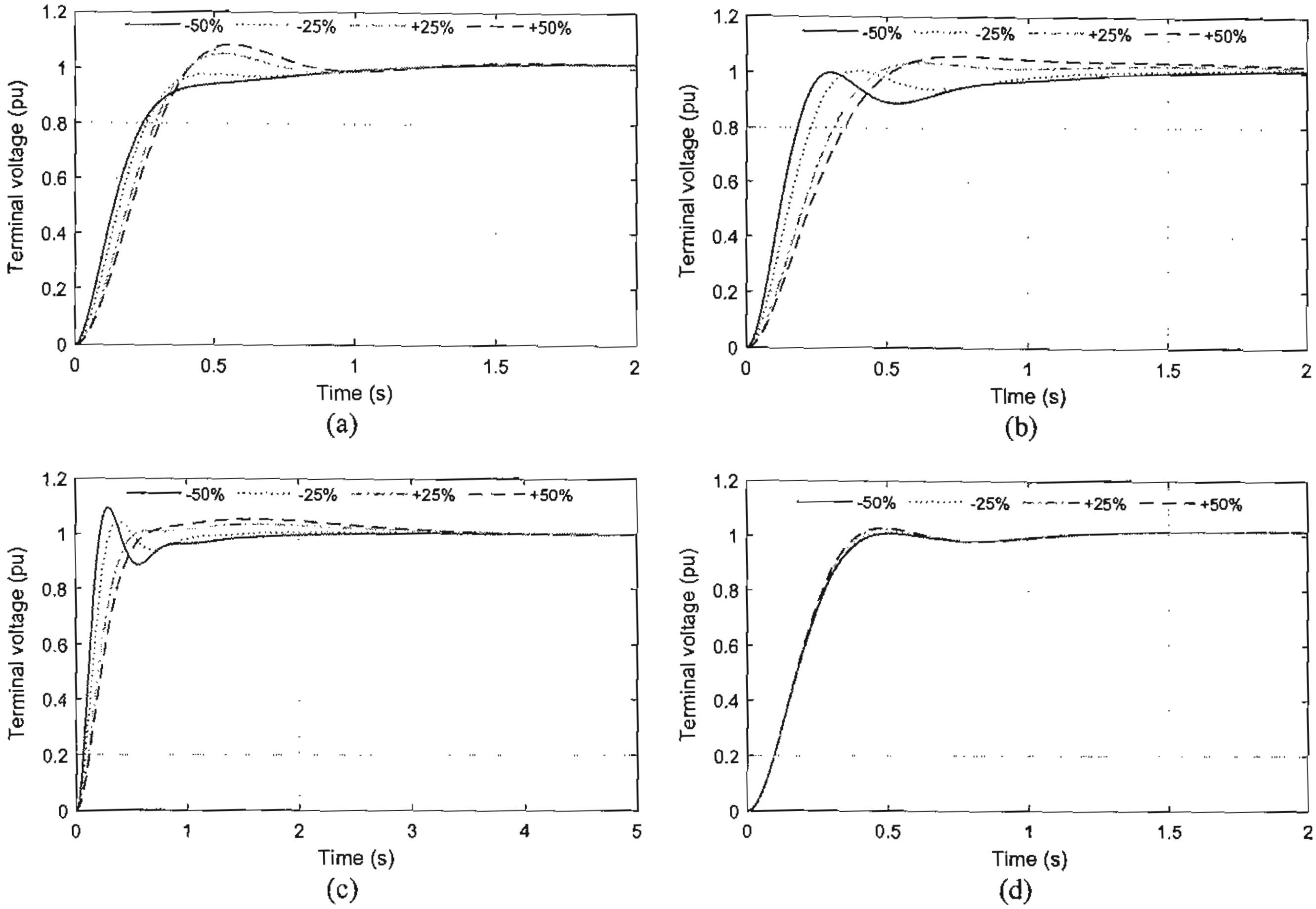

Fig. 11. The step response under the variation of the time constants from −50% to +50% of the nominal value: (a) variation of parameter T_A, (b) variation of parameter T_E, (c) variation of parameter T_G, and (d) variation of parameter T_S.

Table 6
Transient response for the robustness analysis of the real PID controller.

Parameter	Variation (%)	t_r (s)	t_s (s)	OS (%)
T_A	−50	0.2874	0.8632	1.6255
	−25	0.2586	0.8511	1.6766
	+25	0.2645	0.6839	5.2299
	+50	0.2724	1.7641	8.2785
T_E	−50	0.1685	1.1570	1.0615
	−25	0.2153	0.9840	1.3034
	+25	0.2973	2.0659	3.5395
	+50	0.3337	2.2284	5.8276
T_G	−50	0.1466	1.3566	9.3283
	−25	0.201	1.0021	4.3114
	+25	0.3168	2.5269	3.4093
	+50	0.3765	2.8476	5.2868
T_S	−50	0.2665	0.4062	1.7221
	−25	0.2622	0.3963	1.7254
	+25	0.2544	0.8413	2.2334
	+50	0.2505	0.8595	2.7800

are presented in Fig. 11 and Table 6. Precisely, the step responses in which the time constants T_A, T_E, T_G, and T_S deviate from their nominal values are given in Fig. 11, while the transient response parameters of the corresponding step responses are presented in Table 6. The disturbance analysis for the real PID controller is carried out in the same way as for the ideal PID. The impact of the two types of disturbances—control signal and load disturbance—is demonstrated in Fig. 12. In terms of the ability to reject the disturbances, it can be seen that the real PID controller tuned by the SA-MRFO algorithm ensures a faster step response than the other considered algorithms that are applied for the real PID.

5.3. Optimization of the FOPID controller

Unlike the previously described types of PID controller, the FOPID controller introduces derivatives and integrals whose order is not an integer, but a real number [53]. The optimization of the FOPID controller implies determining the optimal values of five parameters—K_p, K_i, K_d, μ, and λ—as the transfer function Eq. (3) indicates. The OF equation given in Eq. (12), which was applied for ideal and real PID optimization, cannot be used for the optimization of the FOPID controller.

Thereby, we consider a novel OF, whose purpose is to improve the transient response, as formulated in Eq. (13).

$$OF = w_1 \int t|e(t)|dt + w_2 OS + w_3 |E_{SS}| + w_4 t_s \tag{13}$$

where w_1–w_4 are the weighting coefficients, whose values are chosen after many experiments: $w_1 = 1$, $w_2 = 0.02$, $w_3 = 1$, and $w_4 = 5$. The lower and upper bounds of the optimization variables are given in Table 7.

Applying the SA-MRFO algorithm for the optimization of the FOPID controller using previously defined settings, the following optimal results are obtained: K_p = 1.8931, K_i = 0.8699,

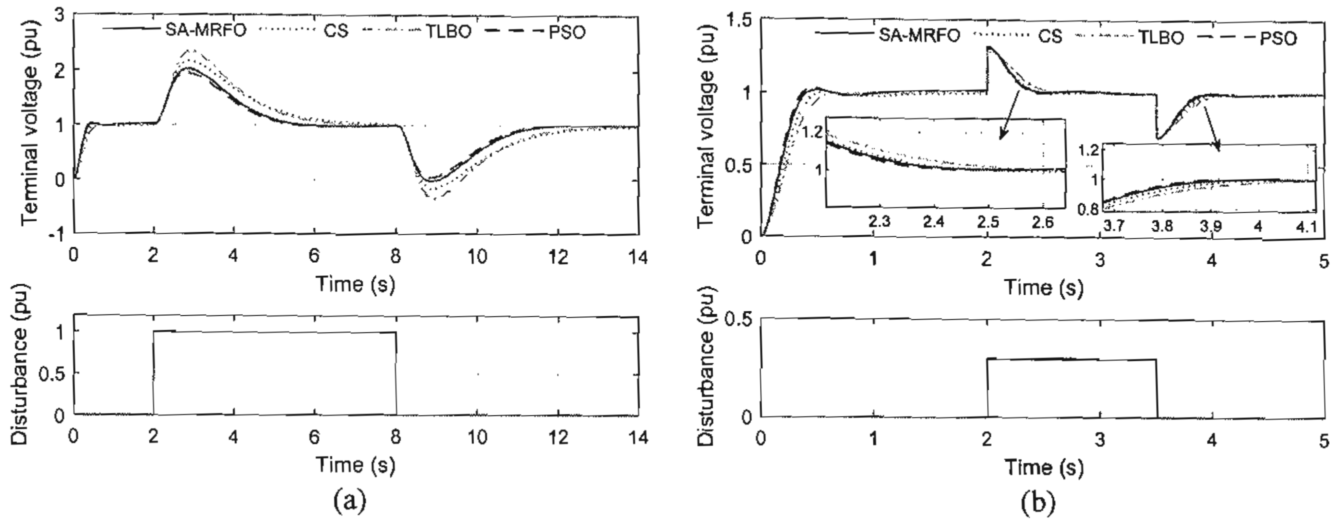

Fig. 12. Step response of the AVR controlled using the real PID controller with disturbances included (a) Control signal disturbance and (b) Load disturbance.

Table 7
Boundaries of the optimization variables of the FOPID controller.

Parameter	Lower bound	Upper bound
K_p	1.0	2.0
K_i	0.1	1.0
K_d	0.1	0.4
λ	1.0	2.0
μ	1.0	2.0

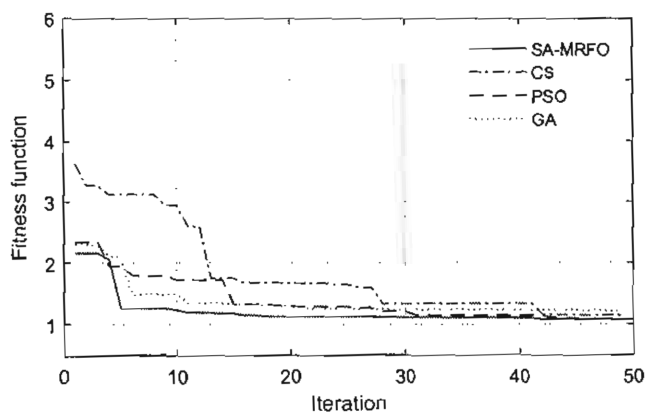

Fig. 13. Comparison of the convergence curves for optimization of the FOPID.

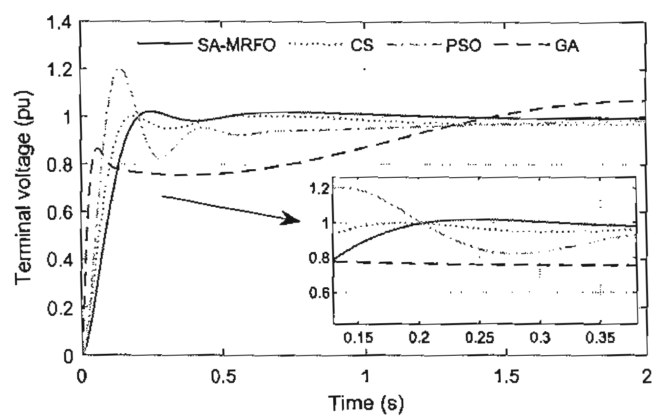

Fig. 14. Comparison of the step responses for the different FOPID controllers.

Table 8
Comparison of the transient response parameters for the FOPID controllers.

Algorithm	t_r (s)	t_s (s)	OS (%)
SA-MRFO	0.1309	0.1909	1.9765
CS [23]	0.0989	0.7203	2.1341
PSO [24]	0.0626	1.8531	20.5618
GA [27]	0.0479	9.0029	11.6334

K_d = 0.3595, μ = 1.278, and λ = 1.0408. For comparison with the SA-MRFO algorithm, among all the studies presented in Table 1 that deal with FOPID controller optimization, the selected algorithms are CS [23], PSO [24], and GA [27]. Firstly, a comparison of the convergence speed of the SA-MRFO algorithm with those of the previously mentioned algorithms is given. According to Fig. 13, the optimal solution is obtained significantly faster by employing the SA-MRFO algorithm.

Next, the step responses of the AVR system with the FOPID controller tuned by the different algorithms are depicted in Fig. 14. The more detailed view of the drawn step responses is provided by calculating the transient response parameters, which are presented in Table 8. Based on the presented results, it is obvious that the SA-MRFO FOPID controller provides the best voltage response of the AVR system. Although the rise time is longest when the SA-MRFO algorithm is used, it is obvious that the usage of the PSO [24] and GA [27] algorithms leads to extremely high overshoot values as shown in Table 8, compared to 1.97% when the SA-MRFO algorithm is employed. Moreover, the shortest settling time is also obtained when the SA-MRFO algorithm is used.

The robustness analysis of the AVR system with the FOPID controller optimized using the hybrid SA-MRFO algorithm is carried out by varying the time constants. The corresponding step responses are given in Fig. 15 which indicates that the obtained AVR system is robust to the variations in the parameters. Additionally, the transient response parameters computed from the obtained step responses are listed in Table 9.

