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Shipboard Microgrids: A Novel Approach to Load Frequency Control

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***Abstract*—Due to the fast development of renewable energy systems and the severe limitations enforced by the Marine Pollution Protocol, the utilizing of wind turbines, solar generation, sea wave energy and energy storage systems in marine vessel power systems has been attracting a lot of attention. Hence, a marine vessel power system with Photovoltaic (PV), WT, SWE and ESS can be considered as a specific mobile islanded microgrid. Consequently, the main target of this paper is to design a new optimal Fractional Order Fuzzy PD+I Load Frequency Controller (LFC) for islanded microgrids in a ship power system. Since the performance of the controller depends on its parameters, the optimization of these coefficients can play a significant role in improving the output performance of the LFC control. Accordingly, a modified black hole optimization algorithm (MBHA) is utilized for the adaptive tuning of the coefficients of non-integer fuzzy PD+I controller. The performance of the shipboard microgrid is evaluated by utilizing real world wind power fluctuation and solar radiation data. Finally, the extensive studies and hardware-in-the-loop (HIL) simulations are applied to prove that the proposed controller can track the reference frequency with lower deviation as well as it is more robust in comparison with the prior-art controllers utilized in the case studies.**

***Index Terms*— Shipboard Microgrids, Load Frequency Control (LFC), Modified Black Hole Algorithm (MBHA), Fractional Controller, Sea Wave Energy (SWE).**

LIST OF ABBREVIATIONS

BESS	Battery Energy Storage System
BHA	Black Hole Algorithm
DG	Distributed Generation
DSPS	Diesel Ship Power System
ESS	Energy Storage System
FC	Fuel Cell
FESS	Flywheel Energy Storage System
FL	Fuzzy Logic
FOC	Fractional-Order Calculus
FOFPID	Fractional-Order Fuzzy PID
FOFPD+I	Fractional-Order Fuzzy PD+I
FPID	Fuzzy PID
HiL	Hardware-in-the-Loop
IAE	Integral of Absolute Error
IFS	Interactive Fuzzy Satisfying
ISDCO	Squared Deviation of Controller Output
ISE	Integral Square Error
ITSE	Integral of Time multiplied Squared Error
ITAE	Integral of Time multiplied Absolute Error
LFC	Load Frequency Control
MBHA	Modified Black Hole Algorithm
MG	MicroGrid
MOPI	Multi-Objective Proportional–Integral
MOFPI	Multi-Objective Fuzzy PI
MOIT2FPI	Multi-Objective interval type-2 fuzzy logic proportional–integral
MOMBHA	Multi-objective MBHA
MPC	Model Predictive Control
PID	Proportional–Integral–Derivative
PHEV	Plug-in Hybrid Electric Vehicle
PV	Photovoltaic
RES	Renewable Energy Source
RTS	Real Time Simulator
SDS	Ship Dispatch System
SG	Solar Generation
SPMS	Shipboard Power Management System
SWE	Sea Wave Energy
WEC	Wave Energy Converter
WT	Wind Turbine

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I. INTRODUCTION

In recent years, due to the decline of fossil fuel resources and their environmental impacts, wind turbine (WT), solar generation (SG) and sea wave energy (SWE) have been introduced into marine vessel power systems and has increasingly attracted attention. The utilization of such technologies offers a new way to decrease the environmental pollution, increase energy efficiency and improve vessel power system stability [1]. Conversely, a high penetration of wind, solar and sea wave energies can lead to a risk of frequency instability and an increment of unwanted power cost caused by the uncertainty of the wind and solar irradiation. Consequently, the application of energy storage systems (ESSs) is one of the best ways for safeguarding the power quality and the reliability of ship power systems [2].

Generally, a marine vessel power system with WT, photovoltaic (PV), SWE and ESS can be considered as a kind of specific mobile islanded microgrids (MGs). Accordingly, a wide range of researches [3]–[7] have been achieved concerning the utilization of the islanded MG in the marine vessel. For instance, in [3] for ship crane operations, a lithium-ion battery is used with diesel generations. Also, the advantage of environmental and economic characteristic of a hybrid diesel/PV system with an ESS is introduced in [4]. In [5] the

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optimal size of a hybrid diesel/ PV/battery vessel power system is analyzed. However, the impact of marine vehicle roll is not considered in this paper. The PV system is used in merchant ship to decrease the fuel cost in [6]. The stability analysis of hybrid diesel/PV/battery vessel power system is investigated in [7]. However, the load frequency control (LFC) is not considered in these studies. It is obvious that the LFC plays a significant role in MGs.

When considering autonomous MGs, both renewable energy sources (RESs) and ESSs need to be coordinated together to limit the frequency fluctuation by compensating the mismatch of generation and demand. This functionality is often referred to as LFC. The proper LFC can not only guarantee the frequency stability of the shipboard MG but can also increase its efficiency (e.g. fuel saving). In order to improve the response of the LFC, many controllers including conventional Proportional–Integral–Derivative (PID) control [8], intelligent control [9], adaptive control [10], robust control [11] and Model Predictive Control (MPC) [12] have been applied to the Distributed Generations (DGs) of islanded MGs. In [12], an MPC based coordinated control of the blade pitch angles of the WT and plug-in hybrid electric vehicle (PHEV) has been suggested for the LFC. In [10], a new technique is suggested for the LFC in MGs by using an intelligent Proportional–Integral (PI) controller for improving the robustness of the whole system. Furthermore, the integral square error (ISE) is applied for optimum tuning of PI's gains to enhance the performance of the suggested controller [11].

