Lecture Notes in Networks and Systems 943

Duy Cuong Nguyen · Do Trung Hai ·
Ngoc Pi Vu · Banh Tien Long ·
Horst Puta · Kai-Uwe Sattler *Editors*

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Lecture Notes in Networks and Systems 943

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Editors
Duy Cuong Nguyen
Faculty of Electronic Engineering
Thai Nguyen University of Technology
Thai Nguyen, Vietnam

Do Trung Hai
Faculty of Electronic Engineering
Thai Nguyen University of Technology
Thai Nguyen, Vietnam

Ngoc Pi Vu
Faculty of Mechanical Engineering
Thai Nguyen University of Technology
Thai Nguyen, Vietnam

Banh Tien Long
Vietnam Association for Science Editing
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Hanoi, Vietnam

Horst Puta
Institute for Automation and Systems Engineering
Ilmenau University of Technology (IUT)
Ilmenau, Germany

Kai-Uwe Sattler
Ilmenau University of Technology (IUT)
Ilmenau, Germany

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Preface

This book covers the proceedings of the 6th International Conference on Engineering Research and Application 2023 (ICERA 2023) that was organized by Thai Nguyen University of Technology (TNUT), Vietnam, and cooperated with Ilmenau University of Technology, Germany. In 2018, the first conference was held. Thus far, the conference has attracted a lot of contributions from researchers of many different universities around the world.

This conference aims to bring together researchers from many fields related to engineering research and applications, theories, and practices. This volume covers the following subjects: Mechanical Engineering, Materials and Mechanics of Materials, Mechatronics and Micromechatronics, Automotive Engineering, Electrical and Electronics Engineering, and Information and Communication Technology.

The up-to-date contributions reported in this book were carefully reviewed by experts and also approved by editors for the last review. All 103 accepted papers were presented and discussed on ICERA 2023, held in Thai Nguyen City, Vietnam, on December 1–2, 2023. The total papers sent to this conference are 232 papers. As a result of the two-stage review process, only 103 excellent contributions were selected for the presentation at the conference and publication in this book. The readers will find here representative samples of the most modern techniques available nowadays for the solution of challenging problems arising in engineering research and application.

We extend our sincere gratitude to the writers for their insightful articles that they contributed to the conference. Also, we sincerely appreciate the reviewers' assessments and suggestions for raising the caliber of the chosen papers. Moreover, we would like to specially thank to our Keynote speakers, Prof. Kai-Uwe Sattler (Ilmenau University of Technology, Germany), Prof. Tuan Le Anh (Hanoi University of Science and Technology, Vietnam), Prof. S.A. Sherif (University of Florida, USA), Prof. Roger A. Sauer (RWTH Aachen University, Germany/Gdansk University of Technology), and Prof. Minh T. Nguyen (Thai Nguyen University of Technology, Vietnam), for their valuable and inspiring contributions to scientists, researchers, and listeners. We also thank to the members of the Organizing Committee of ICERA 2023 for their excellent technical and editorial support.

Last but not least, we would like to deeply thank to Springer Publishers and its Editor staff for helping us in the publication of the proceeding volume of this book.

December 2023

Duy Cuong Nguyen
Do Trung Hai
Ngoc Pi Vu
Banh Tien Long
Horst Puta
Kai-Uwe Sattler

Keynote Addresses

The Power of Graphs in Databases

Kai-Uwe Sattler

Ilmenau University of Technology
kus@tu-ilmenau.de

Abstract. In recent years, graph databases have evolved from specialized systems for a niche market to a mainstream technology. In addition to numerous native open-source and commercial database systems, the SQL standard has introduced property graph queries that promote support for graph queries in relational database systems. Graphs are used for various applications such as analyzing large networks, representing and querying knowledge graphs, and managing master data and complex data structures.

In this talk, we present use cases, challenges, and techniques for managing graphs in database systems. We argue that in addition to analytical tasks, transactional operations are also an important task. Building on this, we discuss approaches we have developed in the Poseidon project to leverage modern hardware technologies such as persistent memory, processing-in-memory, and GPU acceleration for graph database processing.

Status Report on Transitioning to a Hydrogen Economy in the United States

S. A. Sherif

University of Florida
sasherif@ufl.edu

Abstract. In the past few years, there has been a very significant drive worldwide toward transitioning to a hydrogen energy system where hydrogen as an energy carrier is produced by a primary energy source such as solar energy. In the United States, the US Department of Energy has made a strategic shift toward implementing such an energy system in all aspects of the economy and has taken concrete steps toward achieving highly ambitious targets in that effort. The purpose of this presentation is to outline those steps and describe some of the remaining challenges that are needed to transition to this new energy system. This is part of the overall policy of decarbonising the energy sector in the United States and achieving the goal of net-zero energy.