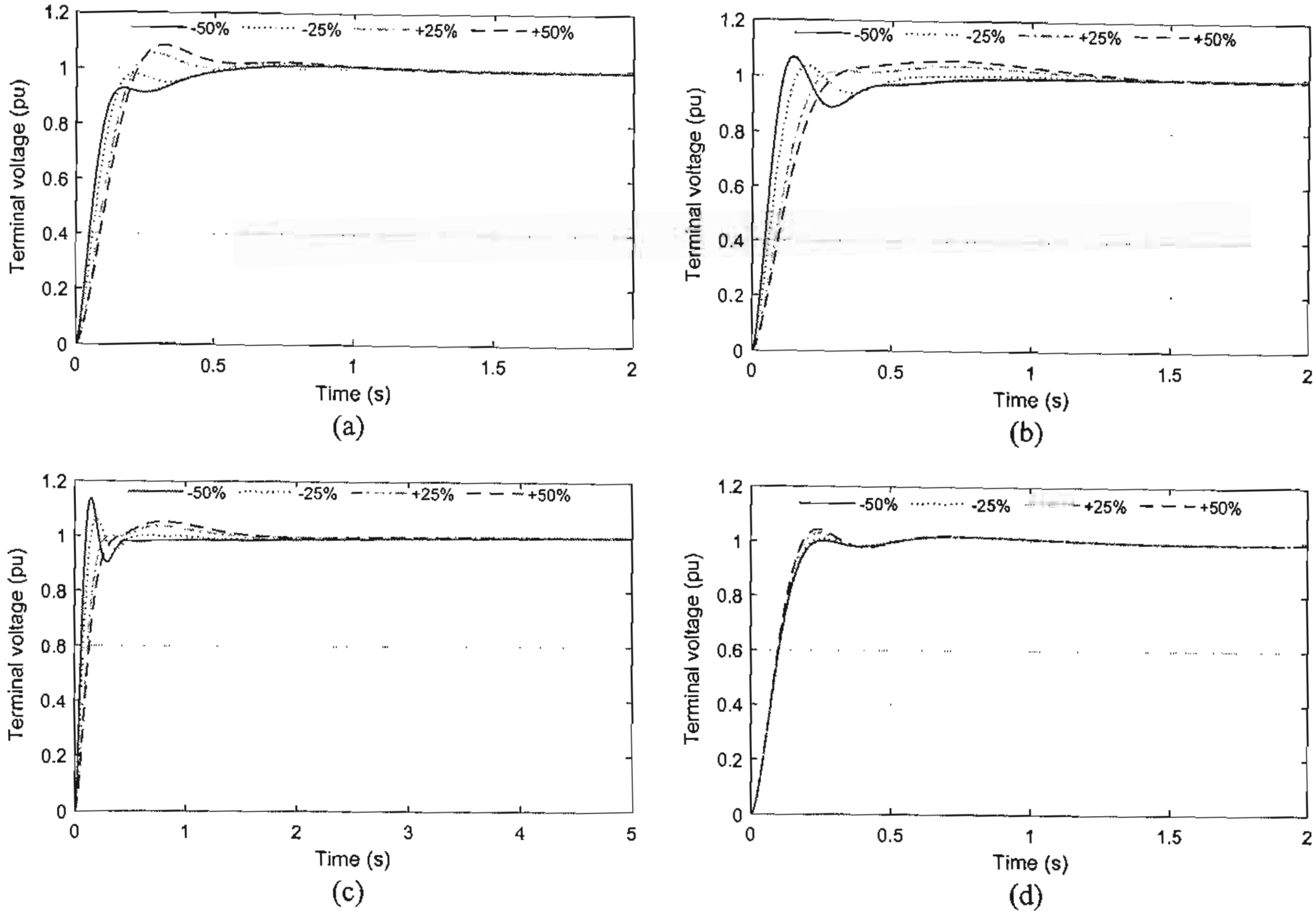

Fig. 15. The step response under the variation of the time constants from −50% to +50% of the nominal value: (a) variation of parameter T_A, (b) variation of parameter T_E, (c) variation of parameter T_G, and (d) variation of parameter T_S.

Table 9
Transient response parameters for the robustness analysis of the FOPID controller.

Parameter	Variation (%)	t_r (s)	t_s (s)	OS (%)
T_A	−50	0.1537	0.4664	1.2013
	−25	0.1466	0.4505	1.4475
	+25	0.1415	0.8305	5.3236
	+50	0.1519	0.8678	8.1757
T_E	−50	0.0956	0.6449	3.1452
	−25	0.1326	0.4977	3.0660
	+25	0.1581	1.0242	3.7745
	+50	0.1848	1.1492	5.8548
T_G	−50	0.0783	0.4394	9.3831
	−25	0.1278	0.4735	5.7077
	+25	0.1650	0.2554	0.000
	+50	0.2022	1.2865	5.1250
T_S	−50	0.1392	0.2100	0.1732
	−25	0.1348	0.1995	1.8593
	+25	0.1272	0.4180	3.1257
	+50	0.1239	0.7366	4.3271

Finally, the disturbance rejection analysis is conducted by introducing the same type of disturbances previously mentioned. For comparison with the SA-MRFO algorithm, the algorithms presented in references [23,24,27] are used, as for the step responses comparison. The step response when a disturbance exists in the AVR system is given in Fig. 16. It is clear that the FOPID controller optimized by the SA-MRFO algorithm outperforms the FOPID controllers tuned by other algorithms in terms of the ability to reject the disturbances. Some of the considered algorithms for optimizing the FOPID controller do not even maintain the voltage at the nominal level, which can represent a huge problem for the stability of the power system.

5.4. Optimization of the PIDD^2 controller

Among all the presented studies, only two papers that deal with the optimization of the PIDD^2 for the AVR system can be found [6,31]. Mosaad *et al.* in [6] used the WOA algorithm to optimize parameters K_a, K_d, K_p, K_i, α, and β of the PIDD^2 controller, whose transfer function is defined as follows:

$$C(s) = \frac{K_a s^3 + K_d s^2 + K_p s + K_i}{s^3 + \alpha s^2 + \beta s} \tag{14}$$

The optimal values of the PIDD^2 parameters obtained are K_a = 103.02, K_d = 500.652, K_p = 777.401, K_i = 397.741, α = 550.118, and β = 915.041 [6]. On the other hand, in [31], the PSO algorithm is employed to optimize the PIDD^2 controller defined by Eq. (4). The obtained optimal results are K_p = 2.7784, K_i = 1.8521, K_d = 0.9997, and K_{d2} = 0.07394.

In this paper, the PIDD^2 controller is optimized by using the SA-MRFO hybrid algorithm. The objective function used for the optimization is the same as for the FOPID controller, presented by Eq. (13), while the lower bounds and upper bounds for all the opti-

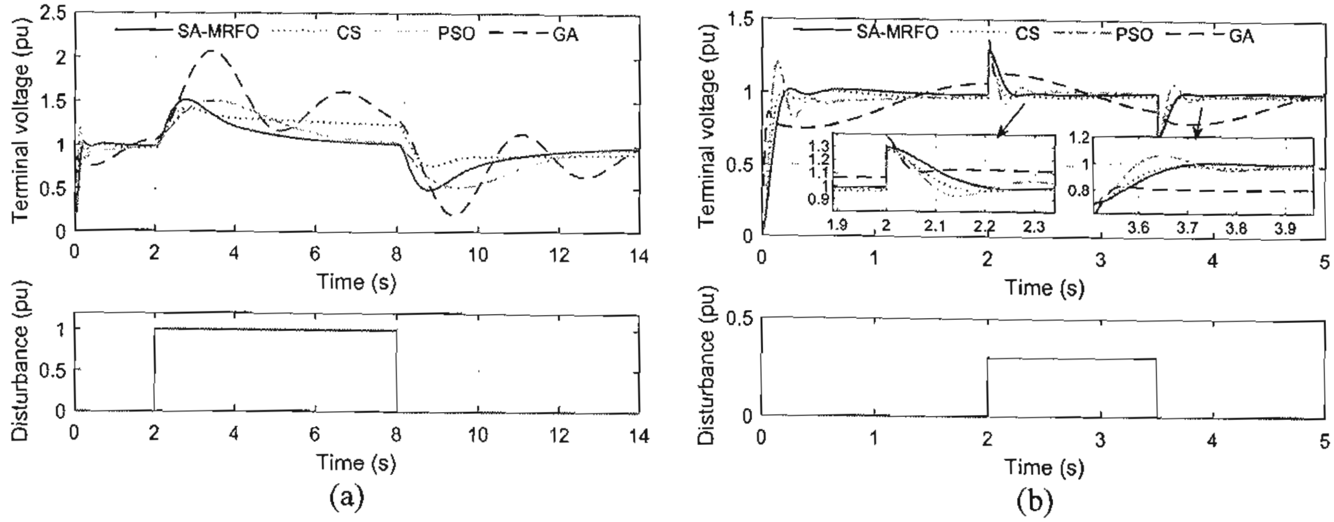

Fig. 16. Step response of the AVR controlled using the FOPID controller with disturbances included (a) Control signal disturbance and (b) Load disturbance.

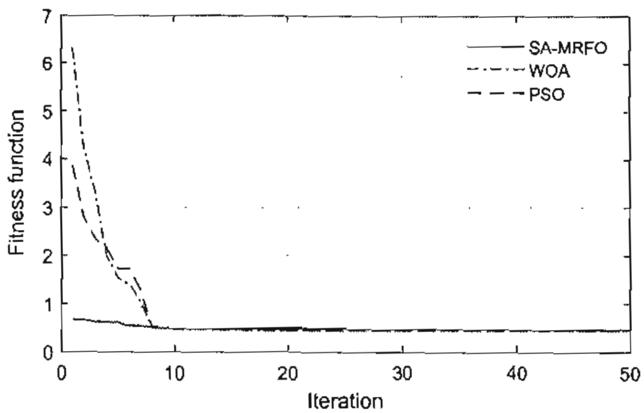

Fig. 17. Comparison of the convergence curves for optimization of the PIDD^2.

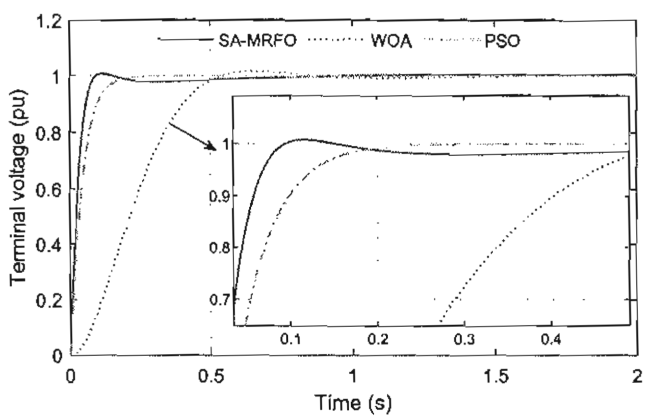

Fig. 18. Comparison of the step responses for the different PIDD^2 controllers.

Table 10
Comparison of the transient response parameters for the PIDD^2 controllers.

Algorithm	t_r (s)	t_s (s)	OS (%)
SA-MRFO	0.0535	0.0798	0.7562
WOA [6]	0.3277	0.4954	1.6483
PSO [31]	0.0929	0.1635	0.0026

mization variables are 0.1 and 3.0, respectively. The optimal results that are provided with the SA-MRFO algorithm are K_p = 2.9943, K_I = 2.9787, K_d = 1.5882, and K_{d2} = 0.102. Firstly, to test the convergence speed, all three algorithms mentioned before are used for the optimization of the PIDD^2 controller using OF given in Eq. (12). The comparison is presented in Fig. 17, which indicates that the SA-MRFO algorithm proposed in this paper provides faster convergence than the algorithms used in [6,31].

The results obtained are compared to the results from [6,31], in terms of the step response quality. To that end, the step responses are plotted in Fig. 18, while the rise time, the settling time, and the overshoot for each step response are presented in Table 10.

Based on the previous results, one can see that the usage of the SA-MRFO algorithm provides a significantly better transient response compared to the other two algorithms from the literature. Furthermore, the robustness analysis of the AVR system with the PIDD^2 controller optimized with the SA-MRFO algorithm is presented. The step responses, when the time constants of the AVR components deviate from their nominal values are depicted in Fig. 19. Also, the corresponding transient response parameters given in Table 11, prove that the PIDD^2 controller optimized using the SA-MRFO can keep the AVR system robust to the variations in the parameters.

The final comparison is conducted in terms of disturbance rejection ability, where the performance of the proposed SA-MRFO algorithm is compared to the results presented in [6,31]. The results in the cases of control signal disturbance and load disturbance are presented in Fig. 20. From the figure, it can be concluded that the PIDD^2 controller tuned by the SA-MRFO algorithm rejects the disturbances slightly better than the same controller with the parameters determined in [6,31].

5.5. Comparison between the controllers optimized by the SA-MRFO algorithm

The application of the novel SA-MRFO algorithm in determining the optimal parameters of the four different types of PID controller is presented, in which the performance of the SA-MRFO algorithm has been compared with other algorithms from the literature. Next, a comparison of the step response quality of the AVR system controlled by the ideal PID, the real PID, the FOPID, and the PIDD^2 is presented. For that purpose, the computed step responses are rep-

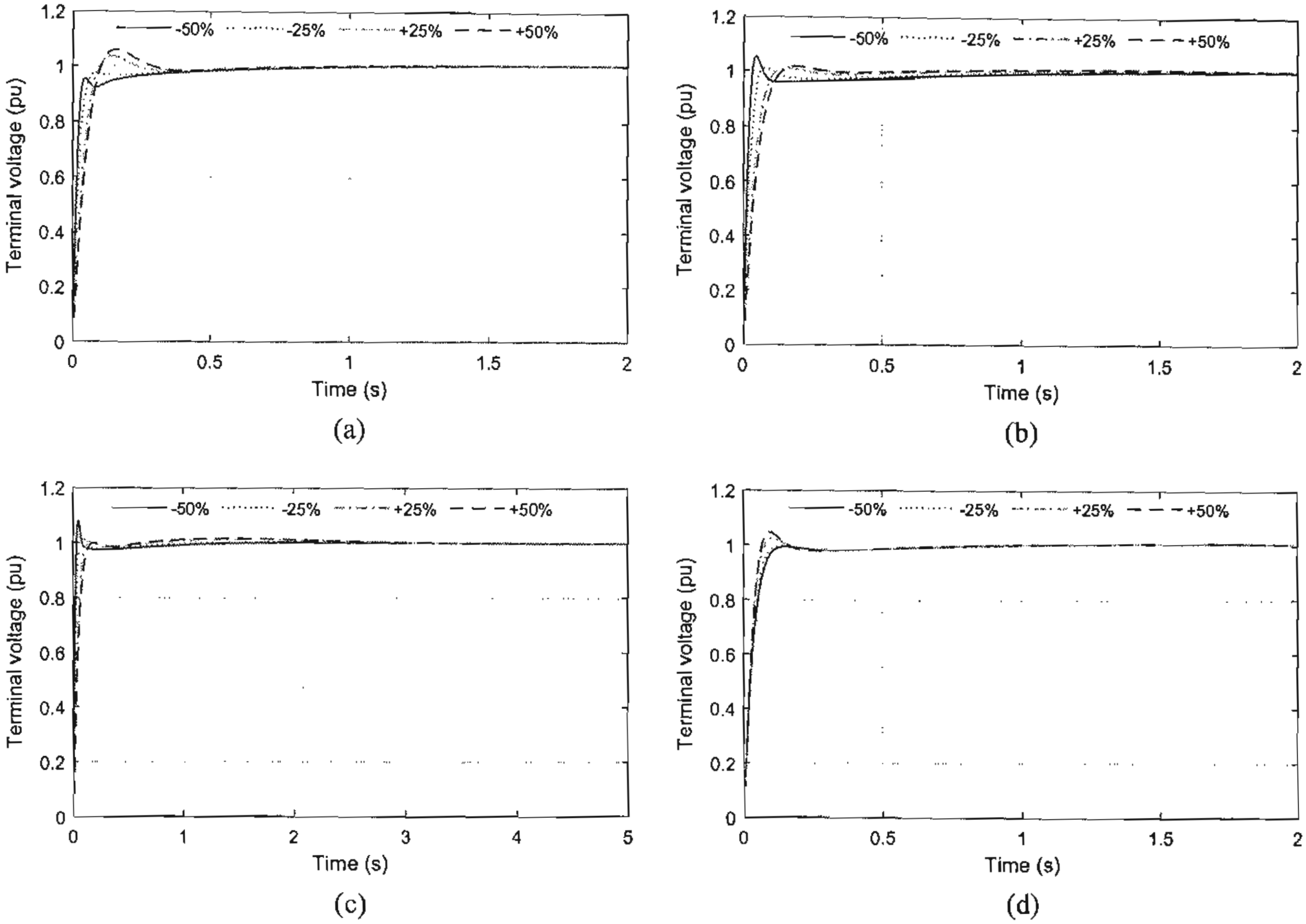

Fig. 19. The step response under the variation of the time constants from −50% to +50% of the nominal value: (a) variation of parameter T_A, (b) variation of parameter T_E, (c) variation of parameter T_G, and (d) variation of parameter T_S.