Since the operation conditions of the LFC widely change, the conventional PI controller tuned in nominal conditions, cannot act properly in other conditions. So, in order to solve this difficulty, the Fuzzy Logic (FL) which adjusts the control parameters according to operation condition is proposed in [13]. One drawback of the system is that its good performance is achieved for only some specific member functions. In [14], the application of robust H-infinity control in the LFC of an isolated MG is studied. The control method, which has been suggested in [14], is too complicated and it is not feasible to implement in the real world. As a result, the small signal analysis of an isolated MG in the presence of energy storage unit has been proposed in [15]. Besides, in order to increase the robustness of isolated MG, the hierarchical control is presented in [16]. Moreover, the reader can refer to [17]-[21] to study more about the LFC and the importance of the LFC in modern power systems.

To sum up, the main goal of this study is to present a new time-varying method by utilizing a modified optimization approach for the adaptive adjusting of the most common Fractional Order Fuzzy Proportional Derivative + Integral (FOFPD+I) controller for the LFC in Shipboard MGs. The FOFPD+I parameters are tuned automatically according to the online measurements, by using a Modified Black Hole Algorithm (MBHA). Unlike the classical tuning approaches, which are not suitable for providing a useful performance over a wide range of operation conditions, many advantages are offered by the proposed optimal tuning scheme for a shipboard MG frequency control with many DGs and RESs. Additionally, the suggested technique is significantly less complex in comparison to the above-mentioned techniques, which makes it attractive for practical applications. The simulation study is performed on a complex Shipboard MG, including different loads and RESs to demonstrate the effectiveness of the proposed control scheme; the superiority of the suggested controller over Multi-Objective Proportional–Integral (MOPI) [22], Multi-Objective Fuzzy Proportional–Integral (MOFPI) [23] and Multi-Objective Interval Type-2 Fuzzy Logic Proportional–Integral (MOIT2FPI) [24] controllers are demonstrated in Section VI. For investigating the performance and robustness of the proposed control system, experimental validation using Hardware-in-the-Loop (HiL) simulations are also given in this paper.

II. The Modeling of a Shipboard Microgrid

A. The model of an isolated shipboard microgrid

Fig. 1 represents an isolated Shipboard MG in which DGs such as PVs, SWEs, WTs and energy storage units like Battery Energy Storage System (BESS) and Flywheel Energy Storage System (FESS) supply the distributed loads [25].

The ship power grid and the MG operation are controlled by the shipboard power management system (SPMS) and the ship dispatch system (SDS), respectively. Also, bidirectional information transfer can be achieved by communication links [1].

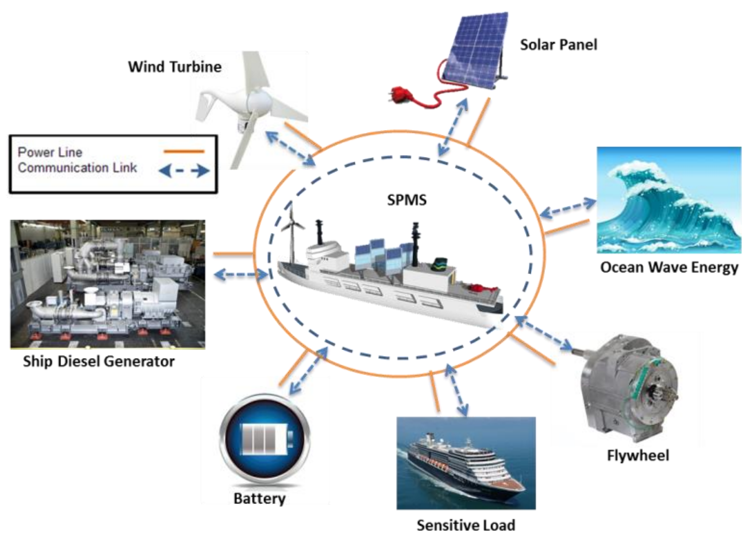

Fig. 1. general scheme of a Shipboard microgrid.

B. Wind Turbine Model

Generally, the wind speed can directly affect the WT generated power. According to the [26], the wind speed is assumed to be the algebraic sum of base ramp wind speed (V_{WR} m/s), wind speed (V_{WB} m/s), noise wind speed (V_{WN} m/s) and gust wind speed (V_{WG} m/s) [26]. Thus, the speed of wind for the WT can be expressed as

$$V_W = V_{WB} + V_{WG} + V_{WR} + V_{WN} \quad (1)$$

Now, the power can be generated by a wind turbine can be represented as

$$P = \frac{1}{2}\rho_A A C_P {V_w}^3 \quad (2)$$

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where the turbine blade area is A (m^2);ρ_A $(\mathrm{kg/m}^3)$, C_P and V are the air density, the power coefficient and the wind speed, respectively. The wind turbine model, which has been applied in this study, is shown in Fig. 2.

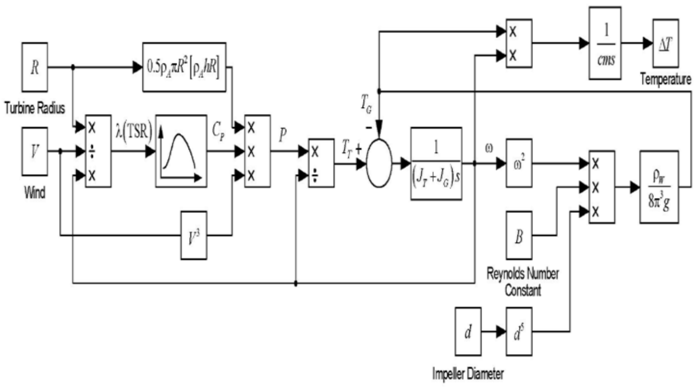

Fig. 2. The WT model in a shipboard MG [26].

The [26]-[27] have been provided to study how the Wind Turbine is formulated and modeled in this paper.