Bio:

Dr. SA Sherif is a tenured Professor of Mechanical and Aerospace Engineering at the University of Florida. He is a Life Fellow of the American Society of Mechanical Engineers (ASME), a Life Fellow of ASHRAE, a Fellow of the Royal Aeronautical Society, a Fellow of the American Society of Thermal and Fluids Engineers (ASTFE), an Associate Fellow of the American Institute of Aeronautics and Astronautics (AIAA), a Vice President of Commission B-2 of the International Institute of Refrigeration, a Member of the Advisory Board of Directors of the International Association for Hydrogen Energy, and Founding Member of the Board of Directors and Vice President of Programs for ASTFE. He served as Editor-in-Chief of the ASME Journal of Thermal Science and Engineering Applications (2014–2019) and as Editor-in-Chief of the ASME Journal of Solar Energy Engineering (2020–2025). He has 600 publications and two US patents.

The Path to Net-Zero: A Vision to Decarbonised Transport in Asia and Vietnam's Actions

Le Anh Tuan[1], Ly Dang[2], and Nguyen Thi Yen Lien[3]

[1] Hanoi University of Science and Technology, Vietnam
[2] NDC-TIA GIZ
[3] University of Transport and Communications, Vietnam
tuan.leanh@hust.edu.vn

Abstract. The talk introduces keypoints of a report on a vision to decarbonised transport in Asia, overcoming blind spots and enabling change, prepared by the NDC-TIA Council for Decarbonising Transport in Asia, and provides some implementation actions in Vietnam aiming at net-zero pledge by 2050.

It is necessary to identify where we are today, what is needed to get to zero-carbon transport, which key blind spots are available that need excessive efforts to overcome then to drive a path to decarbonising transport with 6 foundational principles and 6 enablers for change. Finally, an overview of Vietnam strategies and actions pursuing decarbonisation in transport sector is addressed.

Keywords: Decarbonised transport · Net-zero by 2050 · EV development

Isogeometric Finite Elements: Motivation, Implementation and Applications

Roger A. Sauer

Graduate School AICES, RWTH Aachen University/Civil Engineering, Gdansk University of Technology
sauer@aices.rwth-aachen.de

Abstract. Isogeometric finite elements are a new class of finite elements that have been developed by combining computer-aided design (CAD) with finite element analysis [1]. They use spline-based shape functions that have several advantages over classical Lagrange-based finite element shape functions. They can be locally refined, and they can be embedded straightforwardly into existing finite element software using the Bezier extraction operator [2], although special attention has to be paid to boundary conditions, especially for curved boundaries. The isogeometric paradigm is particularly advantageous for solving high-order partial differential equations, such as those of Kirchhoff-Love shell theory [3]. This is illustrated by several computational application examples from science and engineering.

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Unmanned Aerial Vehicles (UAVs) for Remote Sensing: Applications, Technical Problems, and Research Orientations

Minh T. Nguyen

Thai Nguyen University of Technology–Thai Nguyen University, Vietnam
nguyentuanminh@tnut.edu.vn

Abstract. Over the past few decades, remote sensing has established itself as an effective technique for monitoring and data collection across several industries, weather conditions, and geographic locations. UAV technologies have demonstrated their distinct benefits in a variety of remote sensing applications, including precision agriculture, forestry, power transmission lines, buildings, artificial objects, and natural surroundings. UAV remote sensing techniques can be used in precise ground object identification and detection.

This talk considers UAV sensing networks that comprise hardware and networking techniques. The networks' data collecting algorithms are discussed. Advanced data processing methods for networks are also offered. Some control algorithms for deploying and maneuvering the UAVs in such networks are proposed and evaluated. The issues with the UAVs' energy efficiency are discussed and resolved. The presentation will offer some prospective areas for either future developments or research collaborations.

Short Biography

Minh T. Nguyen received his B.S., M.S., and PhD degrees in Electrical Engineering from Hanoi University of Communication and Transport, Hanoi, Vietnam, in 2001, Military Technical Academy, Hanoi, Vietnam, in 2007, Oklahoma State University, Stillwater, OK, USA, in 2015, respectively. Associate Prof. Dr. Minh T. Nguyen is currently the Director of Human Resource Training and Development Center (HDC) at Thai Nguyen University (TNU), Vietnam, and the Director of Advanced Wireless Communication Networks (AWCN) Lab. He has interest and expertise in a variety of research topics in telecommunications, computer networking, and signal processing areas, especially compressive sensing, and wireless/mobile sensor/robotic networks. He serves as technical reviewers for several prestigious journals and international conferences. He also serves as Editors for some journals, Wireless Communication and Mobile Computing, Transactions on Industrial Networks and Intelligent Systems and Editor in Chief for ICSES Transactions on Computer Networks and Communications.