Table 11
Transient response parameters for the robustness analysis of the PIDD^2 controller.

Parameter	Variation (%)	t_r (s)	t_s (s)	OS (%)
T_A	−50	0.0277	0.4261	0.5216
	−25	0.0422	0.3866	0.3883
	+25	0.0628	0.1874	3.6262
	+50	0.0710	0.2432	6.0381
T_E	−50	0.0222	0.5885	5.2642
	−25	0.0375	0.4729	1.0781
	+25	0.0688	0.1018	1.1785
	+50	0.0831	0.1211	1.7012
T_G	−50	0.0215	0.4780	7.9604
	−25	0.0367	0.3891	2.2559
	+25	0.0706	0.1083	0.2115
	+50	0.0874	0.1364	0.6077
T_S	−50	0.0659	0.1084	0.0000
	−25	0.0595	0.0940	0.0000
	+25	0.0488	0.3175	2.3589
	+50	0.0453	0.3211	4.7336

resented in Fig. 21, and the detailed information is provided by the transient response parameters presented in Table 12.

The analysis of the obtained results indicates that the best quality of the step response can be achieved when the PIDD^2 type is used as the controller in the AVR scheme. That conclusion is drawn based on the values of the rise time, the settling time, and the overshoot, which have the lowest values when this type of controller is used. Furthermore, the disturbance rejection ability of all mentioned types of the PID controller is presented in Fig. 22. Similar to the previous conclusion, the PIDD^2 controller has superior performance compared to the other three types of PID controller.

6. Conclusion

This paper proposes the novel hybrid metaheuristic algorithm called SA-MRFO, whose ability to optimize the parameters of different types of PID controller is demonstrated. The proposed algorithm compounds the SA algorithm, which belongs to the group of single solution-based metaheuristics, and the population-based MRFO algorithm. This approach is based on the initialization of the MRFO population by using the SA algorithm, which significantly contributes to the convergence speed, as was demonstrated while solving different optimization problems. The optimization of the four different types of PID presented in this paper also introduces novel objective functions that tend to improve the step response quality of the AVR system. It is shown that all considered types of controller, ideal PID, real PID, FOPID, and PIDD^2, whose parameters are optimized with the SA-MRFO algorithm dramatically outperform the corresponding controllers from the literature whose parameters are determined by the other algorithms. The improvements made by employing the SA-MRFO algorithm in

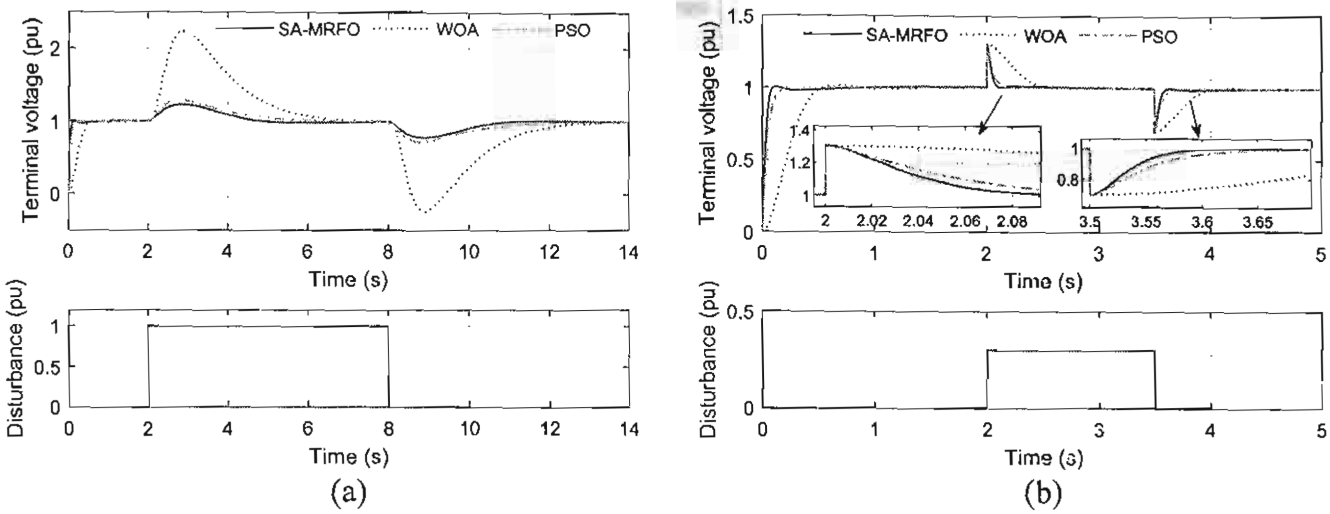

Fig. 20. Step response of the AVR controlled using the $PIDD^2$ controller with disturbances included (a) Control signal disturbance and (b) Load disturbance.

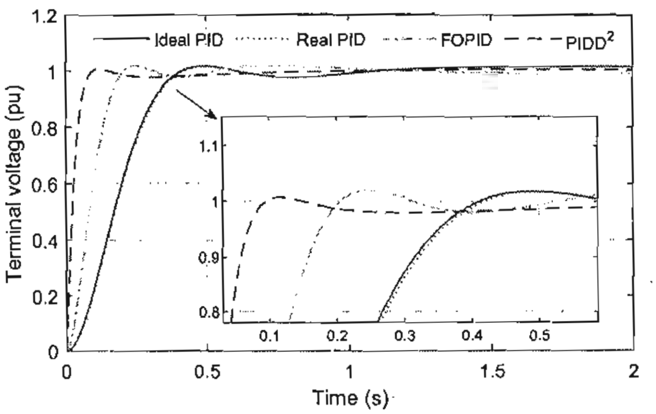

Fig. 21. Comparison of the step responses of the AVR system controlled by the ideal PID, real PID, FOPID, and $PIDD^2$ is presented.

Table 12
Comparison of the transient response parameters of the four PID controllers.

Algorithm	t_r (s)	t_s (s)	OS (%)
Ideal PID	0.2540	0.3802	1.7999
Real PID	0.2576	0.3871	1.7283
FOPID	0.1309	0.1909	1.9765
$PIDD^2$	0.0535	0.0798	0.7562

the optimization process are highlighted by comparing the step responses of the AVR system under nominal conditions, carrying out the robustness analysis, and inspecting the ability of the AVR system to reject different types of disturbances. Furthermore, a comparison between the considered types of controller optimized by the SA–MRFO algorithm is conducted. Despite a few numbers of papers are dedicated to the $PIDD^2$ controller, this type of controller shows significantly better performance than the ideal, real, and fractional-order PID controllers.

The contributions of this paper can be divided into two directions. Firstly, a novel hybrid metaheuristic algorithm is proposed, and it is proven that the proposed algorithm outperforms other algorithms from the literature in the considered optimization problem. Secondly, the analysis of different types of PID controllers conducted in this paper demonstrates that the PID controller with second-order derivative, which is rarely used in the literature, outperforms the other types of the controller.

Finally, different hybridizing strategies will be investigated to propose other novel hybrid algorithms with better performance. Also, other control strategies will be examined to test their applicability in the AVR system. Besides, future works will also include an experimental validation of the presented optimization strategy with the proposed controller, which is currently conducted on a real 120 MW generator in one of the hydropower plants in Montenegro.

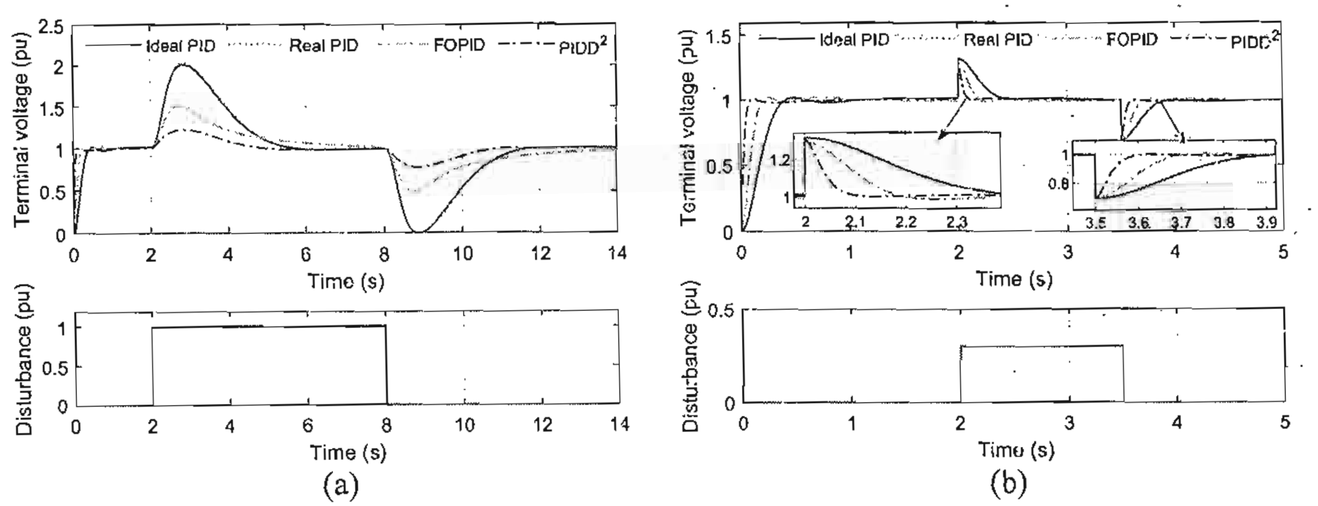

Fig. 22. Step response of the AVR controlled using the four controller types with disturbances included (a) Control signal disturbance and (b) Load disturbance.

Table A1
Transient response of the AVR system using the different parameters of the controllers obtained by the algorithms presented in Table 1.

Algorithm number	t_r (s)	t_s (s)	OS (%)	Algorithm number	t_r (s)	t_s (s)	OS (%)
1	0.1276	0.7531	15.0041	28	0.8867	4.6227	3.6933
2	0.2151	2.1291	7.2357	29	0.0480	9.0010	11.6283
3	0.2924	0.4406	1.7711	30	0.0101	9.3488	33.4763
4	0.9995	3.1627	2.0065	31	0.3431	0.5154	1.9552
5	0.3816	0.7810	2.0041	32	0.1641	0.8813	10.4024
6	0.3054	1.1742	0.1216	33	0.1465	0.8768	11.4432
7	0.3526	0.5359	1.3003	34	0.0892	1.5683	24.7950
8	0.0957	1.3834	22.2811	35	0.2201	1.6487	3.4577
9	0.0957	1.3902	22.1461	36	0.2305	0.8790	2.6127
10	0.0930	1.5608	22.5659	37	0.1884	2.2055	51.8909
11	0.2574	0.8092	1.6664	38	0.2022	1.8107	42.8003
12	0.2914	0.9076	0.6167	39	0.2683	9.7347	72.4792
13	0.0989	0.7203	2.1340	40	0.2523	0.3770	1.9437
14	0.0993	0.7219	2.1085	41	0.2684	0.4010	1.9715
15	0.0933	0.4335	1.4589	42	0.2796	0.4178	1.9688
16	0.3570	0.5832	0.6166	43	0.1549	2.4587	25.4785
17	0.0626	1.8531	20.5617	44	0.259	1.0778	0.6339
18	0.2377	0.8302	2.9905	45	0.2857	1.0354	0.5481
19	0.0782	0.4108	7.5121	46	0.2789	1.0706	0.4904
20	0.1490	0.7997	15.5623	47	0.3019	0.9898	0.3717
21	0.3388	0.5168	0.9541	48	0.2680	1.0944	0.5276
22	0.3348	0.5082	1.0518	49	0.2719	0.4110	1.1653
23	0.1197	0.7095	19.3372	50	0.2566	0.3846	1.7084
24	0.3122	0.4778	0.5911	51	0.2719	0.4109	1.1613
25	0.2113	1.8759	3.1923	52	0.2979	0.4567	0.4818
26	0.0929	0.1635	0.0026	53	0.2800	0.4250	0.9211
27	0.3341	1.9800	2.1580	54	0.2797	0.4239	1.0379

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix

The rise times, settling times, and overshoots obtained from the step responses of the AVR system using the different parameters of the controllers obtained by the algorithms presented in Table 1 are presented in Table A.1.

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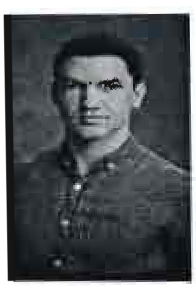

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Tokom druge i treće godine osnovnih studija, kao i na specijalističkim studijama, bio je korisnik stipendije Ministarstva prosvjete Crne Gore za talentovane studente. Nagrađen je od Univerziteta Crne Gore za postignut uspjeh u toku studijske 2016/17. godine i za završene studije sa najboljim uspjehom 2018. godine, kao i od Elektrotehničkog fakulteta za najboljeg studenta sa završenim osnovnim studijama, za odsjek Energetika i automatika. Za studijsku 2017/18. godinu dobitnik je stipendije Inženjerske komore Crne Gore, stipendije Crnogorske akademije nauka i umjetnosti, kao i stipendije koju najboljim studentima dodjeljuje JP Regionalni vodovod Crnogorsko primorje. Dobitnik je Studentske nagrade glavnog grada Podgorice za 2018. godinu, kao i nagrade Crnogorske akademije nauka i umjetnosti za mlade naučnike za 2022. godinu.

Od februara 2019. godine zaposlen je kao saradnik u nastavi na Elektrotehničkom fakultetu.

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6) M. Micev, M. Ćalasan, M. Radulović, „Poređenje talasnih oblika napona sinhronog generatora pri različitim strukturama sistema za regulaciju pobude“, VII Savjetovanje CG KO Cigre, Budva, 2021.
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13) Jasna Zeković, Martin Ćalasan, Mihailo Micev, „Primjena Padé aproksimacija za rješavanje Lambert W jednačine“ “, Informacione tehnologije, Žabljak, Crna Gora, februar 2023.

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KRATKA BIOGRAFIJA – SAJT UNIVERZITETA

Vladan Vujičić roden je 30.08.1968. godine u Titogradu (Podgorica), gdje je završio osnovnu i srednju školu.

Diplomirao je na Elektrotehničkom fakultetu u Podgorici 05.02.1993. godine. Magistarski rad pod nazivom: "Upravljanje grejderskim uređajem po zadatoj putanji" odbranio je na istom fakultetu 29.12.1995. godine. Doktorsku disertaciju pod nazivom: "Proširenje eksploatacione karakteristike pogona sa prekidačkim reluktantnim motorom primjenom nesimetrične konfiguracije motora i pogonskog pretvarača", odbranio je 01.03.2001. godine na Elektrotehničkom fakultetu u Beogradu.