C. The Diesel Ship Power System Model

Due to the advantages of the diesel ship power system (DSPS) (e.g. fast starting speed, low maintenance and high efficiency), such system has been a good backup option in isolated shipboard MGs. The controllable DG can track the load demand with a fast and good response [9]. The fluctuation of uncontrollable DGs such as WT, PV and loads can effectively be compensated by the DSPS.

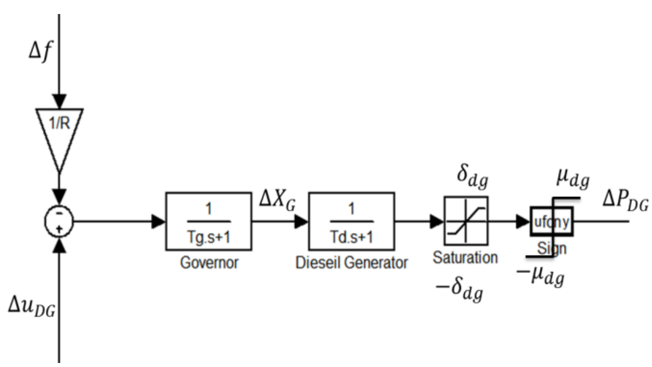

Fig. 3. Diesel Power System Model

Fig. 3 shows the block diagram of the DSPS, which represents the relation between the LFC signal and the output power of DG. As shown in Fig. 3, the model consists of first order inertia models of the governor and diesel generator and two saturation blocks.

In Fig. 3, Δf and Δu_{DG} represent the frequency deviation and the LFC command signal from the DG, respectively. T_g and T_d denote the time constant of governor and the diesel generator, respectively. ΔX_G shows the condition of governor's valve. The speed regulation coefficient of the DG is shown by R in Fig. 3. Also, $\pm\mu_{dg}$ and $\pm\delta_{dg}$ represent the power increment and the ramp rate limits. The output power increment of the diesel power system is illustrated by ΔP_{DG}. $\Delta P_{DG} = 0$ means that the demand and the generation are in a balance condition and there is no need for changing the power. $\Delta P_{DG} > 0$ means that the required power is higher than the actual power while $\Delta P_{DG} < 0$ represents the condition that the actual power is less than the demand [9].

D. Model of Sea Wave Energy

It is obvious that the wave energy in oceans can be considered as a RES, which is not yet fully exploited. The machine/system that turns the ocean wave energy to electricity is called a Wave Energy Converter (WEC). In this study, the WEC is considered as a renewable energy source for shipboard MGs. The transfer function of WECs is assumed to be a simple linear first order lag model by neglecting all the nonlinearities [28]-[30]. The WEC model, which has been considered in this study, is presented in Fig. 4.

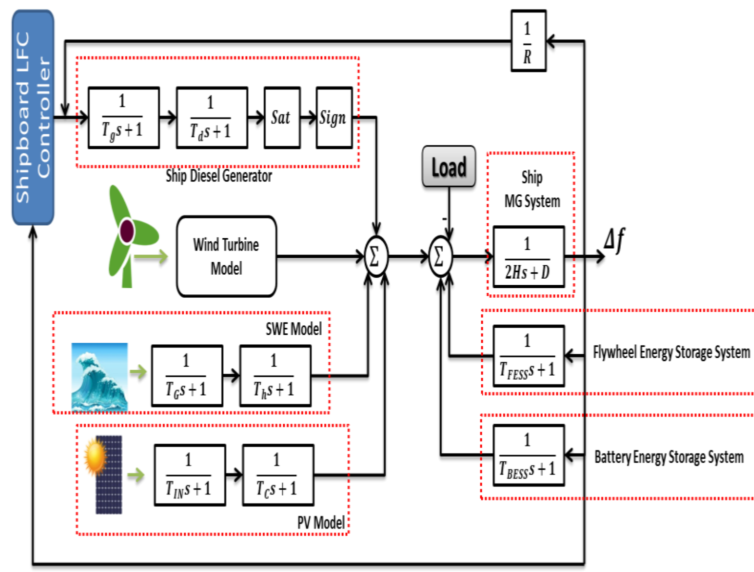

Fig. 4. The overall shipboard microgrid scheme including WT, PV and SWE for LFC.

E. Photovoltaic Generation

PV cells, which are made from semiconductor materials, can directly convert the energy of photons into electrical energy. Due to the boundary and external contact, which are represented by series resistor, and also small leakage current, which is represented by parallel resistance, the power loss is also modeled. The generated power of the PV is intermittent and depends on the sun irradiance and temperature; hence, a random power source can model the behavior of PV [10], [11]. The PV model, which is considered as disturbance for the LFC in the shipboard MG, is depicted in Fig. 4.

F. The general scheme of shipboard MG with LFC controller

The framework of the proposed LFC and an isolated shipboard MG, which consists of DGs such as PV, WECs, WT and diesel ship generator, energy storage units like BESS and FESS and loads is depicted in Fig. 5. As shown in Fig. 5, the PV, Fuel Cell (FC), BESS and FESS units are connected to the AC MG via DC/AC interfacing inverters. The FC is modeled by a third order transfer function [10], [14]-[15]. All small

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scale DGs and energy storage units are connected to the AC bus via a circuit breaker. The spinning reserve for the secondary frequency control is provided by diesel ship power system.