Contents

A New Algorithm for Controlling FESS in the Microgrid

Hoa Thi Thanh Lai[1](✉), Hai Do Trung[1], K. L. Lai[1], and Nguyen Hai Vu[2]

[1] Thai Nguyen University of Technology, Thai Nguyen, Vietnam
laithithanhhoa@tnut.edu.vn
[2] College of Economis and Techniques, Thai Nguyen, Vietnam

Abstract. The Flywheel Energy Storage System (FESS) is a new energy storage technology with several advantages over traditional energy storage methods. This paper proposes a control algorithm for the FESS using a Neural Fuzzy Network (NFC) for the state-of-charge loop and Model Predictive Control (MPC) for the current loop. The FESS is installed on the DC bus of the microgrid, which includes renewable energy sources (wind power, solar power). The modeling and simulation results in Matlab - Simulink/Simcape show that abnormal fluctuations of renewable energy sources will be balanced by the FESS (through energy accumulation or release), thereby maintaining a stable power supply to the grid.

Keywords: FESS; NFC-MPC · Microgrid; Sola Power · wind Power

1 Introduction

Increasing energy consumption, advancements in power generation technology and environmental regulation have resulted in increased penetration of renewable energy forms such as: solar and wind energy systems, new small-scale electrical energy systems such as fuel cells. These types of energy resources, which are often distributed in a network, are called distributed systems (DGs) [1]. The general characteristics and random variability of small power distributed sources give rise to many problems such as power quality or supply-demand imbalance that can occur in Microgrids (MG) [2, 3]. The general solution to overcome these disadvantages of DG is to use an energy storage system (ESS). ESS can supply or store energy in electrical and MG systems as needed. ESS can be used in flexible alternating current transmission systems (FACTS) [4, 5] to increase transmission limits of transmission lines or improve power quality in MGs and power systems [7]. Large ESS can provide electrical power for several hours in the electrical system. Furthermore, ESS can release huge amounts of energy in seconds for military applications [7].

The Flywheel Energy Storage System (FESS), one of the popular ESSs, is a quick-response ESS and one of the early commercialized technologies to solve many problems in MG and electrical systems [8]. This technology, as a clean energy source, has been applied in various applications due to its special properties such as high energy density, no periodic maintenance, no pollution. Contamination, long life, high cycle efficiency

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(about 85%), etc. [7]. Although this energy storage system has a relatively high capital cost ($5000/kWh), it has low annual operating and maintenance costs ($19/kW-year) [7].

Nowadays, the application of this FESS has been increased in various aspects of human life. Electric vehicles, space projects, military equipment and power system applications are some of its different application cases. The problem of controlling FESS operation suitable for each specific application has always attracted the attention of many scientists such as the spatial vector modulation method for FESS using IM machines [9]; using fuzzy neurons to control induction motors [10]; predictive control method for matrix inverters [11].

This paper proposes to use fuzzy neural network (NFC) for magnetic flux loop and model predictive control (MPC) for current loop to control FESS mounted on a DC busbar of a microgrid consisting of renewable energy sources. The following contents of the paper are presented as follows: Sect. 2 presents the structure and operation of FESS in microgrids; Sect. 3 presents the fuzzy Neural control design algorithm and model-based predictive control for FESS; Sect. 4 presents the simulation results with different change scenarios of renewable energy sources and finally the conclusion and recommendations.

2 Structure and Operation of FESS in Microgrids

Considering a microgrid with a block diagram as shown in Fig. 1, the power source consists of a diesel generator directly connected to the AC Bus, providing a power P_1 to the microgrid; Wind and solar power systems are connected together at the DC Bus (DC Bus), they provide a capacity of $P_{ren} = P_{WT} + P_{PV}$ for the DC Bus, this power always fluctuates randomly according to environmental conditions, the flywheel energy storage system is connected to the DC bus, which is then connected to the AC busbar via a DC/AC converter. Assuming $P_1 = \text{const}$, $P_2 = \text{const}$, for the grid to work properly, $P_{Grid} = P_{WT} + P_{PV} + P_F = P_{Ren} + P_F = \text{const}$.