Od 01.04.1993. godine radi na Elektrotehničkom fakultetu u Podgorici. Do 1996. godine radio je kao saradnik, a u periodu od 1996. do 2002. godine kao asistent na Katedri za teorijsku i primijenjenu automatiku. U zvanje docenta izabran je u junu 2002. godine, a u zvanje vanrednog profesora u julu 2007. godine. Krajem juna 2012. godine izabran je u zvanje rednovnog profesora Univerziteta Crne Gore za predmete: Energetska elektronika, Projektovanje energetskih poluprovodničkih pretvarača, Mehatronika i Specijalne električne mašine.

U junu 2001. godine boravio je na Katoličkom univerzitetu u Luvenu, kao dobitnik stipendije udruženja evropskih Univerziteta ("COIMBRA Group"). Na kraćim boravcima, u okviru realizacije međunaronih i bilateralnih projekata, bio je na Univerzitetu u Ljubljani (januar 2004. godine), Univerzitetu La Sapienza u Rimu (jun 2006. godine) i Univerzitetu rudarstva i tehnologije u Kini (Xuzhou, decembar 2015. godine).

U periodu od 2002. do 2004. godine obavljao je funkciju šefa Katedre za teorijsku i primijenjenu automatiku. Od juna 2011. godine do maja 2019. godine bio je predsjednik Studijskog komiteta B4 – Jednosmjerni sistemi i energetska elektronika – Crnogorskog Komiteta Međunarodnog vijeća za velike električne mreže (CG KO CIGRE).

Objavio je preko sedamdeset naučnih radova u međunarodnim i domaćim časopisima, kao i na međunarodnim i domaćim konferencijama. Kao autor ili koautor objavio je tri udžbenika i desetak skripti koje se koriste u nastavi. Učestvovao je u izradi devet domaćih i međunarodnih naučno-istraživačkih i stručnih projekata. Za projekat realizovan u periodu 2005. do 2007. godine dobitnik je posebnog priznanja (*Certificate of excellence - Best content*) od strane WUS-Austria. Recenzent je u nekoliko međunarodnih časopisa iz edicije IEEE i IET. Pod njegovim mentorstvom odbranjene su dvije doktorske disertacije, tri magistarske teze i veliki broj diplomskih i specijalističkih radova.

Član je Međunarodnog udruženja inženjera elektrotehnike (Institute of Electrical and Electronics Engineers - IEEE) i Međunarodnog vijeća za velike električne mreže (Conseil International des Grands Réseaux Electriques - CIGRE).

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DESET NAJZNAČAJNIJIH NAUČNO-ISTRAŽIVAČKIH RADOVA

1. M. P. Ćalasan, **V. P. Vujičić**, "Sensorless control of wind SRG in dc microgrid application", *International Journal of Electrical Power & Energy Systems*, vol. 99, pp. 672–681, July 2018. (ISSN: 0142-0615, 2017 *JCR Impact Factor*: 3.610, https://doi.org/10.1016/j.ijepes.2018.02.014)
2. M. P. Ćalasan, **V. P. Vujičić**, "A robust Continuous Conduction Mode control strategy of Switched Reluctance Generator for wind power plant applications,"*Archiv für Elektrotechnik - Electrical Engineering*, vol. 99, no. 3, pp.943-958, Sep. 2017. (ISSN: 0948-7921, 2017 *JCR Impact Factor*: 1.269, DOI: 10.1007/s00202-016-0459-1)
3. M. P. Ćalasan, **V. P. Vujičić**, "SRG Converter Topologies for continuous conduction operation: A Comparative Evaluation," *IET Electric Power Applications*, vol. 11, no. 6, pp. 1032-1042, July 2017. (ISSN 1751-8660, 2017 *JCR Impact Factor*: 2.211, DOI: 10.1049/iet-epa.2016.0659)
4. **V. P. Vujičić**, M. P. Ćalasan, "Simple Sensorless Control for high-speed Operation of Switched Reluctance Generator,"*IEEE Transactions on Energy Conversion*, vol. 31, no 4., pp. 1325-1335, Dec. 2016. (ISSN 0885-8969, 2016 *JCR Impact Factor*: 3.808, DOI: 10.1109/TEC.2016.2571841)
5. **V. P. Vujičić**, "Minimization of Torque Ripple and Copper Losses in Switched Reluctance Drive," *IEEE Transactions on Power Electronics*, vol. 27, no. 1, pp. 388-399, Jan. 2012. (ISSN 0885-8993, 2012 *JCR Impact Factor*: 4.08)
6. **V. P. Vujičić**, "Modeling of a Switched Reluctance Machine Based on the Invertible Torque Function," *IEEE Transactions on Magnetics*, vol.44, no.9, pp.2186-2194, Sept. 2008. (ISSN:0018-9464, 2008 *JCR Impact Factor*: 1.129)
7. **V. P. Vujičić**, S. N. Vukosavić, and M. Jovanović: "Asymmetrical Switched Reluctance Motor for a Wide Constant Power Range," *IEEE Transactions on Energy Conversion*, vol. 21, no.1, pp. 44-51, March 2006. (ISSN 0885-8969, 2006 *JCR Impact Factor*: 0.716)
8. **V. Vujičić**: "Torque Ripple and Output Power Characteristics of the Asymmetrical Switched Reluctance Drive," *WSEAS Transactions on Systems*, Issue 9, Vol. 4, pp. 1474-1481, September 2005. (ISSN: 1109-2777)
9. **V. Vujičić**, R. Stojanović: "Highly Accurate Modeling of the Switched Reluctance Drive," *WSEAS Transactions on systems*, Issue 10, Volume 3, pp. 3217-3222, December 2004. (ISSN:1109-2777)
10. **V. Vujičić**, S. N. Vukosavić, "A simple nonlinear model of the switched reluctance motor," *IEEE Transactions on Energy Conversion*, vol. 15, no. 4, pp. 395-400, December 2000. (ISSN 0885-8969, 2000 *JCR Impact Factor*: 0.187)

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ODLUKU
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Dr VLADAN VUJIČIĆ bira se u akademsko zvanje **redovni profesor** Univerziteta Crne Gore za predmete: Energetska elektronika, akademske studije, studijski program EA, Projektovanje energetskih poluprovodičkih pretvarača, specijalističke akademske studije, strudijski program EA, Specijalne električne mašine, specijalističke akademske studije, studijski program EA i Mehatronika, specijalističke akademske studije, studijski program EA, **na Elektrotehničkom fakultetu.**

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Research Expertise and Interests

Stability and stabilization of dynamic systems, and differential games
- applications in medical robotics
- applications in machine learning
- applications in guaranteed collision-free monitoring and surveillance
- applications in control of electronic circuits

Robust control and decision analysis
- applications in control of systems with multiple objectives
- applications in improving human-robot interactions

Decentralized control and estimation
- applications in control and coordination of multiple vehicles
- applications in networks of sensors and actuators, and power systems

Professional Preparation

University of Belgrade	Electrical Engineering	Five years BSEE program, 1994
Santa Clara University	Electrical Engineering	M.S.E.E., June 1996
Santa Clara University	Electrical Engineering	Ph.D., March 2000
Stanford University	Control Systems	Postdoctoral Specialization, 2001-2004

Appointments

2017-present **Professor**
Department of Industrial and Enterprise Systems Engineering, Coordinated Science Laboratory and Information Trust Institute, University of Illinois at Urbana-Champaign, Illinois, USA.

2010-2017 **Associate Professor**
Department of Industrial and Enterprise Systems Engineering, Coordinated Science Laboratory and Information Trust Institute, University of Illinois at Urbana-Champaign, Illinois, USA.

2004-2010 **Assistant Professor**
Department of Industrial and Enterprise Systems Engineering and the Coordinated Science Laboratory, University of Illinois at Urbana-Champaign, Illinois, USA.

2001-2004 **Research Associate**
Hybrid Systems Laboratory, Department of Aeronautics and Astronautics, Stanford University, California, USA.

1998-2001 **Adjunct Lecturer and Research Associate**
Department of Electrical Engineering, Santa Clara University, California, USA.

Visiting and Honorary Appointments

2005-present **Visiting Professor**

	Department of Robotics and Telematics, Faculty of Mathematics and Computer Science, Julius Maximilian University, Würzburg, Germany
2012-present	**Visiting Professor** School of Electrical Engineering, University of Belgrade, Belgrade, Serbia
2019-preset	**Visiting Professor** School of Engineering, University of Novi Sad, Serbia
2010-present	**Member of the Scientific Advisory Board** Adaptive Robotics Center, Würzburg, Germany
2017-2018	**Visiting Scholar** *Electrical Engineering and Computer Science Department, University of California at Berkeley, California, USA.*
2010-2011	**Visiting Associate Professor** *Electrical Engineering and Computer Sciences Department, University of California at Berkeley, California, USA.*

Professional Activities and Services

- Associate Editor, *Journal of Optimization Theory and Applications* (2014-2022).
- Technical Program Co-Chair for the BIGCOM 2021 conference (http://staff.ustc.edu.cn/~bigcom2021/).
- Associate Editor, *IEEE Transactions on Circuits and Systems I: Fundamental Theory* (2008-2010).
- Associate Editor and a Member of the Program Committee for the 2010 IEEE Control and Decision Conference.
- Associate Editor, *IEEE Transactions on Circuits and Systems II* (2006-2008).
- Associate Editor serving on the IEEE Control Systems Society Conference Editorial Board (2005-2006).

Awards

- 2006 Excellence in Teaching Award, General Engineering Department, University of Illinois.
- 2008 Alexander von Humboldt Research Fellowship Award, Bonn, Germany.
- 2009 Xerox Award for Faculty Research, College of Engineering, University of Illinois.
- 2009 Arnold O. Beckman Research Award, University of Illinois.
- 2014 Sharp Outstanding Teaching Award, ISE Department, University of Illinois.
- 2016 Arthur Davis Faculty Scholar Award, University of Illinois.
- 2017 Friedrich Wilhelm Bessel Research Award, Alexander von Humboldt Foundation, Germany. Area: Mathematics (control theory and calculus of variations).
- National Thousand Talent Award, China, 2022

Books

Nonlinear Systems - Recent Developments and Advances, Intech Open, 2023, B. Yang and D. Stipanović (Editors).

Book Chapters

B1. I. Hwang, D. M. Stipanović, and C. J. Tomlin. Polytopic Approximations of Reachable Sets applied to Linear Dynamic Games and to a Class of Nonlinear Systems, in *Advances in Control, Communication Networks, and Transportation Systems: In Honor of Pravin Varaiya*, E.H. Abed (Editor), Systems and Control: Foundations and Applications Series, Birkhäuser, Boston, 2005, pp. 3-19.

B2. D. D. Šiljak and D. M. Stipanović. Stability of Two-Variable Polynomials via Positivity, in *Positive Polynomials in Control*, Series: Lecture Notes in Control and Information Sciences, Vol. 312, D. Henrion and A. Garulli (Editors), 2005, pp. 165-177.

B3. A. Jovičić and D. M. Stipanović. Parametric Adaptive Identification and Kalman Filter, *Wiley Encyclopedia of Biomedical Engineering*, April 2006, pp. 2682-2686.

B4. A. Jovičić and D. M. Stipanović. State-Space Methods, *Wiley Encyclopedia of Biomedical Engineering*, April 2006, pp. 3329-3333.

B5. K. Srivastava and D. M. Stipanović, Stochastic Optimal Control Formulations of Decision Problems, *Wiley Encyclopedia of Operations Research and Management Science*, June 2010, pp. 1-10.

B6. M. S. Stanković, D. M. Stipanović, and S. S. Stanković. Consensus Based Multi-Agent Control Algorithms, in *Efficient Modeling and Control of Large-Scale Systems*, J. Mohammadpour and K. M. Grigoriadis (Editors), Springer, New York, 2010, pp. 197-218.

B7. D. M. Stipanović, C. J. Tomlin, and C. Valicka. Collision Free Coverage Control with Multiple Agents, in *Robot Motion and Control 2011*, K. R. Kozlowski (Editor), Springer-Verlag, London, 2012, pp. 259-272.

B8. K. Srivastava, A. Nedić, and D. M. Stipanović. Distributed Bregman-Distance Algorithms for Min-Max Optimization, in *Agent-Based Optimization*, I. Czarnowski, P. Jedrzejowicz, and J. Kacprzyk (Editors), Springer, London-New York , 2013, pp. 143-174.

B9. E. J. Rodríguez-Seda and D. M. Stipanović. Guaranteed Collision Avoidance with Discrete Observations and Limited Actuation," in *Advances in Intelligent Vehicles*, Y. Chen and L. Li (Eds.), Academic Press, 2014, pp. 89-110.

B10. D. Panagou, D. M. Stipanović, and P. G. Voulgaris. Distributed Control of Robot Swarms: A Lyapunov-Like Barrier Functions Approach, *Handbook of Research on Design, Control, and Modeling of Swarm Robotics*, Y. Tan (Ed), IGI Global, 2016, pp. 115-144.

B11. A. E. Abbas and D. M. Stipanović. Achieving Multiple Objectives with Limited Resources Using Utility Theory and Control Theory, *Improving Homeland Security Decisions*, edited by Ali Abbas, Milind Tambe, and Detlof von Winterfeldt, Cambridge University Press, 2017, pp. 427-444.

Journal Publications

J1. M. R. Matаušek and D. M. Stipanović. A New Approach to Nonlinear Control System Design, *Journal of Automatic Control*, vol. 5, pp. 31-42, 1994.

J2. M. R. Matаušek and D. M. Stipanović. Modified Nonlinear Internal Model Control, *Control and Intelligent Systems* (changed its name to *Mechatronic Systems and Control*), vol. 26, pp. 57-63, 1998.

J3. D. D. Šiljak and D. M. Stipanović. Robust D-stability via positivity, *Automatica*, vol. 35, pp. 1477-1484, 1999.

J4. D. M. Stipanović and D. D. Šiljak. Stability of polytopic systems *via* convex M-matrices and parameter-dependent Liapunov functions, *Nonlinear Analysis*, vol. 40, pp. 589-609, 2000.

J5. D. M. Stipanović and D. D. Šiljak. Jacobi and Gauss-Seidel Iterations for Polytopic Systems: Convergence *via* convex M-matrices, *Reliable Computing*, vol. 6, pp. 123-137, 2000.

J6. D. D. Šiljak and D. M. Stipanović. Robust Stabilization of Nonlinear Systems: The LMI Approach, *Mathematical Problems in Engineering*, vol. 6, pp. 461-493, 2000.

J7. D. M. Stipanović and D. D. Šiljak. Robust stability and stabilization of discrete-time nonlinear systems: The LMI approach, *International Journal of Control*, vol. 74, pp. 873-879, 2001.