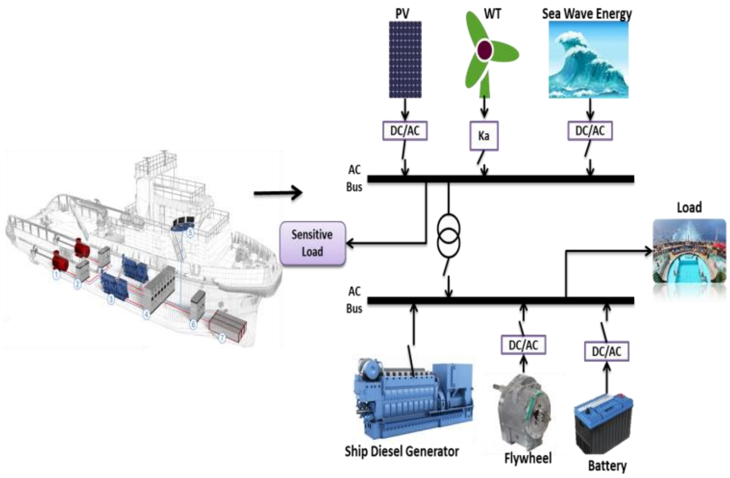

Fig. 5. The case study for the LFC in a shipboard MG system.

The parameters of the shipboard MG system, which is depicted in Fig. 4, are listed in Table. I.

Table I: Shipboard MG power system's parameters

Symbol and Abbreviation	Values	Symbol and Abbreviation	Values
T_g	2 s	T_c	0.5 s
T_d	1 s	Turbine radius, R	0.5 m
R	3 (pu MW/second)	Turbine height, h	2 m
δ_{dg}	0.01 (pu MW/second)	Maximum of power coefficient, C_p	0.195
μ_{dg}	0.025 (pu MW)	Optimum STR, λ_E	0.53
T_G	0.5 s	Turbine inertia, J_τ	1.97 Km m^2
T_h	4 s	Air density, ρ_A	1.225 Km/m^3
D	0.012 (pu/Hz)	Water density, ρ_W	1000 Km/m^3
2H	0.2 (pu s)	Water specific heat, C	4180 J/Km C
T_{FESS}	0.1 s	Reynolds number constant, B	5
T_{BESS}	0.1 s	Heat generator inertia, JG	1.53 Km m^2
T_{In}	4 s	Impeller diameter, d	0628 m
Mass of liquid in the tank, m	200 Kg	"s" means Second	

III. Fractional Order Fuzzy PD+I Controller

A. *Fractional-order calculus (FOC) in Control Systems*

Fractional calculus is one of the most important branches of calculus in which the power of the differential and integration operators can take a non–integer value. During the last few decades, the FOC has been made possible to apply in many fields of automatic control systems [31]. Fractional Calculus-Based Control Systems can be illustrated by $\alpha D_t^r f_x(t)$ where $r \in \mathcal{R}$ is the order of operation and t *and* a, respectively, are the limits [32]. There exists a large number of definitions, such as Grünwald–Letnikov, Cauchy integral formula and Riemann–Liouville, which are applied to define the FOC. However, in automatic control systems, the Cauchy integral formula is frequently applied for realizing the fractional-order differentiations and integrations of the FO-Fuzzy-PID (FOFPID) controller [33].

$$0D_t^r f_x(t) = \frac{1}{\Gamma(m-r)} \int_0^t \frac{D^m f_x(t)}{(t-\tau)^{r+1-m}} d\tau, r \in \mathcal{R}^+,\ m \in Z^+ \quad and \quad m-1 \le r < m \tag{3}$$

B. *Design of fractional order proportional integral-derivative (FOPID) controller*

The main advantage of the FOFPD+I controller, which has been used in this study, is that it encompasses the benefits of the combination of fuzzy logic with PID controller which is comprehensively discussed in [31]. In the proposed method, K_d and K_e are considered as the fuzzy logic input and, K_{PI} and K_{PD} as fuzzy logic outputs. The advantages of this kind of FOFPD+I structure over the Model Predictive Control (MPC) and the conventional PID are presented in [34]. In the original FPID controller, the power of the input error derivative is an integer. In this study, in contrast, this power is fractional-order (δ). Moreover, the order of the integral in the output is changed by the fractional order counterpart (μ). The general scheme of the proposed method is shown in Fig. 6.

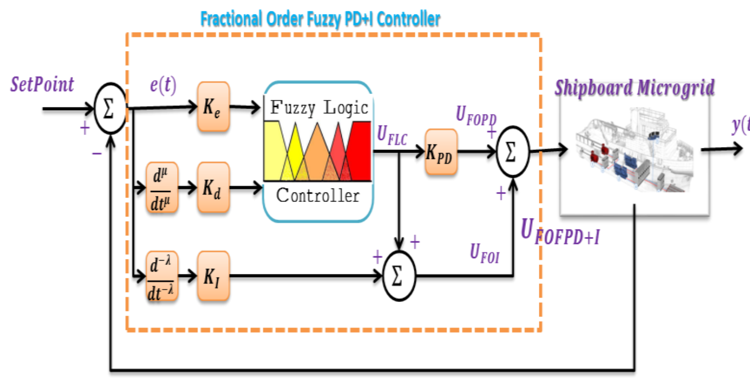

Fig. 6. The general scheme of Fractional-order Fuzzy PD+I (FOFPD+I) controller.

By considering the general scheme of Fig. 6, the control law can be written as:

$$U_{FOFPD+I} = U_{FOPD} + U_{FOI}\ . \tag{4}$$

The other conventional controllers such as the integer PID and the Fuzzy PID can be obtained by considering the values of λ and δ being equal to one. Table II displays the set of optimal FOFPID rules. The fuzzy linguistic variables, which are similar to the input and output variables, are assumed as (NS), (NM), (NL), (ZR), (PS), (PM), and (PL) that they refer to Negative Small, Negative Medium, Negative Large, Zero, Positive Small, Positive Medium and Positive Large. They have been collocated based on triangular MF(s). Furthermore, the former parts of each rule will be made by using AND function (with hermeneutics of minimum). Additionally, the Mamdani fuzzy inference engine is also applied in this study [35].