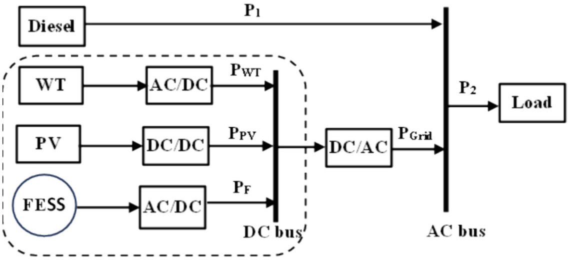

Fig. 1. Block diagram of a microgrid with FESS

The structure of the flywheel is shown in Fig. 2 [9] The flywheel stores energy in a rotating block of composite material housed in a hollow cylinder supported by a magnetic bearing to minimize the friction between the shaft and the base surface. The shaft of the flywheel is connected to the rotor shaft of the electric machine, these machines are designed to operate at high speed and with minimal friction, they can operate either in engine mode or in generator mode.

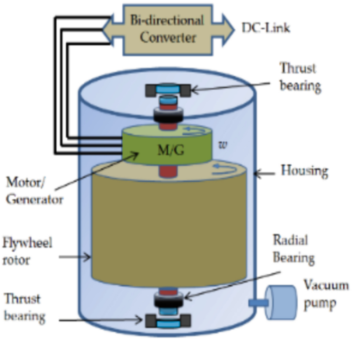

Fig. 2. Structure of the energy storage flywheel [8]

The operating principle of FESS in microgrid can be summarized as follows: Under normal working conditions, the electric machine in the flywheel works in the motor mode (Standby mode), performing energy storage in the form of kinetic energy proportional to the rotor moment of inertia and the square of the rotational speed.

$$E_F = \frac{1}{2} J_F \omega_F^2 \tag{1}$$

where E_F is kinetic energy; J_F is the moment of inertia of the flywheel, ω_F is the angular velocity of the flywheel.

When there is a fluctuation in the source or load, for example when the power of a renewable energy generator (P_{ren}) increases, the accelerated FESS absorbs the increase in the P_{Ren} power, at that time, the machine in the flywheel works in the area of weak magnetic flux. When P_{Ren} is reduced the generator acts as a generator providing the extra power needed to keep the system stable. During the discharge of energy, the speed of the flywheel decreases gradually. The relationship between the power and the energy stored in the flywheel is determined:

$$\mathrm{P_F} = \frac{\mathrm{dE_F}}{\mathrm{dt}} \tag{2}$$

where $P_F(W)$ is the maximum power that can be supplied by the storage system (equal to the rated power of the asynchronous machine integrated in the flywheel); E is stored energy in Jul. From (1) and (2) we have the relationship between energy, moment of inertia and rotational speed of flywheel as:

$$\frac{\mathrm{dE_F}}{dt} = \frac{1}{2}\mathrm{J_F}\frac{d\omega_{\mathrm{F}}^2}{\mathrm{dt}} \tag{3}$$

Expression (3) shows that the energy that FESS can store or release is expressed by the formula

$$\Delta E = \frac{1}{2} J \left(\omega_{\max}^2 - \omega_{\min}^2 \right) \tag{4}$$

where, $\omega_{\max}$ and $\omega_{\min}$ are the maximum and minimum angular speed of the flywheel. Normally, FESS is not discharged to conserve energy we usually choose

$$\omega_{\min} = \frac{1}{2} \omega_{\max}$$

From (4) we see that the stored energy can be increased by increasing the moment of inertia or the maximum angular speed of the flywheel. We perform an increase in stored energy by increasing the angular velocity of the flywheel within the allowable range. Therefore, speed regulation over a wide range is very important for the energy storage capacity and depth of charge and discharge of the FESS.

3 Neural Design - FESS. Control MPC

From Fig. 3, the control problem posed here is to control the operation of the flywheel so that when there is a fluctuation of renewable energy, the total capacity pumped by the renewable energy system and the flywheel system into the grid is the least volatile. That means

$$\mathrm{p}_{\mathrm{Grid}} = \mathrm{p}_{\mathrm{Ren}} + \mathrm{p}_{\mathrm{Fly}} \approx \mathrm{const} \tag{5}$$

The block diagram of the operation control system of FESS is shown in Fig. 3.

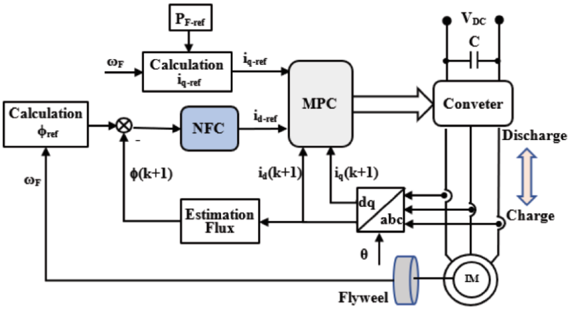

Fig. 3. Control system block diagram FESS

In the converter diagram (Converter) is a bidirectional converter, the operation control of the Converter is performed by the predictive controller (MPC). The flywheel speed varies according to the change of renewable energy capacity supplied to the microgrid. In standby mode, the speed of the FESS is equal to the rated speed of the machine.