J8. D. M. Stipanović and D. D. Šiljak. SPR Criteria for Uncertain Rational Functions and Matrices Via Polynomial Positivity and Bernstein's Expansion, *IEEE Transactions on Circuits and Systems I: Fundamental Theory and Applications*, vol. 48, pp. 1366-1369, 2001.

J9. D. M. Stipanović and D. D. Šiljak. Connective Stability of Discontinuous Dynamic Systems, *Journal of Optimization Theory and Applications*, vol. 115, No. 3, pp. 711-726, 2002.

J10. D. D. Šiljak, D. M. Stipanović, and A. I. Zečević. Robust Decentralized Turbine/Governor Control Using Linear Matrix Inequalities, *IEEE Transactions on Power Systems*, vol. 17, No. 3, pp. 715-722, 2002.

J11. D. M. Stipanović, G. İnalhan, R. Teo, and C. J. Tomlin. Decentralized Overlapping Control of a Formation of Unmanned Aerial Vehicles, *Automatica*, vol. 40, pp. 1285-1296, 2004.

J12. D. M. Stipanović, I. Hwang, and C. J. Tomlin. Computation of an Over-Approximation of the Backward Reachable Set using Subsystem Level Set Functions, *Dynamics of Continuous, Discrete and Impulsive Systems, Series* A: *Mathematical Analysis*, vol. 11, pp. 399-411, 2004.

J13. D. M. Stipanović, Sriram, and C. J. Tomlin. Multi-Agent Avoidance Control using an *M*-Matrix Property, *Electronic Journal of Linear Algebra*, vol. 12, pp. 64-72, 2005.

J14. S. S. Stanković, D. M. Stipanović, and D. D. Šiljak. Decentralized Dynamic Output Feedback for Robust Stabilization of a Class of Nonlinear Interconnected Systems, *Automatica*, vol. 43, pp. 861-867, 2007.

J15. D. M. Stipanović, P. F. Hokayem, M. W. Spong, and D. D. Šiljak. Avoidance Control for Multi-Agent Systems, *ASME Journal of Dynamic Systems, Measurement, and Control*, vol. 129, pp. 699-707, 2007, special issue on "Multi-Agent Systems."

J16. I. I. Hussein and D. M. Stipanović. Effective Coverage Control for Mobile Sensor Networks with Guaranteed Collision Avoidance, *IEEE Transactions on Control Systems Technology*, vol. 15, pp. 642-657, 2007.

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J18. J. S. Mejía and D. M. Stipanović. Computational Receding Horizon Approach to Safe Trajectory Tracking, *Integrated Computer-Aided Engineering*, vol. 15, pp. 149-161, 2008.

J19. D. M. Stipanović, A. Melikyan, and N. Hovakimyan. Some Sufficient Conditions for Multi-Player Pursuit-Evasion Games with Continuous and Discrete Observations, *Annals of the International Society of Dynamic Games*, vol. 10, pp. 133-145, 2009.

J20. S. S. Stanković, M. S. Stanković, and D. M. Stipanović. Consensus Based Overlapping Decentralized Estimator, *IEEE Transactions on Automatic Control*, vol. 54, pp. 410-415, 2009.

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C52. E. J. Rodríguez-Seda, P. O. López-Montesinos, D. M. Stipanović, and M. W. Spong. Model Reference Robust Control for a Class of Nonlinear Systems with Input and Measurement Delays, *Proceedings of the 2010 American Control Conference*, pp. 6585-6592.
C53. M. S. Stanković, K. H. Johansson, and D. M. Stipanović. Distributed Seeking of Nash Equilibria in Mobile Sensor Networks, *Proceedings of the 2010 IEEE Control and Decision Conference*, pp. 5598-5603.
C54. K. Srivastava, A. Nedić, D. M. Stipanović. Distributed Constrained Optimization over Noisy Networks, *Proceedings of the 2010 IEEE Control and Decision Conference*, pp. 1945-1950.
C55. T. Brdar, S. Bieniawski, D. M. Stipanović, and J. Vian. Application of Collision Avoidance on Flying Vehicles, *Proceedings of the AIAA Guidance, Navigation, and Control Conference*, Toronto, Ontario, Canada, August 2-5 (2010), 10 single-column single-space pages, Chapter DOI: 10.2514/6.2010-8085
C56. E. J. Rodríguez-Seda, D. M. Stipanović, and M. W. Spong. Collision Avoidance Control with Sensing Uncertainties, *Proceedings of the 2011 American Control Conference*, pp. 3363-3368.
C57. G. Atinc and D. M. Stipanović. Cooperative Collision-Free Control of Lagrangian Multi-Agent Formations, *Proceedings of the 2011 American Control Conference*, pp. 2801-2806.
C58. Z. Li, N. Hovakimyan, and D. M. Stipanović. Distributed Multi-Agent Tracking and Estimation with Uncertain Agent Dynamics, *Proceedings of the 2011 American Control Conference*, pp.2204-2209.
C59. K. Srivastava, A. Nedić, and D. M. Stipanović. Distributed Min-Max Optimization in Networks, *Proceedings of the 17th International Conference on Digital Signal Processing*, pp. 1-8.
C60. E. J. Rodríguez-Seda, D. M. Stipanović, and M. W. Spong. Lyapunov-Based Cooperative Avoidance Control for Multiple Lagrangian Systems with Bounded Sensing Uncertainties, *Proceedings of the 2011 IEEE Control and Decision Conference*, pp. 4207-4213.
C61. M. S. Stanković, S. S. Stanković, and D. M. Stipanović. Decentralized Identification for Errors-in-Variables Systems Based on a Consensus Algorithm, *Proceedings of the 2011 IEEE Control and Decision Conference*, pp. 2951-2956.
C62. H. Huang, W. Zhang, J. Ding, D. M. Stipanović, and C. J. Tomlin. Guaranteed Decentralized Pursuit-Evasion in the Plane with Multiple Pursuers, *Proceedings of the 2011 IEEE Control and Decision Conference*, pp. 4835-4840.

C63. S. Pan, H. Huang, W. Zhang, J. Ding, D. M. Stipanović, and C. J. Tomlin.Pursuit, Evasion, and Defense in the Plane, *Proceedings of the 2012 American Control Conference*, pp. 4167-4173.

C64. C. Franco, G. Lopez-Nicolas, D. M. Stipanović, and C. Sagues. Anisotropic Vision-Based Coverage Control for Mobile Robots, *Proceedings of the 2nd Workshop on Visual Control of Mobile Robots*, October 11th, 2012, Vilamoura, Algarve, Portugal, in conjunction with the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), pp. 31-36.

C65. C. Valicka, D. M. Stipanović, and A. E. Abbas. Multiattribute Copulas for Multiobjective Control, *Proceedings of the 2013 American Control Conference*, pp. 3218-3223.

C66. G. M. Atinc, D. M. Stipanović, P. G. Voulgaris, and M. Karkoub. Collision-Free Trajectory Tracking while Preserving Connectivity in Unicycle Multi-Agent Systems, *Proceedings of the 2013 American Control Conference*, pp. 5392-5397.

C67. G. M. Atinc, D. M. Stipanović, P. G. Voulgaris, and M. Karkoub. Supervised Coverage Control with Guaranteed Collision Avoidance and Proximity Maintenance, *Proceedings of the 2013 IEEE Control and Decision Conference*, pp. 3463 - 3468.

C68. D. Panagou, D. M. Stipanović, and P. G. Voulgaris. Multi-Objective Control for Multi-Agent Systems using Lyapunov-like Barrier Functions, *Proceedings of the 2013 IEEE Control and Decision Conference*, pp. 1478 - 1483.

C69. A. Zatezalo, D. M. Stipanović, R. K. Mehra, and K. Pham. Constrained Orbital Intercept-Evasion, in Proceedings of SPIE 2014.

C70. A. Zatezalo, D. M. Stipanović, R. K. Mehra, and K. Pham. Space Collision Threat Mitigation, in Proceedings of SPIE 2014.

C71. G. M. Atinc, D. M. Stipanović, P. G. Voulgaris, and M. Karkoub. Swarm-Based Dynamic Coverage Control, *Proceedings of the 2014 IEEE Control and Decision Conference*, pp. 6963-6968.

C72. D. Panagou, D. M. Stipanović, and P. G. Voulgaris. Vision-based dynamic coverage control for nonholonomic agents, *Proceedings of the 2014 IEEE Control and Decision Conference*, pp. 2198-2203.

C73. A. Zatezalo, D. M. Stipanović, and A. E. Abbas. Multi-Agent Multi-Objective Control Design with Discrete-Time Information Updates and Preferences, *Proceedings of the 2015 IcETRAN Conference*.

C74. V. Cichella, T. Marinho, D. M. Stipanović, N. Hovakimyan, I. Kaminer, and A. Trujillo. Collision Avoidance Based on Line-of-Sight Angle, *Proceedings of the 2015 IEEE Control and Decision Conference*, pp. 6779-6784.

C75. A. Lekić, D. M. Stipanović. and N. Petrović. Controlling the Ćuk Converter Using Polytopic Lyapunov Functions, *Proceedings of the 19th Symposium Power Electronics Ee2017, October 19-21, 2017.*

C76. A. Lekić and D. M. Stipanović. Stable switching control of DC-DC converters. Proceedings of the 2017 Telecommunication Forum (TELFOR), November 21-22, pp. 1-7.

C77. D. M. Stipanović, B. Murmann, M. Causo, A. Lekić, V. R. Royo, C. J. Tomlin, E. Beigne, S. Thuries, M. Zarudniev and S. Lesecq, "Some local stability properties of an autonomous long short-term memory neural network model," in *Proceedings of the 2018 IEEE International Symposium on Circuits and Systems*, Florence, Italy, 2018.

C78. M. Amrouche, S. A. Deka, A. Lekić, V. R. Royo, D. M. Stipanović, B. Murmann and C. J. Tomlin, Long Short-Term Memory Neural Network Equilibria Computation and Analysis, in Workshop on Modeling and decision-making in the spatiotemporal domain, 32nd Conference on Neural Information Processing Systems (NIPS), Montreal, Canada, 2018.

C79. T. Marinho, M. Amrouche, V. Cichella, D. M. Stipanović and N. Hovakimyan, Guaranteed collision avoidance based on line-of-sight angle and time to collision, in Proceedings of the 2018 American Control Conference, 2018.

C80. S. A. Deka, D. M. Stipanović, B. Murmann and C. J. Tomlin, Long-Short Term Memory Neural Network Stability and Stabilization using Linear Matrix Inequalities, in Proceedings of the 2019 IEEE International Symposium on Circuits and Systems, Sapporo, Japan, 2019.

C81. I. Vasiljević, A. Lekić and D. M. Stipanović. Lyapunov Analysis of the Chaotic Colpitts Oscillator, in Proceedings of the 2019 IEEE International Symposium on Circuits and Systems, Sapporo, Japan, 2019.

C82. A. Lekić, A. E. Aroudi and D. M. Stipanović. Polytopic Control of a PV-Fed SEPIC DC-DC Converter, in Proceedings of the 2019 IEEE International Symposium on Circuits and Systems, Sapporo, Japan, 2019.

C83. M. Amrouche, T. Marinho, and D. M. Stipanović. Vision Based Collision Avoidance for Multi-Agent Systems Using Avoidance Functions, in Proceedings of the 2020 European Control Conference, Saint Petersburg, Russia, May 2020.

C84. A. Lekić-Vervoort, M. Majstorović, L. Ristić, and D. M. Stipanović. Hysteresis Control of the Pseudo Boost PFC Converter, in Proceedings of 29th IEEE International Symposium on Industrial Electronics, Delft, The Netherlands, June 2020.

C85. W. Zhang, D. M. Stipanović, and D. Zhou. Cooperative Avoidance Control with Relative Velocity Information and Collision Sector Functions for Car-Like Robots, in Proceedings of the 2020 American Control Conference, Denver, Colorado, July 2020.

C86. Y. Li, N. M. Freris, P. Voulgaris, and D. M. Stipanović. D-SOP: Distributed Second Order Proximal Method for Convex Composite Optimization, in *Proceedings of the 2020 American Control Conference*, Denver, Colorado, July 2020.

C87. S. A. Deka, D. M. Stipanović and C. J. Tomlin. Feedback-Control Based Adversarial Attacks on Recurrent Neural Networks, in Proceedings of the *2020 IEEE Conference on Decision and Control*, Jeju, Korea (South), 2020, pp. 4677-4682, doi: 10.1109/CDC42340.2020.9303949. Also available online: https://arxiv.org/abs/2009.02874.

C88. T. Marinho, M. Amrouche, D. M. Stipanović, V. Cichella, and N. Hovakimyan. Biologically Inspired Collision Avoidance Without Distance Information, in *Proceedings of the 2021 American Control Conference*, New Orleans, Louisiana, May 2021. Also available online: https://arxiv.org/abs/2103.12239.

C89. Y. Li, Y. Gong, N. Freris, P. Voulgaris, and D. Stipanović, "Distributed BFGS-ADMM for Large-Scale Multi-agent Optimization," in *Proceeding of the 2021 IEEE Conference on Decision and Control*, December 2021.

C90. Y. Li, N. Freris, P. Voulgaris, and D. Stipanović, "DN-ADMM: Distributed Newton ADMM for Multi-agent Optimization," in *Proceeding of the 2021 IEEE Conference on Decision and Control*, December 2021.

C91. T. Mamalis, D. M. Stipanović, P. Voulgaris, "Stochastic Learning Rate Optimization in the Stochastic Approximation and Online Learning Settings," in *Proceedings of the 2022 American Control Conference*, June 2022.

Abstracts

A1. Sriram, D. M. Stipanović, and C. J. Tomlin. Collision Avoidance Strategies for a Three Player Game, in the *Book of Abstracts of the 13th International Symposium on Dynamic Games and Applications*, Wroclaw, Poland, June 30-July 3 (2008), pp. 195-197.

A2. D. M. Stipanović, A. Melikyan, and N. Hovakimyan. Guaranteed Strategies for Nonholonomic Players in Pursuit-Evasion Games, in the *Book of Abstracts of the 13th International Symposium on Dynamic Games and Applications*, Wroclaw, Poland, June 30-July 3 (2008), pp. 209-210.

A3. D. M. Stipanović, A. Melikyan, and N. Hovakimyan. Differential Inequalities for Dynamic Games, in the *Book of Abstracts of the Second International Conference on Game Theory and Management*, St. Petersburg, Russia, June 26-27 (2008), pp. 205-207.

A4. D. M. Stipanović, A. Melikyan, and N. Hovakimyan. Nonlinear Pursuit Evasion Games with Incomplete Information, in the *Book of Abstracts of the L. S. Pontryagin Centennial Anniversary Conference*, Moscow, Russia, June 17-22 (2008), pp. 297-298.

A5. D. M. Stipanović. Control of Complex Dynamic Systems with Multiple Objectives, in the *Book of Abstracts of the International Conference on Control of Dynamic Systems*, Moscow, Russia, January 26-30 (2009), pp. 104.