Table II: The MOFOFPD+I controller Rules Set

$\dot{e}$ \ e	NL	NM	NS	PS	PM	PL
S	NL	NM	NS	PS	PS	PM
M	NL	NL	NM	PS	PM	PM
L	NL	NL	NL	PM	PM	PM

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In fuzzy control systems, changing the scaling factors of the fuzzy output has more positive influence on the performance of the FOFPD+I controller than alterations in the form of the MF(s). As a result, the tuning of all coefficients in the FOFPD+I cannot be equally effective in affecting the total performance of the control system. The main idea of this study is to explore the result of tuning fractional-orders (δ and λ) since keeping the rules set and the form of MFs unaltered to increase the total closed loop performance of the FOFPD+I controller. Consequently, this technique can be more effective in decreasing the volume of calculations, as well as the output of the FOFPD+I controller can be extremely influenced by tuning fractional-orders instead of tuning the MF(s) variables or other fuzzy inferencing parameters. So, the next section presents a new modified multi-objective optimization algorithm to tune the parameters of the proposed controller.

IV. Overview of the Original Black Hole Algorithm (BHA)

The BHA is inspired from the intelligent collective behavior of stars around a black hole. The movement characteristic of the stars can be expressed as [36]-[37]:

$$X_{m,\ new}^{iter} = X_{m}^{iter} + rand(.)(Best^{iter} - X_{m}^{iter}); \quad m = 1,\dots,N_{Pop} \qquad (5)$$

where X_{m}^{iter} and $X_{m,\ new}^{iter}$ represent the position of target and the updated agent in iteration *iter*, respectively. A comprehensive introduction with details of this algorithm is presented in [36].

- *MBHA Mechanism [37]:*

A novel method has been suggested for the collapsing process; hence, the exploration properties of BHA will be enhanced. At the first step, the updating mechanism of BHA will be enhanced by (6):

$$X_{m,\ new}^{iter} = X_{m}^{iter} + rand_1(.)(Best^{iter} - X_{m}^{iter}) + rand_2(.)(X_{r}^{iter} - X_{m}^{iter}) \qquad (6)$$

where r (r ≠ m) is chosen randomly in the range of [1, N_{Pop}]. At the second step, the modification of the event horizon of the BH (R^{iter}) based on distribution and collection of stars should be done using (7) and (8) [37].

$$R_{m,\ Mean}^{iter} = \left\| X_{m,\ new}^{iter} - Mean^{iter} \right\|; \quad m = 1,\dots,N_{Pop} \qquad (7)$$

$$R^{iter} = 0.1 \times \sum_{m=1}^{N_{Pop}} \frac{R_{m,\ Mean}^{iter}}{N_{Pop}} \qquad (8)$$

It should be mentioned that a new concept of Absorption Capacity (AC) has been proposed for BH. The elimination of hyper dispersion of solutions and controlling the number of stars, which are located in event horizon, is achieved in this method. In BHA, after collapsing a star in BH, a new star is born randomly. The optimum usage of data obtained by members of the population is achieved by a new formulation expressed in (9) [37].

$$X_{m,\ new}^{iter} = Best^{iter} + \frac{\max_{m} R_{m,\ Best}^{iter}}{N}.(2 \times rand(1,N) - 1) \qquad (9)$$

$$R_{m,\ Best}^{iter} = \left\| X_{m,\ new}^{iter} - Best^{iter} \right\|; \quad m = 1,\dots,N_{Pop} \qquad (10)$$

The implementation process of modified optimization algorithm

```
For all X_m do
Modify each candidate m using (6)
Compute Cost Function
End for
Compute the R^iter_{m,Mean} using (7)
Compute the R^iter_{m,Best} using (10)
For the whole of X^iter_{m,new} and X^iter_m do
If F(X^iter_{m,new}) < F(X^iter_m) do
X^iter_m ← X^iter_{m,new} and F(X^iter_m) ← F(X^iter_{m,new})
End if
End for
Compute R^iter_{m,Sort} = sort(R^iter_{m,Best}); m = 1, ..., N_Pop
For all X_m which m ≤ ac do
If R^iter_{m,Sort} < R^iter do
Generate a new solution using (9) and sub it with the old one
End if
End for
```

Fig.7. The pseudo-code of the modified algorithm.

The pseudo-code of the modified optimization algorithm is illustrated in Fig. 7.

V. Multi-objective Interactive Fuzzy Satisfying (IFS) Method

The value and the number of control signals are some of the most important factors for a designer to consider in the hardware application. In other words, in an application with large values of control signal, a big size actuator is required as well as the total cost of the system will be increased. Consequently, effective control of a system requires a smooth control that can track the set point fast. Using the multi-objective optimization approaches can overcome the complexity in optimal control problem. Weighting the cost function of the optimum problem with some index such as Squared Deviation of Controller Output (ISDCO), Integral of Absolute Error (IAE), Integral of Time multiplied Squared Error (ITSE) and Integral of Time Multiplied Absolute Error (ITAE) can prevent a high control signal. It should be mentioned that the aforementioned objectives (IAE, ISDCO, ITSE and ITAE) can act in contrast to each other in the control problems. As a consequence, formulating the control system as a multi-objective stochastic optimization problem can lead to reduce the value of the control effort.