3.1 Mathematical Model of the System

The mathematical model of a three-phase asynchronous machine represented in the state space in the reference system (d,q) is described by [12]

$$\frac{d}{dt}\begin{bmatrix}\phi_{dr}\\ \phi_{qr}\\ i_{ds}\\ i_{qs}\end{bmatrix}=\begin{bmatrix}\frac{-R_r}{L_r} & (\omega_s-p\omega_F) & \frac{MR_r}{L_r} & 0\\ (\omega_s-p\omega_F) & \frac{-R_r}{L_r} & 0 & \frac{MR_r}{L_r}\\ \frac{MR_r}{\sigma L_sL_r^2} & \frac{Mp\omega_F}{\sigma L_sL_r} & \frac{-R_{sr}}{\sigma L_s} & \omega_s\\ -\frac{Mp\omega_F}{\sigma L_sL_r} & \frac{MR_r}{\sigma L_sL_r^2} & -\omega_s & \frac{-R_{sr}}{\sigma L_s}\end{bmatrix}\begin{bmatrix}\phi_{dr}\\ \phi_{qr}\\ i_{ds}\\ i_{qs}\end{bmatrix}+\begin{bmatrix}0 & 0\\ 0 & 0\\ \frac{1}{\sigma L_s} & 0\\ 0 & \frac{1}{\sigma L_s}\end{bmatrix}\begin{bmatrix}u_{ds}\\ u_{qs}\end{bmatrix} \tag{6}$$

With $R_{sr}=R_s+\frac{M^2}{L_r^2}R_r$ and $\sigma=1-\frac{M^2}{L_sL_r}$.
where: R_s (Ω), R_s (Ω) are the stator and rotor phase resistance; L_s, L_r are the stator and rotor phase inductance in Henry; M is mutual inductance of stator and rotor in Henry; u_{ds}, u_{qs} are the perpendicular components of the stator voltage; i_{ds}(V), i_{qs}(V) are the perpendicular components of the stator current; ϕ_{dr}(Wb), ϕ_{qr}(Wb) are the perpendicular components of the rotor flux; p is the number of pole pairs; ω_s is the rotational speed of the stator magnetic field in radial per second.

Assumption:

$$\phi_{dr}=\phi;\ \phi_{qr}=0 \tag{7}$$

The system of state Eqs. (6) becomes:

$$\frac{d}{dt}\begin{bmatrix}\phi_{dr}\\ i_{ds}\\ i_{qs}\end{bmatrix}=\begin{bmatrix}\frac{-R_r}{L_r} & \frac{MR_r}{L_r} & 0\\ \frac{MR_r}{\sigma L_sL_r^2} & \frac{-R_{sr}}{\sigma L_s} & \omega_s\\ -\frac{Mp\omega_F}{\sigma L_sL_r} & -\omega_s & \frac{-R_{sr}}{\sigma L_s}\end{bmatrix}\begin{bmatrix}\phi_{dr}\\ i_{ds}\\ i_{qs}\end{bmatrix}+\begin{bmatrix}0 & 0\\ \frac{1}{\sigma L_s} & 0\\ 0 & \frac{1}{\sigma L_s}\end{bmatrix}\begin{bmatrix}u_{ds}\\ u_{qs}\end{bmatrix}. \tag{8}$$

The reference flux is determined by the expression:

$$\phi_{f-ref}=\begin{cases}\phi_{rn}\ \text{khi}\ |\omega_f|\le\omega_{fn}\\ \phi_{rn}\frac{\omega_{fn}}{|\omega_f|}\ \text{khi}\ |\omega_f|>\omega_{fn}\end{cases} \tag{9}$$

$$\phi_{rn}=\frac{L_r}{M}\phi_{sn} \tag{10}$$

is the rated flux of the rotor; is the rated flux of the stator

$$\phi_{sn}=\sqrt{3}\frac{u_s}{\omega_s} \tag{11}$$

where us is the mean value of the stator phase voltage; ω_s the grid voltage angular speed is equal to 314.16 rad/s, we have:

$$\phi_{rn}=\sqrt{3}\frac{L_r}{M}\frac{u_s}{\omega_s} \tag{12}$$

The reference stator current is determined:

$$\mathrm{i_{ds-ref} = PI(\phi_{r-ref} - \phi_{r-est})} \tag{13}$$

PI is the law that adjusts the rate of integration. The estimated value of the rotor flux is:

$$\mathrm{\phi_{dr-est} = \frac{M}{1 + \frac{L_r}{R_r} s} i_{ds}} \tag{14}$$

where s is the Laplace operator

The set (reference) power of the asynchronous machine is determined by formula (1). From this, the reference electromagnetic moment can be calculated:

$$\mathrm{M_{F-ref} = \frac{P_{F-ref}}{\omega_F}} \tag{15}$$

The converter in Fig. 3 is the voltage source inverter [9], they have 8 possible opening and closing states as in Table 1.