A6. D. M. Stipanović, E. Cristiani, and M. Falcone. Designing Strategies for Non-Zero Sum Differential Games using Differential Inequalities, in the *Book of Abstracts of the Fourth International Conference on Game Theory and Management*, St. Petersburg, Russia, June 28-30 (2010).

A.7. W. Street, C. Burns, F. Wang, and D. Stipanović. Visual Search and Spatial Learning in Teleoperation, Journal of Vision August 13, 2012 vol. 12 no. 9 article 201.

A.8. D. M. Stipanović, C. J. Tomlin, and G. Leitmann. Design of Multi-Objective Control Strategies, in the *Book of Abstracts of the Eighth International Conference on Game Theory and Management*, St. Petersburg, Russia, June 25-27 (2014).

A9. D. M. Stipanović and I. Shevchenko. A Design of Strategies in Pursuit-Evasion Games Based on Switching Goal Functions, in the Book of Abstracts of the Ninth International Conference on Game Theory and Management, St. Petersburg, Russia, July 8-10 (2015).

A10. I. Shevchenko and D. M. Stipanović. Smooth Approximations for Minimum and Maximum Functions and Their Use in the Strategy Design, in the Book of Abstracts of the Tenth International Conference on Game Theory and Management, St. Petersburg, Russia, July 7-9 (2016).

Invited Presentations and Seminars

- *Technical Guarantees for Controlling Dynamical Systems with Illustrations of Their Importance in Applications*, PowerWeb Lecture. November 2022, Delft University of Technology (TU Delft), Delft, Netherlands.
- *Control and Applications of Dynamic Systems with Multiple Objectives*, University of Novi Sad, Novi Sad, Serbia, May 2022.
- *Avoidance Control for Multi-Robot Systems*, Polish Chapter of IEEE Robotics & Automation Society, November 26, 2021.
- *Control and Applications of Dynamic Systems with Multiple Objectives*, Uwe Helmke seminar series, Würzburg, Germany, June 2021.
- *Control and Applications of Dynamic Systems with Multiple Objectives*, University of Novi Sad, Novi Sad, Serbia, June 2021.
- *Control of Multiple Dynamical Systems with Multiple Objectives*, NIO Company, San Jose, California, July 10, 2019.
- *Control of Dynamic Systems with Multiple Objectives*, Industrial and Systems Engineering Department, University of Southern California, February 2017.
- *Control of Dynamic Systems with Multiple Objectives*, School of Computer Science and Mathematics, Bavarian Julius Maximilian University in Wuerzburg, Germany, June 2016.
- *Control of Dynamic Systems with Multiple Objectives*, Information-Oriented Control Department, Technical University of Munich, Munich, Germany, June 2016.
- Control of Multiple Dynamic Systems with Multiple Objectives, ISL colloqium talk at Stanford, April 28,2016.
- *Control of Multi-Agent Systems with Multiple Objectives*, Robotics Seminar, CSL, UIUC, April 2016.
- *Controlling Multiple Agents with Multiple Objectives*, invited talk, IcETRAN conference, Silver Lake, Serbia, June 2015.

- *Controlling Multiple Agents in Their Pursuit of Multiple Objectives*, Instituto de Investigación en Ingeniería de Aragón (I3A), University of Zaragoza, Zaragoza, Spain, May 2015.
- *Controlling Dynamic Systems with Multiple Objectives: Some Particular Problems*, Scientific Systems Company, Boston, October 2013.
- *Control of Multi-Vehicle Systems*, Department of Aerospace and Mechanical Engineering, University of Southern California, April 2013.
- *Controlling Dynamic Systems with Multiple Objectives*, Applied Mathematics Department, ENSTA Paris Tech, Paris, France, December 2012.
- *Control of Multiple Agent Systems: Issues and Accomplishments*, Department of Control and Systems Engineering, Poznan University of Technology, Poznan, Poland, June 2012.
- *Control of Dynamic Systems with Multiple Objectives*, Department of Mathematics, University of Rome "Sapienza," Rome, Italy, December 2011.
- *Control and Coordination of Multiple Agent Systems*, 5th Semiannual Workshop on Control Systems, Plenary Talk, Faculty of Engineering and Computer Science, Concordia University, Montreal, Canada, October 2011.
- *Control and Coordination of Multi-Agent Systems*, College of Engineering, University of Texas at Dallas, October 2011.
- *Accomplishing Multiple Objectives with Multiple Agents*, Plenary Talk, *2011 IEEE RoMoCo Conference*, June 2011, Bukowy Dworek, Wasowo, Poland.
- *Controlling Dynamic Systems with Multiple Objectives*, Dynamic Systems and Control Group Seminar, UC San Diego, March 2011.
- *An Approach to Control Dynamic Systems with Multiple Objectives*, Department of Aerospace and Mechanical Engineering, University of Southern California, March 2011.
- *Safe Control and Coordination of Multi-Vehicle Systems*, Boeing-ITI seminar series, Boeing Company, Seattle, October 2009.
- *Control of Complex Dynamic Systems with Multiple Objectives*, Department of Mechanical Engineering, Columbia University, New York, October 2009.
- *Safe Control of Multiple Vehicle Systems*, Institute of Control and Systems Engineering, Poznan University of Technology, Poznan, Poland, August 2009.
- *Guaranteed Strategies for the Nonlinear Multi-Player Pursuit-Evasion Games and Differential Inequalities*, Department of Mathematics, University of Rome "Sapienza," Rome, Italy, July 2009.
- *Sufficient Conditions for Multi-Player Dynamic Games and Beyond*, Graduate School of Management, St. Petersburg State University, St. Petersburg, Russia, July 2009.
- *Control of Complex Dynamic Systems with Multiple Objectives*, Institute for Problems in Mechanics, Russian Academy of Sciences, Moscow, Russia, January 2009.
- *Dealing with Complexity*, Center for Mathematics and Statistics and the Department of Applied Computer Science, Technical University, Novi Sad, Serbia, December 2008.
- *Row Stochastic Matrices and Consistent Parameter and State Estimation*, Hamilton Institute, National University of Ireland, Maynooth, Ireland, August 2008.
- *Control of Multi-Agent Systems: Theory and Applications*, Institute for Problems in Mechanics, Russian Academy of Sciences, Moscow, Russia, October 2007.
- *Control of Multi-Vehicle Systems*, University of Belgrade, Belgrade, Serbia, June 2007.
- *Safety, Strategies and Applications for Multi-Agent Systems*, University of Bologna, Bologna, Italy, June 2007.
- *Safe and Reliable Control of Multi-Vehicle Systems*, Topics in Systems Seminar Series, UIUC, April 2007.
- *Control and Optimization of Multi-Agent Systems*, the Boeing Company, Seattle, February 2007.

- *Some New Results in Reliable Control of Multi-Agent Systems*, Bavarian Julius Maximilian University in Wuerzburg, Germany, December 2006.
- *Control and Optimization of Multi-Agent Systems*, AAE Colloquium, School of Aeronautics and Astronautics, Purdue University, April 2006.
- *Control and Optimization of Multiple Unmanned Vehicle Systems*, Bavarian Julius Maximilian University in Wuerzburg, Germany, December 2005.
- *Control and Optimization of Multiple Unmanned Vehicle Systems*, the Boeing Company, Seattle, December 2005
- *Decentralized Control and Optimization of Multi Agent Systems*, Department of Aerospace and Ocean Engineering, Virginia Polytechnic Institute, Blacksburg, November 2005.
- *Control and Optimization of Complex Systems*, Nonlinear Dynamics and Complex Systems Seminar, Department of Physics, University of Illinois at Urbana-Champaign, March 2005.
- *Multi-Player Games: An Overview, General Strategies, and Avoidance Conditions*, Bavarian Julius Maximilian University in Wuerzburg and University of Applied Sciences FH Ravensburg-Weingarten, Germany, December 2004.
- *Decentralized Optimization using Block Iterative Schemes: Convergence via M-Matrices*, Hamilton Institute, National University of Ireland, Maynooth, Ireland, July 2004.
- *Decentralized Control of Large-scale Dynamic Systems: Theory and Applications*, University of Applied Sciences FH Ravensburg-Weingarten, Germany, December 2003.
- *Decentralized Control and Optimization of Large-scale Dynamic Systems*, Bavarian Julius Maximilian University, Wuerzburg, Germany, December 2003.
- *Decentralized Overlapping Control and Optimization of Complex Systems*, University of Hawaii at Manoa, Hawaii, November 2003.
- *Decentralized Overlapping Control and Optimization of Complex Systems*, Hamilton Institute, National University of Ireland, Maynooth, Ireland, September 2003.
- *Overlapping Decentralized Approach to Control and Optimization of Complex Systems*, Center for Control Engineering and Computation Seminar, UC Santa Barbara, January 2003.
- *Overlapping Decentralized Approach in Control, Optimization, and Computation of Reachable Sets*, Dynamic Systems and Control Group Seminar, UC San Diego, January 2003.
- *Overlapping Decentralized Optimization Methods for Multiple Vehicle Coordination and Control*, Robert Bosch Corporation, June 2002.
- *Connective Stability of Discontinuous Interconnected Systems via Parameter-Dependent Liapunov Functions*, Hybrid Systems Seminar, UC Berkeley, Spring 2000.

Post-docs, Graduate Students and Visitors

Post-docs:
- Islam I. Hussein (Ph.D., 2006, University of Michigan) 2006-2007
- Dimitra Panagou (Ph.D., 2012, National Technical University of Athens) 2012-2014

Ph.D. Students and the year of graduation:
- Peter Hokayem (ECE) (co-adviser) 2007
- Silvia Mastellone (IESE) (co-adviser) 2008
- Juan Mejía (ISE) 2009
- Miloš S. Stanković (ISE) 2009
- Chad Burns (MechSE) 2011
- Erick Rodríguez-Seda (ECE) (co-adviser) 2011
- Kunal Srivastava (ISE) (co-adviser) 2011
- Christopher Valicka (ISE) 2013
- Gokhan Atinc (MechSE) 2014

- Aleksandra Lekić (EE, University of Belgrade) 2017
- Shankar Deka (MechSE) 2019
- Massinissa Amrouche (ISE) 2021
- Theodoros Mamalis (ECE) 2023-expected
- Yichuan Li (MechSE) (second co-adviser) 2022

M.S. Students and the year of graduation:

- Chad Burns (MIE) 2006
- Juan Mejía (IESE) 2006
- Christopher Valicka (IESE) 2008
- Benoit Blanquet (ECE) 2008
- Timothy Brdar (MechSE) 2008
- Todd Baxter (IESE) 2009
- Wilfredo Morales (ECE) 2009
- Gokhan Atinc (MechSE) 2009
- Xi Chen (IESE) (co-advisor) 2009
- Joseph Zearing (MechSE) 2010
- Sam Naghshineh (IESE) 2011
- Richard Rekoske (ISE) 2013
- John Nguyen (ISE) 2016
- Shankar Deka (MechSE) 2016
- Ankit Bhardwaj (MechSE) 2016
- Yichuan Li (MechSE) 2018

Visiting Scholars:

- Yonghong Wu (Ph.D., 2011, University of Science and Technology, Wuhan) 2014-2015

Visiting Ph.D. Students:

- Martin Saska (Julius Maximilian University, Germany) February-May 2008
- Martin Hess (Julius Maximilian University, Germany) September-December 2008
- Carlos Franco (University of Zaragoza, Spain) March-June 2012
- Wenxue Zhang (Harbin Institute of Technology, China) August 2018-August 2020

Research Grants

G1. 2005-2010, Trustworthy collision avoidance over information links, The Boeing Company, role: PI, $702,000 awarded to D. M. Stipanović (total: $702,000).

G2. 2008-2011, Safe coordination of multiple autonomous vehicles, NSF, role: PI, $174,990 awarded to D. M. Stipanović (total: $300,000).

G3. 2009-2010, Autonomous and semi-autonomous control of unmanned vehicles, UIUC Campus Research Board, role: PI, $20,000 awarded to D. M. Stipanović (total: $22,620).

G4. 2010-2013, Decentralized estimation and vision-based guidance of fast autonomous systems with guaranteed performance in uncertain environments, US Army Research Office, role: Co-PI, $161,304 awarded to D. M. Stipanović (total: $360,189).

G5. 2010-2012, Trustworthy collision avoidance over information links, The Boeing Company, role: PI, $160,000 (plus one semester student RA) awarded to D. M. Stipanović.

G6. 2011-2014, Smart systems for field monitoring and surveillance, Qatar National Research Fund, role: Co-PI. $150,000 awarded to D. M. Stipanović (total: $300,000).

G7. 2013, Game-Theoretic Space Situational Analysis Toolbox, Small Business Technology Transfer (STTR) proposal (Phase 1). $50,000 awarded to UIUC, role: PI, total: $150,000.

G8. 2015-2016, Efficient Surveillance, Rescue, and Threat Detection using Decision Theory and Multi-Objective Control for Multi-Vehicle Systems, 64K awarded to D. M. Stipanović, USC CREATE Homeland Security Center, Department of Homeland Security.

G9. 2015-2018, NSF National Robotics Initiative: Collaborative Research: ASPIRE: Automation Supporting Prolonged Independent Residence for the Elderly, role: Co-PI, 1.2M total.

G10. 2017-2018, Distributed Control for Urban Flooding Mitigation, UIUC-Zhejiang University collaboration, $37,500 awarded to D. M. Stipanović (total: $75,000), role: Co-PI.

G11. 2020-2023, NSF National Robotics Initiative and USDA-NIFA: Multi-Vehicle Systems for Collecting Shadow-Free Imagery in Precision Agriculture, $225,000 awarded to D. M. Stipanović (total: $749,182), role: PI.

G12. 2021-2023, Jump ARCHES: Community-based Tele-Rehabilitation Health Network for Robotic Stroke Therapy, PI: D. M. Stipanović, Co-PI: T. Kesavadas (total $75,000).

G13. 2022-2024, Jump ARCHES: Telerehabilitation of Stroke Patients through an Adaptive Multirobot Architecture, PI: D. M. Stipanović, Co-PI: A. Horowitz. 160K awarded to D. M. Stipanović (total: $200,000),

UNIVERSITY OF ILLINOIS SYSTEM

NOTIFICATION OF APPOINTMENT

Name/Home Unit:

Stipanovic, Dusan M
Department of Industrial and Enterprise Systems Engineering
117 Transportation Building
104 S Mathews
M/C - 238

University of Illinois
Board of Trustees
352 Henry Administration Building
Urbana, Illinois 61801-3640

Generation date: 08/23/2023

UIN: 669260040
Campus: Urbana - Champaign
Employee Class: Acad 9/12mth Ben Elig
Home Unit: 1/422000 - Industrial&Enterprise Sys Eng

This confirms your appointment to the following position(s) for the pay, periods and other conditions indicated, subject to all immigration laws and other eligibility requirements for employment, and subject to approval by the Board of Trustees. It is valid only if based upon the actual acquisition of required credentials upon which the appointment is based. If the start date for the Period of Payment is later than the Generation Date of this document, approval by the Board of Trustees is still pending. Annual reappointments with a Period of Payment start date of August 16 are traditionally submitted to the Board of Trustees for approval at the September meeting.