Using the shipboard MG system can inherently emulate some of the uncertainties in the operation of MGs such as DG output variations, storage batteries to the control system; hence, using integer and non-integer controller can be a good choice for the system in which the operating point changing in a wide range. For solving the problem, in this paper a new online multi-objective optimization method for the optimum tuning of the common FOFPD+I controller is proposed. In this method, the Multi-objective MBHA (MOMBHA) is applied for the optimum tuning of the FOFPD+I controller by using the online measurement. The MOMBHA problem can be formulated by (10).

$$\begin{aligned} &Min\ F(X) = [f_1(X), f_2(X), f_3(X), \dots, f_n(X)]^T \\ &s.t \\ &h(X) < 0 \\ &g(X) = 0 \end{aligned} \qquad (11)$$

Here, an IFS approach is used for resolving the above multi-objective problem [32]. In this method, the sufficient degree of each objective can be defined by the operator. Generally speaking, the non-inferior solution set in the most optimal solution would be chosen in such a way the preferences of operators are satisfied:

$$F(X) = \min_{x\in\Omega}\left\{\max_{w\in W}\left|\mu_w^{ref}(X) - \mu_w^{f}(X)\right|\right\} \quad (12)$$

where μ^{ref} is the satisfying degree of the related target, which is determined by the operator in the range [0, 1]. In addition, μ_w^f denotes the MF value of w^{th} objective and is designed by trapezoidal fuzzy membership as given below:

$$\mu_w^f(X) = \begin{cases} 1 & for\ f_w(X) \ll f_w^{min} \\ \frac{f_w^{max} - f_w(X)}{f_w^{max} - f_w^{min}} & for\ f_w^{min} \ll f_w(X) \ll f_w^{max} \\ 0 & for\ f_w(X) \gg f_w^{max} \end{cases} \quad (13)$$

It should be noted that in the heuristic algorithm such as MBHA only information about the fitness function is required. As a consequence, in order to online tune the FOFPD+I controller's parameters, the objective functions vector that should be minimized in the Interactive Fuzzy Satisfying Method is proposed as given in the following equation:

$$Min\ F(X) = [f_1(X), f_2(X)]^T \qquad where$$

$$f_1 = ITSE_{Set-Point} = \int_0^\infty t e_{set-point}^2(t).dt \quad (14)$$

$$f_2 = ISDCO = \int_0^\infty \Delta u^2(t).dt \quad (15)$$

it is worth mentioning that in the above equation, the first objective function is used for providing fast tracking of desired set-point, while the accuracy of the tracking of the set point is achieved by a second objective function. Next section, the overall scheme of the hybrid Fractional-order controller, Fuzzy logic and optimization algorithm will be discussed for implementing in the shipboard MG.

VI. The Overall Scheme of The Proposed Approach For The LFC in The Shipboard MG

It is obvious that the choice of the proposed non-integer controller coefficients can play a significant role in improving the efficiency and performance of the LFC in the shipboard MG. As aforementioned, in order to achieve a desirable performance of the controller, a modified stochastic optimization algorithm is utilized in this paper to tune the parameters of the FOFPD+I controller. According to (14) and (15), the two contradictory fitness functions (ISDCO and ITSE) have been adopted to find the best value of the proposed controller parameters. In order to have a rapid tracking of the desired set-point, the first objective function, ITSE, is applied, while the second objective function is used to decrease the error in the control signal. Additionally, by considering the fact that alteration in the scaling factors of the FOFPD+I has better influence on the controller performance over variations in the form of the membership functions, the proposed non-integer controller parameters have been optimally tuned by the MOMBHA. Finally, the schematic of the online tuning of the FOFPD+I controller based on the MOMBHA technique is depicted in Fig. 8.

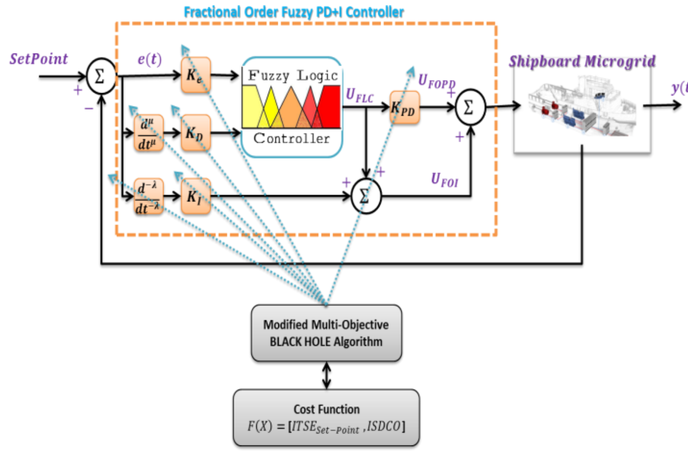

Fig. 8. The general scheme of the suggested controller for LFC

As shown in Fig.8, the proposed controller parameters ($K_p, K_d, K_i, K_{PD}, \delta$ and λ) are optimally tuned by the modified optimization algorithm. Finally, for implementing the suggested heuristic population based algorithm on the proposed non-integer controller, the pseudo-code of the MOMBHA was done as depicted in Fig. 7.

VII. Simulation Results

In this section, for verification of the control method, a shipboard MG, which is depicted in Fig. 4, is simulated in MATLAB/Simulink software. The parameters of the isolated shipboard microgrid are listed in Table I. The performance of the suggested controller is compared with those of the MOPI, the MOFPI and the MOIT2FPI controllers. Since the response of the system depends on the parameters of these controllers, all of the parameters are optimized by the MOMBHA optimization algorithm to the different controllers. In order to evaluate the performance of the proposed control method in the context of the shipboard MG as depicted in Fig. 4, the Hardware-In-the Loop (HIL) simulation approach is utilized. The real time HIL method is used to emulate errors and delays that do not exist in the classical off-line simulations and to ensure that the proposed controller can be running in real-time without overruns.