Table 1. Table of switching states of the converter

Status	SA	SB	SC	Voltage vector
1	0	0	0	$V_0 = 0$
2	1	0	0	$V_1 = 2*V_{dc}/3$
3	1	1	0	$V_2 = \frac{V_{dc}}{3} + j\frac{\sqrt{3}}{3} V_{dc}$
4	0	1	0	$V_3 = -\frac{V_{dc}}{3} + j\frac{\sqrt{3}}{3} V_{dc}$
5	0	1	1	$V_4 = -2*V_{dc}/3$
6	0	0	1	$V_5 = -\frac{V_{dc}}{3} - j\frac{\sqrt{3}}{3} V_{dc}$
7	1	0	1	$V_6 = \frac{V_{dc}}{3} - j\frac{\sqrt{3}}{3} V_{dc}$
8	1	1	1	$V_7 = 0$

3.2 MPC Design for FESS

To design a model predictive control for FESS, we need to find states S_A, S_B, S_C to minimize the given objective function and satisfy the constraints. Performing discretization (8) we get:

$$\mathrm{\phi_{dr}(f+1) = \frac{-R_r}{L_r}\phi_{dr}(k) + \frac{MR_r}{L_r} i_{dr}(k)} \tag{16}$$

$$\mathrm{i_{ds}(k+1) = \frac{MR_r}{\sigma L_s L_r^2}\phi_{dr}(k) - \frac{R_{sr}}{\sigma L_s} i_{dr}(k) + \omega_s i_{qs}(k) + \frac{1}{\sigma L_s} u_{ds}(k)} \tag{17}$$

$$i_{qs}(k+1) = -\frac{Mp\omega_F}{\sigma L_s L_r}\phi_{dr}(k) - \omega_s i_{dr}(k) - \frac{R_{sr}}{\sigma L_s} i_{qs}(k) + \frac{1}{\sigma L_s} u_{qs}(k) \tag{18}$$

For the purpose of flux and component i_d, i_{qs} tracking the reference signal, we have the objective function

$$J = (\phi_{dr-ref} - \phi_{dr}(k+1))^2 + \lambda_1 \left(i_{ds-ref} - i_{ds}(k+1)\right)^2 + \lambda_2 \left(i_{qs-ref} - i_{qs}(k+1)\right)^2 \rightarrow \min \tag{19}$$

where λ_1 and λ_2 are the weights that tell the difference between terms in the objective function.

The constraints ensure the safe operation of the machine, so that during the starting process, the starting current should not exceed 2.5 times the rated current, ie:

$$I_{max} < I_n \tag{20}$$

The steps to design MPC are as follows:

- Step 1: Update system parameters, select period T_s any initial optimal objective function value J_0 (this value is usually chosen quite large in the first step).
- Step 2: Calculate the predicted magnetic flux according to (16) and the components of the forecast current according to (17), (18).
- Step 3: Calculate the objective function (19) for 8 possible states of the converter and choose the optimal state (with $J = \min$), thereby obtaining the S_A, S_B, S_C values according to Table 1.

The calculation is repeated for the next cycles.

3.3 Neural Fuzzy Controller Design for Magnetic Flux Control Loop

The magnetic flux control loop using neural fuzzy network (NFC) is a type of artificial neural network based on the Takagi-Sugeno fuzzy inference system [13, 14], NFC allows building input-output mapping based on human knowledge (through the if-then rule of fuzzy control) combined with training input-output pairs. By combining both neural networks and fuzzy logic, NFC promotes the advantages of both types.

The NFC architecture, as give in Fig. 4, consists of five layers interconnected neurons. The architecture is briefly explained as follows.