JOB: U59804-00 Org Code/Campus/Name: 422000/Urbana - Champaign/ Industrial&Enterprise Sys Eng

Title	FTE	Service Basis	Period of Payment Begin	Period of Payment End	Salary
PROF	100%	9/12 mth	08/16/2023	08/15/2024	$149,790.50 A

Tenure Status	Tenure Effective Date	Tenure Service Basis	Tenure Percent
Indefinite Tenure	08/16/2010	Academic Year	100%

JOB: U67949-00 Org Code/Campus/Name: 239000/Urbana - Champaign/ Coordinated Science Lab

Title	FTE	Service Basis	Period of Payment Begin	Period of Payment End	Salary
PROF, CSL	0%	9/12 mth	08/16/2023	08/15/2024	$0.00 A

JOB: U68120-00 Org Code/Campus/Name: 917000/Urbana - Champaign/ Mechanical Sci & Engineering

Title	FTE	Service Basis	Period of Payment Begin	Period of Payment End	Salary
PROF	0%	9/12 mth	08/16/2023	08/15/2024	$0.00 A

JOB: UA9807-00 Org Code/Campus/Name: 727000/Urbana - Champaign/ Information Trust Institute

Title	FTE	Service Basis	Period of Payment Begin	Period of Payment End	Salary
PROF, ITI	0%	9/12 mth	08/16/2023	08/15/2024	$0.00 A

JOB: UB2709-00* Org Code/Campus/Name: 422000/Urbana - Champaign/ Industrial&Enterprise Sys Eng

Title	FTE	Service Basis	Period of Payment Begin	Period of Payment End	Salary
ARTHUR DAVIS FAC SCHOLAR	0%	9/12 mth	08/16/2023	08/15/2024	$0.00 A

JOB: UC6479-00 Org Code/Campus/Name: 345000/Urbana - Champaign/ European Union Center

Title	FTE	Service Basis	Period of Payment Begin	Period of Payment End	Salary
PROF	0%	9/12 mth	08/16/2023	08/15/2024	$0.00 A

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- The amount appearing in the "Salary" column is the gross annual (A) or monthly (M) compensation of the appointee for services required during a full appointment year or monthly period, whether payable in the form of salary, earnings, purchases of annuity contracts, or in any other manner authorized or required by law. In the case of appointments where service is required for less than a full appointment year or monthly period only a proportionate amount of the "Salary" will be payable on the basis of the period of payment indicated in proportion to a full appointment year or month. For example, an appointment for one semester of an academic year is compensated at approximately one-half of the annual "Salary" rate.
- Unless your appointment is designated elsewhere within this document as being "salaried, non-exempt," your appointment (consisting of one or multiple jobs) falls within one of the recognized exemptions to the overtime provisions of the Federal Fair Labor Standards Act, and as such, you are not eligible to receive overtime pay regardless of the number of hours that you work in any given workweek.
- If determined that an employee has been excluded from participation in Federal or State Health Care Programs because of having engaged in fraud, abuse or misconduct as well as any other mandated governmental exclusion listing, the employee is subject to immediate dismissal without notice.
- Falsification of information on a job application or credential materials may result in immediate dismissal.
- As of August 9, 2011, the Explanation of Service Basis, Standard Period of Service and Periods of Payments can be found at **https://nessie.uihr.uillinois.edu/pdf/personal_info/ExplanationofServiceBasis.pdf** If this link is no longer available, the terms in effect for this NOA can be found at the internet location where this document is viewable.
- An asterisk (*) symbol following the Job number indicates that all or a portion of this appointment is made on the condition that employment and payment is contingent upon receipt of funds. For appointments made "subject to receipt of funds" (such as those from grants or contracts), the University reserves the right to terminate the appointment prior to the Period of Payment End Date if the grant(s) or other source of funding for the position has ended. For such appointments, the University reserves the right to terminate the appointment prior to the Period of Payment End Date if the grant or source of funds for the position becomes unavailable, and will provide prior notice, if applicable, in accordance with the notice periods set forth in Article IX(11)(b)(2) of the University of Illinois Statutes. If an asterisk (*) symbol does not appear next to the Job number on this Notification of Appointment, your appointment is not subject to the receipt of funds and not subject to earlier termination based on the loss of such funding.

  Regardless of past source of funds supporting the position(s) above, presence or absence of the * symbol indicating "subject to receipt of funds" indicates funding status as of the generation date of this Notification of Appointment.

  For an academic professional employee who is entitled to notice of nonreappointment and whose position is supported by multiple sources of funds, calculation of minimum length of notice of nonreappointment will be based on the relevant funds for the portion of the appointment for which a notice of nonreappointment is issued, or on the predominant source of funds in the case of elimination of the position.
- Unless you notify your unit(s) to the contrary within 30 days of the Generation Date of this document, your acceptance of this appointment will be presumed. If you have questions regarding your appointment, please contact your unit office.

Secretary

Prof. dr Gojko Joksimović

UNIVERZITET CRNE GORE, ELEKTROTEHNIČKI FAKULTET

KRATKA BIOGRAFIJA

Rođen u Beranama 1967. godine, gdje završava osnovnu školu i gimnaziju. Nakon odsluženog vojnog roka, 1987. godine počinje studije na Elektrotehničkom fakultetu Univerziteta Crne Gore na kom diplomira u decembru 1991. godine. Maja 1992. godine zasniva radni odnos na Katedri za električne mašine na istom fakultetu. Magistrirao je 1995. godine a doktorirao 2000. godine na Elektrotehničkom fakultetu u Podgorici. U zvanje docenta Univerziteta Crne Gore je biran 2001. godine a u zvanje redovnog profesora 2011. godine. Tokom 1997/98 godine, godinu dana boravi na Univerzitetu Aberdeen, Škotska, UK a akademsku 2001/02 godinu provodi na Tehničkom Univerzitetu Darmstadt, Njemačka kao stipendista Alexander von Humboldt fondacije.

Na kraćim studijskim boravcima i u posjetama je bio na mnogim svjetskim univerzitetima: Univerzitet La Sapienza u Rimu, Tehnički Univerzitet u Beču, Moskovski energetski institut, Liverpool John Moores University u Liverpulu, Tehnički Univerzitet u Darmstadtu, Sveučilište u Zagrebu, Univerzitet u Ljubljani, Šleski Univerzitet tehnologije u Gljivicama, Poljska, Politehnički Univerzitet u Temišvaru, Rumunija, Univerzitet rudarstva i tehnologije u Xuzhou, Kina itd.

Koautor je jedne međunarodne naučno-istraživačke monografije u izdanju IET-a, autor druge naučno-istraživačke monografije na našem jeziku, autor tri univerzitetska udžbenika, koautor tri univerzitetska udžbenika i autor više skripti koje studenti ETF-a koriste u nastavi. Autor je i dva udžbenika za srednje stručno obrazovanje. Dvadeset i dva naučna rada je objavio u najznačajnijim međunarodnim naučnim časopisima iz obasti elektrotehnike. Radovi su mu citirani 1849 puta, h-indeks mu je 17 a i10 indeks 30 (Google Scholar Citations, oktobar 2023). Recenzent je u brojnim međunarodnim naučnim časopisima, na prvom mjestu časopisima iz IEEE i IET edicija.

U zadnje četiri godine je na rang-listi kolokvijalnog naziva „Stanfordova lista", koja nabraja 2% najuticajnijih svjetskih naučnika u svojim oblastima istraživanja, u oblasti elektrotehnike (Elsevier & Stanford University, 2020, 2021, 2022, 2023).

Dva puta je bio član komisije za odbranu doktorske disertacije na Tehničkom Univerzitetu u Beču (januar 2014. godine, maj 2018. godine). Bio je i eksterni član komisije (external pre-examiner) za odbranu doktorske disertacije na Aalto Univerzitetu u Helsinikiju, Finska, 2015. godine.

U više navrata je bio prodekan na Elektrotehičkom fakultetu kao i rukovodilac studijskog programa.

Član je IEEE asocijacije. U zvanje Senior Member izabran je 2011. godine.

Član je Odbora za tehničke nauke Crnogorske akademije nauka i umjetnosti, CANU.

Govori engleski jezik, a čita stručnu literaturu i na njemačkom i ruskom jeziku.

Otac je tri sina.

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Prof. dr Gojko Joksimović
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Uža naučna istraživačka oblast: Električne mašine
Nastava: Osnove elektrotehnike i Električne mašine

DESET NAJZNAČAJNIJIH RADOVA PUBLIKOVANIH U MEĐUNARODNIM ČASOPISIMA

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[8] G. Joksimović, J. Penman, "The detection of inter-turn short circuits in the stator windings of operating motors", IEEE Transactions on Industrial Electronics, vol. 47, no. 5, pp. 1078-1084, October 2000.

[9] G. Joksimović, M. Đurović, J. Penman, N. Arthur, "Dynamic simulation of dynamic eccentricity in induction machines - winding function approach", IEEE Transactions on Energy Conversion, vol. 15, no. 2, pp. 143-148, June 2000.

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O D L U K U
O IZBORU U ZVANJE

Dr GOJKO JOKSIMOVIĆ bira se u akademsko zvanje **redovni profesor** Univerziteta Crne Gore za predmete: Osnove elektrotehnike I (osnovne studije), Osnove elektrotehnike II (osnovne studije ETR), Uvod u električne mašine i transformatore (osnovne studije) i Električne mašine u elektroenergetskim sistemima (osnovne studije) na **Elektrotehničkom fakultetu**.

УНИВЕРЗИТЕТ ЦРНЕ ГОРЕ
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02/2-763
Подгорица, 09.06. 2011 год.

REKTOR

Prof.dr Predrag Miranović

Biografija – prof. dr Milovan Radulović

Rođen sam 18.06.1962. godine u Nikšiću gdje sam završio osnovnu i srednju školu sa odličnim uspjehom. Za postignute rezultate u učenju nagrađen sam diplomom LUČA.

Školske 1981/82. godine upisao sam se na studije Elektrotehnike - smjer elektronika, na Elektrotehničkom fakultetu u Podgorici. Na istom fakultetu sam diplomirao 28. marta 1986. godine, odbranivši diplomski rad "MAPPY- samodovoljni mobilni robot" sa ocjenom 10(deset).

Postdiplomske studije upisao sam u školske 1992/93 godine na Elektrotehničkom fakultetu u Podgorici, smjer Robotika i vještačka inteligencija. Magistarski rad pod naslovom "Modeliranje i analiza moblnih robota sa dva nezavisno upravljana pogonska točka" odbranio sam 28.12.1995. godine.

Doktorsku disertaciju pod nazivom "Novi metod analize performansi moblnih robota" odbranio sam 07.05.2004. godine na Elektrotehničkom fakultetu - Univerziteta Crne Gore u Podgorici.

Publikovao sam 54 rada u međunarodnim i domaćim časopisima i na međunarodnim i domaćim konferencijama. Od ovog broja sedam radova je publikovano u vodećim časopisima (Q1 i Q2 časopisi po Scopusovom rangiranju).

Učestvovao sam u više evropskih i nacionananih projekata kao predstavnik Univerziteta Crne Gore:

- Međunarodni projekat: Učesnik projekta (član Didactic Working Group sa Univerziteta Crne Gore), „ Developing information Literacy for lifelong learning and knowledge economy in Western Balkan countries (RINGIDE)", finansiran od strane EU u okviru programa TEMPUS, 2012-2014,
- Međunarodni projekat: Učesnik projekta (koordinator za Elektrotehnički fakultet) „Development of Regional Interdisciplinary Mechatronic Studies" - DRIMS)", finansiran od strane EU u okviru programa TEMPUS IV Project: 158644 -JPCR, 2010-2013. Kao član projektnog tima (koordinator sa strane Elektrotehničkog fakulteta) učestvovao sam u realizaciji aktvnosti na osnivanju studijskog programa Mehatronika na Mašinskom fakultetu.
- Međunarodni projekat: Učesnik u realizaciji projekta „Energy Efficiency, Renewable Energy Sources andEnvironmental Impacts (ENERESE)«, finansiran od strane EU u okviru programa TEMPUS Project JPCR 530194 -2012,
- Nacionalni projekat: 2012-2015 Član projektnog tima nacionalnog interdisciplinarnog projekata IRSALPEE (Istraživanje rešetkastih stubova od Al legura za prenos električne energije) , Građevinski fakultet Podgorica, 2012-2015.
- Kao član tima Inovativno istraživačkog EUREKA projekat, Device for FAult and STate detection of Rotary machineries based on acoustic signals – FASTER. (Uređaj za detekciju stanja i otkaza na rotacionim mašinama na bazi akustičkih signal), koji realizuju ETF Podgorica, ETF Beograda i dvije kompanije "Mika" iz Beograda i "Čikom" iz Podgorice, a u saradnji sa Elektroprivredom Crne Gore (TE Pljevlja), Rudnikom Uglja Pljevlja, Rudnikom Šuplja stijena i TE Kostolac, uključen sam u dizajniranje računarski baziranog uređaja koji, na osnovu analize snimljenog zvuka, može da procijeni stanje rotirajućih djelova mašina.

- Tokom realizacije projekta sa međunarodnim partnerima, Centar izvrsnosti u bio-informatici (BIO-ICT), koji je realizovan na Elektrotehničkom fakultet UCG, u periodu: jun 2014-novembar 2017, kao član tima-konsultant, angažovan sam u realizaciji dijela projekta pripreme i montaže opreme za proizvodnju štampanih ploča i kao konsultant po pitanjima automatskog upravljanja uređajima za akviziciju podataka.

Angažovan sam od strane više kompanija i institucija u Crnoj Gori kao stručni konsultant, vršioc stručnog nadzora ili revident tehničke dokumentacije. Projektovao i učestvovao u realizaciji više značajnih infrastrukturnih projekata.

Član sam organizacionog i programskog odbora domaćeg Naučno-stručnog skupa INFORMACIONE TEHNOLOGIJE – sadašnjost i budućnost koji se tradicionalno organizuje već 25 godina na Žabljaku. U okviru ovih aktivnosti recenzirao sam preko 200 radova objavljenih na navedenoj konferenciji. U periodu od poslednjeg izbora u zvanje recenzirao sam 51 rad objavljen u Zbornicima radova ili u IEEE Explorer bazi sa navedene konferencije.

Član sam upravnog odbora Crnogorskog komiteta CIGRE i predsjednik Studijskog komiteta D2 (Informacioni sistemi i telekomunikacije).