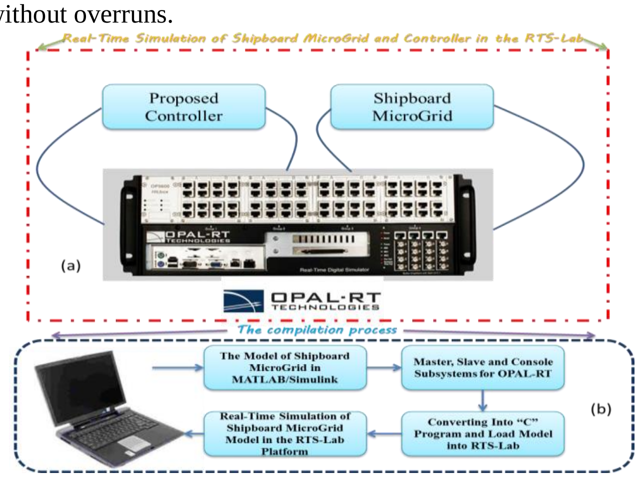

Fig.9.The real time experimental setup. a) the real-time simulation of shipboard MG and controller in the RTS-LB b) the compilation process

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Fig. 9 illustrates the schematic diagram of the HIL setup, which consists of: 1) OPAL-RT as a Real Time Simulator (RTS), which simulates the MG depicted in Fig. 4; 2) a PC as command station (programming host) in which the Matlab/Simulink based code that will be executed on the OPAL-RT is generated; 3) a router that is used as a connector of all the setup devices in the same sub-network. The OPAL-RT is also connected to the DK60 board through Ethernet ports. More details about the components of this setup can be found in [38], [39]. The model-to-data workflow of the proposed method under test is shown in Fig. 9b.

A. *Case A*

At the first step, it is assumed that the load demand in the isolated shipboard MG is constant i.e., $\Delta P_L = 0$. In other words, the power fluctuations of the WT (ΔP_w), SWE (ΔP_{SWE}) and PV (ΔP_{pv}) are considered in the LFC system. The wind power fluctuation data, which is extracted from an offshore wind farm in Sweden [40] is depicted in Fig. 10a, while Fig. 10b shows the solar radiation data in Aberdeen (United Kingdom) [41], which is used in this case study. Furthermore, the sea wave energy fluctuation is presented in Fig. 10c and the SWE data has been applied from the National Oceanographic Data Center [42]. Fig. 11 shows the frequency response of the simulated shipboard MG system.

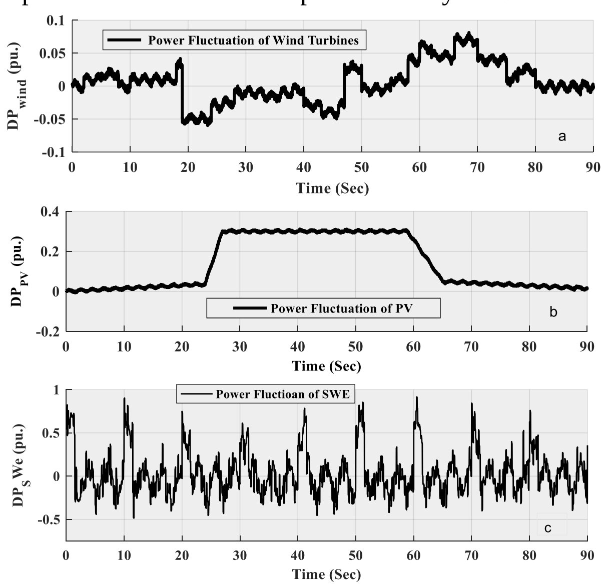

Fig. 10. Power fluctuations, a- WPG, b- PV, c- SWE.

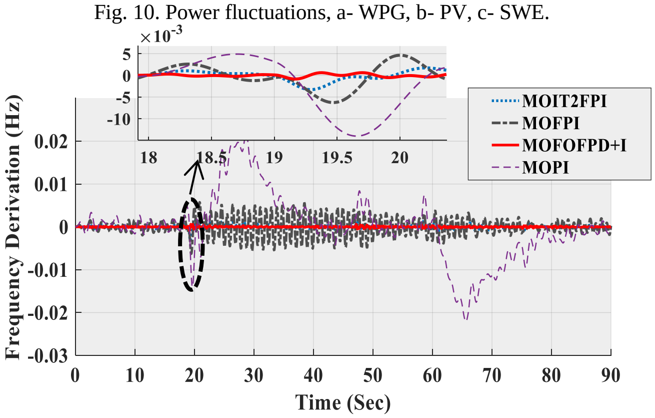

Fig. 11. Frequency response according to the power fluctuation of WPG, SWE and PV

As shown in Fig. 11, the peak value of the frequency deviation is decreased and the damping of the deviation is achieved faster in comparison to the MOPI, MOFPI and MOIT2FPI controllers. As a result, since a stable output frequency adjustment of the MG is achieved faster and with less fluctuation using the MOFOFPD+I, the equipment life of the batteries and the DG will be increased. Consequently, the simulation results in this case show that the LFC can track the reference frequency with less overshoot and much smaller settling time using the MOFOFPD+I controller compared to the three other controllers.

B. *Case B*

In this scenario, multi-step load variation is applied to the LFC as a disturbance. The load steps are depicted in Fig. 12, while the frequency deviation responds of the MOPI, MOFPI, MOIT2FPI and the MOFOFPD+I controls are depicted in Fig. 13.

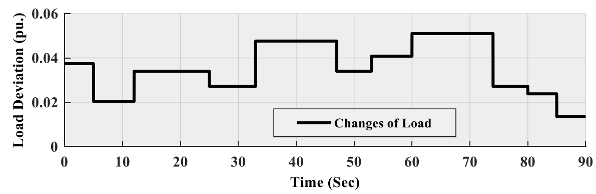

Fig. 12. Step changes of the load in the time interval of 90 seconds.