Layer 1. It is the Fuzzification Layer where each neuron is an adaptive node and holds the fuzzy value of the crisp inputs. The node output is calculated

$$O_i^1 = \begin{cases} \mu_{Ai}(x), & i = 1, 2 \\ \mu_{Bi}(y), & i = 1, 2 \end{cases} \tag{21}$$

where μ is a membership function for the fuzzy sets A_i, B_i. The Gaussian function is choice. The formula for Gaussian function is

$$f(x) = a.\exp\left\{\frac{(x-b)^2}{2c^2}\right\} \tag{22}$$

Layer 2. The node output is calculated as follow:

$$O_i^2 = w_i = \mu_{Ai}(x).\mu_{Bi}(y), \quad i = 1, 2 \tag{23}$$

Layer 3. The node output is calculated as follow:

$$O_i^3 = \overline{w}_i = \frac{w_i}{\sum w_i} \quad i = 1, 2 \tag{24}$$

Layer 4. is the Defuzzification Layer where each neuron is also an adaptive node and holds the consequent parameters of the architecture. The node output is calculated as follows:

$$O_i^4 = \overline{w}_i f_i = \overline{w}_i.\left(p_i s + q_i y + s_i\right) \quad i = 1, 2 \tag{25}$$

Layer 5. It is an Output Layer where a single neuron is present for output, which is the sum of all the inputs. The node output is calculated as follows:

$$O_i^5 = f(s, y) = \sum_i \overline{w}_i f_i = \frac{\sum_i w_i f_i}{\sum_i w_i} \quad i = 1, 2 \tag{26}$$

The IF-THEN rules for a 2-input Takagi-Sugeno system are described as follows:

+ *Rule 1: IF* x *is* A_1 *and* y *is* B_1 *THEN* $f_1 = p_1x + q_1y + s_1$.

+ *Rule 2: IF* x *is* A_2 *and* y *is* B_2 *THEN* $f_2 = p_2x + q_2y + s_2$.

where x, y are the inputs in the crisp set; A_i, B_i are the linguistic labels; p_i, q_i are the consequent parameters; f_1, f_2 are the output fuzzy membership functions.

In this paper, the input 1 is the error between the reference flux and the actual flux, input 2 is the error integral, the output is the reference torque value ($i_{q\text{-ref}}$).

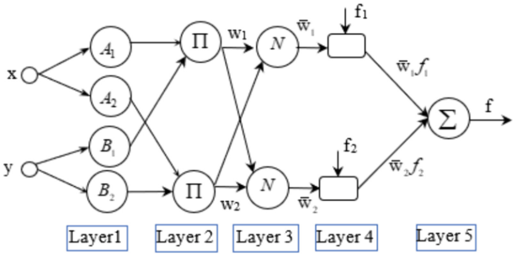

Fig. 4. Structure of NFC

The training and testing data set of 1000 samples obtained from Eq. 1 of (8), 70% of the samples are used to train the network, the rest of the samples are used for testing. After 30 training periods with hybrid jurisprudence, we get an NFC controller with an error of 2.10^{-4}.

4 Simulation and Discussion

To clearly see the operation of the flywheel system in compensating for the abnormal lack of energy caused by the renewable energy system, we simulate the system in Matlab-Simulink with simulation scenario and parameters. as follows:

4.1 Simulation Parameters and Scenarios

From Fig. 1, we assume that ignoring losses in normal working conditions, the active power provided by renewable energy is $P_{Ren} = P_{Grid}$, power fluctuation $\pm \Delta P_{Ren}$. In order to maintain the stable working state of the system, this power fluctuation will be overcome by FESS to maintain an almost unchanged power for the microgrid. The power variation of the FESS is calculated:

$$P_F = \pm DP_{Ren} \tag{27}$$

P_F is used as the reference signal that controls the operation of the FESS.

The simulation parameters are listed in Table 2.

Table 2. Simulation parameters

Parameter	: Value
Power of the electric machine P_m (kW)	: 50
No. of Poles	: 2
Stator Resistance (Ω)	: 0,05
Rotor Resistance (Ω)	: 0,043
Stator Inductance (H)	: 40,7.10–3
Rotor Inductance (H)	: 40,1.10–3
mutual inductance of stator and rotor (H)	: 40.10^{-3}
Inertia moment of IM (kgm^2)	: 0.043
Inertia moment of FESS (kgm^2)	: 13
Simulation time (s)	: 10
$\lambda 1 = \lambda 2$	: 1,2
P_{Grid} (kW)	: 500
$\pm \Delta P_{Ren}$ (kW)	: ± 50

The simulation time is 10 s, corresponding to 3 working modes of FESS, in the first 3 s FESS works in charging mode, then in standby mode for 2 s, followed by discharge mode providing P_F to maintain P_{Grid} and finally the charging mode.