Član sam organizacionog i predsjednik programskog odbora Stručnog skupa Dani elektroinženjera Inženjerske komore Crne Gore koji se organizuje od 2017. godine. Odgovorni urednik sam Zbornika radova sa ovog skupa, izdanja 2018 i 2019. godine U okviru navedenih aktivnosti recenzirao sam 19 radova.

Kao član Strukovne komore elektroinženjera IKCG angažovan sam u Komisiji za polaganje stručnog ispita kao koordinator za oblast slabe struje tokom 2017. godine.

Član sam Komisije za Akreditaciju i Tehničkog komiteta za akreditaciju laboratorija Akreditacionog tijela Crne Gore. Član sam međunarodne asocijacije elektro inženjera – IEEE i Inženjerske komore Crne Gore. Član sam Tehničkog komiteta Privredne komore CG, za proizvode iz domena elektrotehnike, u proceduri sticanja zaštitnog znaka Dobro iz Crne Gore.

U periodu od 14. 05. 2015. do 12. 12. 2017 godine, bio sam član Suda časti Univerziteta Crne Gore.

Od strane Centra za stručno obrazovanje i Zavoda za izdavanje udžbenika Crne Gore angažovan sam kao recenzent udžbenika za srednje stručne škole, kao i savjetnik za utvrđivanje kvaliteta u procesu utvrđivanja kvaliteta nastave u srednjim stručnim školama iz oblasti elektrotehnike.

Posjedujem Licence:

- Ovlašćenog inženjera za obavljanje djelatnosti izrade tehničke dokumentacije i građenje objekata i
- Revizora za obavljanje djelatnosti revizije tehničke dokumentacije i stručnog nadzora nad građenjem objekata,

Izdate od strane Ministarstva održivog razvoja i turizma Crne Gore.

Radovi u naučnim časopisima

SCI Lista:

M. Micev, M. Ćalasan, **M. Radulović**, S. H. E. A. Aleem, H. M. Hasanien and A. F. Zobaa, "Artificial Neural Network-Based Nonlinear Black-Box Modeling of Synchronous Generators," in *IEEE Transactions on Industrial Informatics*, vol. 19, no. 3, pp. 2826-2837, March 2023, doi: 10.1109/TII.2022.3187740.

Mihailo Micev, Martin Ćalasan, Dušan Stipanović, **Milovan Radulović**, Modeling the relation between the AVR setpoint and the terminal voltage of the generator using artificial neural networks, Engineering Applications of Artificial Intelligence, Volume 120, 2023, 105852, ISSN 0952-1976, https://doi.org/10.1016/j.engappai.2023.105852.

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Ćalasan, M.; Micev, M.; **Radulović, M.**; Zobaa, A.F.; Hasanien, H.M.; Abdel Aleem, S.H.E. Optimal PID Controllers for AVR System Considering Excitation Voltage Limitations Using Hybrid Equilibrium Optimizer. *Machines* **2021**, *9*, 265. https://doi.org/10.3390/machines9110265E

Micev, M., Ćalasan, M. & **Radulović, M.**," Full Synchronous Machine Parameters Identification Based on Field and Armature Current During the Short-Circuit", IEEE Transactions on Industry Applications, vol. 57, Issue: 6, pp.5959 – 5968, Nov.-Dec. 2021., doi: 10.1109/TIA.2021.3112141

Milovan Radulović, Žarko Zečević, Božo Krstajić, "Dynamic Phasor Estimation by Symmetric Taylor Weighted Least Square Filter", *IEEE Transactions on Power Delivery* (ISSN 0885-8977), vol. 35, no. 2, pp. 828 -836, april 2020., doi: 10.1109/TPWRD.2019.2929246

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Martin Ćalasan, Danilo Mujičić, Vesna Rubežić and **Milovan Radulović**, "Estimation of Equivalent Circuit Parameters of Single-Phase Transformer by Using Chaotic Optimization Approach", *Energies* (ISSN 1996-1073), vol.12 (9), p.n.1697, maj 2019; doi:10.3390/en12091697

Z. Zecevic, B. Krstajic, **M. Radulovic**, „A new adaptive algorithm for improving the ANC system performance," AEU - International Journal of Electronics and Communications, Volume 69, Issue 1, 2015, Pages 442-448, ISSN 1434-8411, https://doi.org/10.1016/j.aeue.2014.11.002.

Zecevic, Zarko; Krstajic, Bozo; **Radulovic, Milovan**: 'Frequency-domain adaptive algorithm for improving the active noise control performance', IET Signal Processing, 2015, 9, (4), p. 349-356, DOI: 10.1049/iet-spr.2014.0182

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Danilo S Mujičić, Martin P Ćalasan, **Milovan V Radulović**, "Primjena PSO algoritma u estimaciji parametara transfomatora", *Tehnika*, (ISSN 0040-2176), vol. 74, br. 2, str. 251-257, april 2019., doi: 10.5937/tehnika1902251M

Novica Daković, **Milovan Radulović**, "Flatness and LQR control of Furuta pendulum", *ETF Journal of Electrical Engineering,* (ISSN 0354-8653), vol. 21. no.1, pp. 138-146, decembar 2015

Marko Č Bošković, Tomislav B Šekara, **Milovan Radulović**, Marko Cvetković, "A novel method for optimization of PID/PIDC controller under constraints of phase margin and sensitivity to measurement noise based on non-symmetrical optimum method", *ETF Journal of Electrical Engineering,* (ISSN 0354-8653), vol. 22. no.1, pp. 15-23, novembar 2016.

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Milan Zejak, **Milovan Radulović**, " Hibridni koncept Smart Home Sistema", ", *22nd International Conference on Information Technology ((IT 2017)* (ISBN 978-86-85775-20-8), 27.02.-04.03. 2017, Žabljak, Crna Gora

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Tomislav B. Šekara, Marko Bošković, **Milovan Radulović**, Boško Cvetković, "Nova metoda za optimizaciju PIDC regulatora pod ograničenjima na pretek faze i osjetljivost na mjerni šum", *21st International Conference on Information Technology ((IT 2016)* (ISBN 978-86-85775-18-5), 29.02.-05.03. 2016, Žabljak, Crna Gora.

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Danilo Mujičić, Martin Ćalasan, **Milovan Radulović**, "Efikasnost energetskih transformatora", *VI Savjetovanje CG-KO CIGRE,* Bečići, Crna Gora, 14-17.05.2019., A2-05, str. 1-8, www.cigre.me, ISSN: 2336-9604

Milica Bulatović, Martin Ćalasan, **Milovan Radulović**, "Pregled metoda za podešavanje parametara PID regulatora kod automatskog upravljanja frekvencijom dvogeneratorskih sistema", *VI Savjetovanje CG-KO CIGRE*, Bečići, Crna Gora, 14-17.05. 2019., C6-10, str. 1-10, www.cigre.me, ISSN: 2336-9604.

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02/1 415

Na osnovu člana 72 stav 2 Zakona o visokom obrazovanju („Službeni list Crne Gore" br 44/14, 47/15, 40/16, 42/17, 71/17, 55/18, 3/19, 17/19, 47/19, 72/19 i 74/20) i člana 32 stav 1 tačka 9 Statuta Univerziteta Crne Gore, Senat Univerziteta Crne Gore na sjednici održanoj 10.03.2021. godine, donio je

ODLUKU
O IZBORU U ZVANJE

Dr Milovan Radulović bira se u akademsko zvanje redovni profesor Univerziteta Crne Gore za **oblast Automatika,** na Elektrotehničkom fakultetu Univerziteta Crne Gore, na neodređeno vrijeme.

SENAT UNIVERZITETA CRNE GORE
PREDSJEDNIK

Prof. dr Vladimir Božović, vršilac funkcije rektora

Ćalasan Martin - Biografija

Rođen sam 05. oktobra 1986. godine u Plužinama. Osnovnu školu sam pohađao u mjestu Brezna, Opština Plužine, a Gimnaziju, prirodno matematički smjer, u Plužinama. Za uspjeh u osnovnoj i srednjoj školi dobitnik sam diplome »Luča 1« i nosilac priznanja »Đak generacije«.

Školske 2005/2006. započeo sam studije na Elektrotehničkom fakultetu Univerziteta Crne Gore, odsjek Energetika i automatika. Osnovne studije završio sam u junu 2008. godine sa prosječnom ocjenom 9.86. Nakon druge i treće godine studija dobio sam novčane nagrade Elektrotehničkog fakulteta za najboljeg studenta odsjeka Energetika i automatika. Specijalističke studije, smjer Industrijska elektrotehnika, na istom fakultetu, završio sam u junu 2009. godine sa prosječnom ocjenom 10.00. Tokom osnovnih i specijalističkih studija bio sam korisnik stipendija Vlade Republike Crne Gore za talentovane studente i učenike, Opštine Plužine, Regulatorne agencije za energetiku i Elektroprivrede Crne Gore AD Nikšić (EPCG).

Magistarske studije na Elektrotehničkom fakultetu Univerziteta Crne Gore, smjer Industijska elektrotehnika, završio sam odbranom magistarske teze naslova »*Simulacioni model i dinamika statičkog pobudnog sistema sinhronih generatora u HE "Perućica"*«, pod mentorstvom prof. dr Milutina Ostojića, u junu 2010. godine s opštim uspjehom 10, čime sam stekao akademski naziv magistra elektrotehničkih nauka.

Doktorsku disertaciju naslova »*Upravljanje prekidačkim reluktantnim generatorom i tolopogije energetskog pretvarača za rad u kontinualanom režimu*«, pod mentorstvom prof. dr Vladana Vujičića, redovnog profesora Elektrotehničkog fakulteta Univerziteta Crne Gore, odbranio sam 15.06.2017. godine, čime sam stekao naučni stepen doktora elektrotehničkih nauka.

U zvanje DOCENTA za oblast Električne mašine i pogoni (Električne mašine – osnovne studije – studijski program Energetika i automatika; FACTS i HVDC komponente energetske elektronike – master studije – studijski program Elektroeneregetski sistemi; Električni pogoni – master studije – studijski program Automatika i Industrijska elektrotehnika; Upravljanje i regulacija električnih pogona – master studije - studijski program Automatika i Industrijska elektrotehnika) na Elektrotehničkom fakultetu Univerziteta Crne Gore, izabran sam na sjednici Senata UCG na sjednici od 12.02.2019. godine. U dosadašnjem radu na Elektrotehničkom fakultetu u Podgorici, Pomorskom fakultetu u Kotoru i Mašinskom fakultetu u Podgorici izvodio sam nastavu iz većeg broja predmeta iz izborne oblasti - oblasti električnih mašina i pogona. Na doktorskim studijama na Elektrotehničkom fakultetu ustanovio sam i predmet Sistemi za skladištenje električne energije.

U dosadašnjem naučno-istraživačkom radu objavio sam oko 55 radova na SCI/SCIE listi, kao i oko 150 radova u ostalim časopisima, kao i na domaćim, regionalnim i međunarodnim konferencijama. Objavio sam knjigu „*Mašine jednosmjerne struje*" u izdanju Naučne knjige iz Beograda (Srbija), kao i nekoliko poglavlja u knjigama međunarodnih izdavača. Recenzirao sam preko 2000 radova u časopisima sa SCI/SCIE liste i bio sam učesnik nekoliko međunarodnih projekata. Bio sam jedan od urednika u šest specijalnih izdanja časopisa sa SCI/SCIE liste:

[1] "*Renewable Based Energy Distributed Generation*" – časopis Energies (ISSN 1996-1073)

[2] "*Power System Dynamics, Operation, and Control including Renewable Energy Systems and Smart Grid: Technology and Applications*" – časopis Electronics (ISSN 2079-9292)

[3] „*Energy Hubs in Modern Energy Systems with Renewables and Energy Storage*" – časopis Frontiers in Energy Research - Smart Grids (ISSN 2296-598X)

[4] „*Electrical Vehicles Technologies and the Power Quality Challenges*" - časopis International Transactions on Electrical Energy Systems (ISSN: 2050-7038)

[5] „*Mathematical Modeling in Energy Sector*" – časopis Energies (ISSN 1996-1073)

[6] „*Technical and Environmental Implications of Electrifying Waterborne Transportation Systems*" – časopis Water (ISSN 1996-1073).

U prethodnom periodu, bio sam i član organizacionog/naučnog odbora većeg broja međunarodnih, domaćih i regionalnih konferencija, dok sam održao i veći broj predavanja na naučnim skupovima, ljetnjim školama i stručnim savjetovanjima.

Za svoj nastavni i naučno-istraživački rad dobio sam sljedeće nagrade i priznanja:

- Priznanja UCG za postignute rezultate i doprinose razvoju naučno-istraživačkog, umjetničkog i stručnog rada na Elektrotehničkom fakultetu u 2019, 2020 i 2022. godini
- Nagradu CANU za 2020. godinu iz Fonda Crnogorske akademije nauka i umjetnosti za podsticanje podmlatka,
- DANUBIUS nagradu za mlade naučnike koju dodjeljuje Austrijsko ministarstvo za obrazovanje, nauku i istraživanje i Institut za Dunavsku regiju i Centralnu Evropu, u oktobru 2021. godine
- Nagrada Ministarstva nauke za najboljeg pronalazača u Crnoj Gori u 2017. godini,
- Nagrada Ministarstva nauke za najboljeg naučnika Crne Gore u 2022. godini, i
- Državnu nagradu OKTOIH za 2022. godinu.

Imam naučnu saradnju sa profesorima i istraživačima iz preko 10 zemalja i sa preko 25 međunarodnih institucija. U periodu od marta 2021. godine do septembra 2021. godine bio sam član Savjeta za nauku Vlade Crne Gore. Od juna 2022. godine član sam Odbora direktora Elektroprivrede Crne Gore. Član sam IEEE i CIGRE, dok sam od 2021. godine potpredsjednik Crnogorskog komiteta CIGRE – CG KO CIGRE.

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Na osnovu člana 72 stav 2 Zakona o visokom obrazovanju („Službeni list Crne Gore“ br. 44/14, 47/15,40/16,42/17,71/17 i 55/18) i člana 32 stav 1 tačka 9 Statuta Univerziteta Crne Gore, Senat Univerziteta Crne Gore, na sjednici održanoj 12.02. 2019.godine, donio je

O D L U K U
O IZBORU U ZVANJE

Dr MARTIN ĆALASAN bira se u akademsko zvanje **docent Univerziteta Crne Gore za oblast Električne mašine i pogoni** (Električne mašine–osnovne studije–studijski program Energetika i automatika;FACTS i HVDC komponente energetske elektronike– master studije–studijski program Elektroeneregetski sistemi; Električni pogoni–master studije–studijski program Automatika i Industrijska elektrotehnika; Upravljanje i regulacija električnih pogona–master studije-studijski program Automatika i Industrijska elektrotehnika) **na Elektrotehničkom fakultetu Univerziteta Crne Gore, na period od pet godina.**

SENAT UNIVERZITETA CRNE GORE
PREDSJEDNIK

Prof.dr Danilo Nikolić, rektor