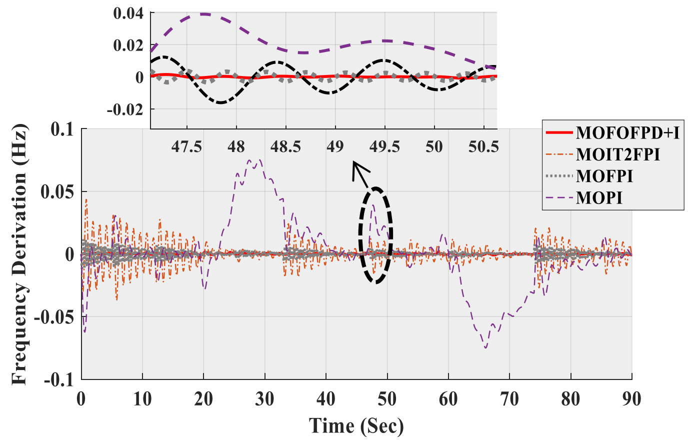

Fig. 13. Frequency response according to the power fluctuation of WPG, SWE, PV and load disturbances.

As displayed in Fig. 13, the frequency deviation overshoot is decreased and the LFC control can eliminate the effect of the load disturbance more effectively by using the proposed method than other approaches. The performance of the controllers are examined by applying a big load step as a severe condition at t=60s in the simulation. According to Fig. 13, the performance of the LFC in eliminating the load disturbance can be improved by using the proposed controller; especially as shown in Fig. 13, the settling time of the frequency response is decreased significantly.

C. *Case C*

For robustness evaluation of the proposed controller, some parameters of the isolated shipboard MG are changed in case study. The changing of the parameters is made in one scenario, which is displayed in Table III.

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Table III. Uncertain parameters of the MG system

Parameters	Variation Range
R	**+25%**
D	**-15%**
H	**+45%**
T_e	**-35%**
T_g	**+15%**
T_{FESS}	**-15%**
T_{BESS}	**+25%**

As shown in Table III, a severe change of the parameters is applied to evaluate the robustness of the proposed control method. Fig. 14 depicts the response of the LFC in the scenario by using the proposed, MOPI, MOFPI and MOIT2FPI controllers.

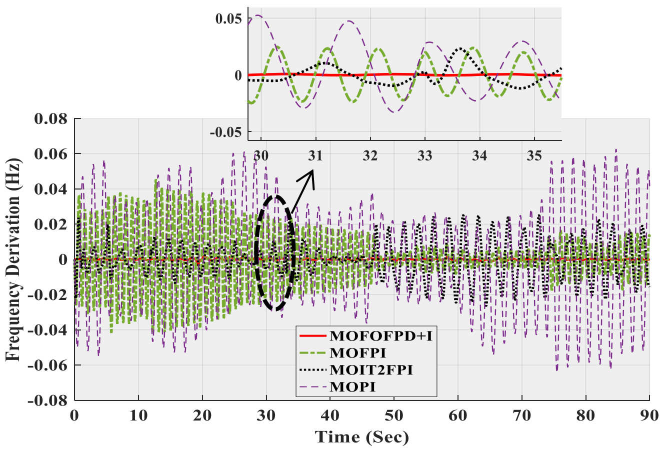

Fig. 14. The frequency deviation of the shipboard MG according to case 3.

As revealed in Fig. 14, the proposed controller enhances the performance of the LFC compared to the other three control methods, especially from a overshoot point of view. In other words, the results show that the proposed controller is more robust against the changes of the parameters compared to the other controllers. It is also revealed that the performance of the MOPI, MOFPI and MOIT2FPI controllers in this scenario with severe changes of the parameters is not acceptable.

VIII. The Advantages of The Proposed Approach

The goal of this study is to develop a hybrid non-integer fuzzy PD+I controller for the shipboard microgrid systems. In the design of the proposed method, considerations have been made that have a prominent role in its practical implementation:

1. The suggested new optimal hybrid non-integer control method is easy to implement and can be utilized to a reasonably wide class of microgrids.
2. The suggested approach is able to be applied in different configurations of the microgrid, with different loads, renewable sources and grid topologies.
3. The proposed control signals are based only on the available plant input/output information and can be calculated on-line.
4. Another advantage of the suggested control technique is its light burden in terms of computations, which is an important feature in a practical implementation and for online control cases.
5. At the end, to examine the effectiveness and robustness of the proposed framework, several simulations in various MG operation conditions were carried out. By using the real-data, the performance of the proposed new non-integer controller is investigated.

IX. Conclusion

In this study, a new adaptive and time-varying controller was presented for LFC of an isolated shipboard microgrid. A stochastic multi-objective optimization algorithm is used for optimization of parameters of the controller to track the reference frequency in the presence of PV, SWE, WT and load disturbances. The controller consists of two levels named as Fractional-Order Fuzzy and a conventional PD+I controller in order to enhance the robustness of the controller against uncertainties in the shipboard MG. Since the performance of the fuzzy systems depends on their membership functions, the membership function parameters are optimized by using modified/improved of MOBHA optimization algorithm. This novel approach enhances the performance of the LFC with low computational burden and complexity. In this brief, both load disturbance and the output power of DG units are considered as power disturbance ΔP in the model of shipboard MG; hence, the control approach can be adaptive at different loads, renewable energy sources and typologies of a shipboard MG. In order to validate the performance and robustness of the controller, Hardware in the Loop (HiL) simulations are utilized in this study. Furthermore, the performance of the controller is compared with MOPI, MOFPI and MOIT2FPI controllers, which are the recent state in the LFC.

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