4.2 Simulation Results and Discussion

The simulation results are shown in the figures from Fig. 5, 6, 7 and Fig. 8, in which Fig. 5 shows the variation of machine speed with time. During the charging phase, the speed of FESS increases, remains constant in standby mode, and decreases gradually in discharging mode. Figure 6 shows that the variation of the FESS power always follows the reference trajectory, thus maintaining the P_{Grid} power almost unchanged (Fig. 7). Figure 8 shows the variation of the machine rotor flux compared with the reference flux, when the speed is higher than the base speed the machine is operating in flux-depleted mode.

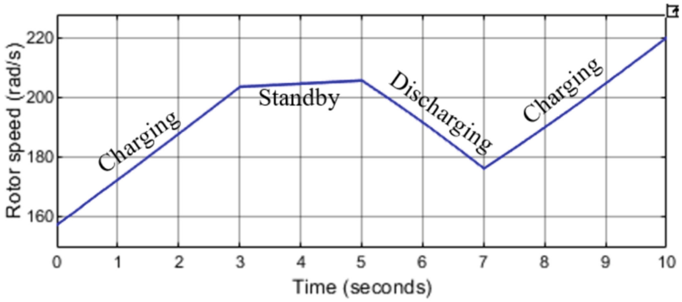

Fig. 5. Electric machine speed curve

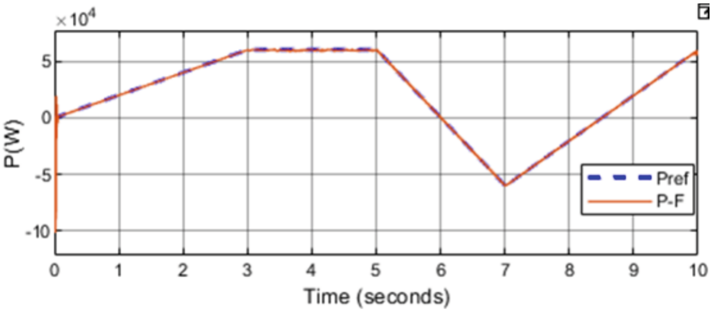

Fig. 6. FESS capacity during charge, standby and discharge times

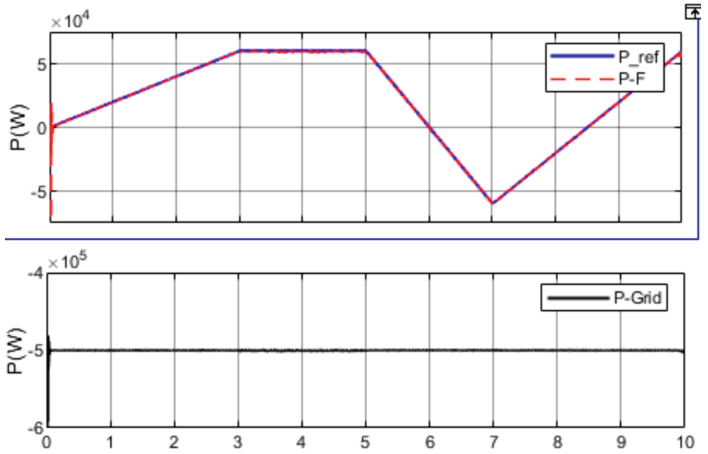

Fig. 7. Power response of FESS relative to the given signals

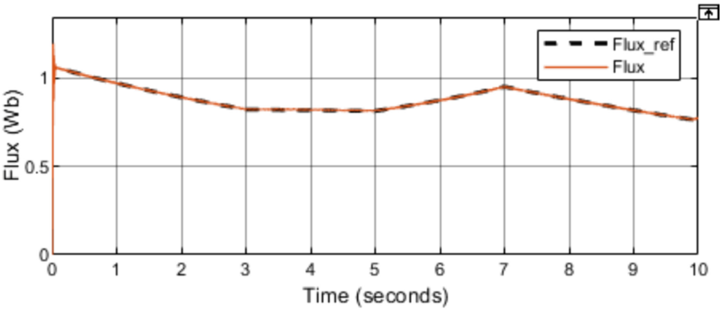

Fig. 8. Magnetic flux response of electric machine

5 Conclusion

The NEC-MPC control strategy is applied to the operational control of FESS in this paper. MPC allows choosing the optimal working mode of the converter through the objective function, the neural network with learning ability allows to design the controller without knowing the exact object model. The simulation results have shown the correctness and feasibility of the proposed solution.

The integration of FESS in the microgrid with renewable energy sources allows to overcome the random fluctuations of renewable energy, maintaining a stable capacity for the microgrid. This system can be used to balance energy supply - energy demand in renewable energy systems working independently or connected to the microgrid. Some issues that need further research are to build an experimental model to test and complete the proposed results; find a new algorithm to control the FESS system more efficiently.

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