



Tidal Energy Integrated Robust Frequency Control of an Islanded AC Microgrid with Improved-MFO Tuned Tilt Controller

Debashish Mishra, Prakash Chandra Sahu, Ramesh Chandra Prusty,

Abstract: In recent electrical energy scenario different renewable energy based distribution generation (DG) systems have been developed to provide electrical power to distant and remote consumers. In view of this current research article presents a Tidal Power Plant (TPP) and its integration with an Islanded AC Microgrid system. The tidal energy based TPP is modelled to generate required electrical power. However the inherent dynamic behaviour of TPP largely affects the microgrid system frequency especially in islanded mode of operation. In regard to this to obtain necessary control mechanism in an islanded AC microgrid system, present research article proposes a tilt multistage TDF/(1+TI) controller and to show effectiveness of proposed tilt controller for microgrid control it has been compared with multistage PDF/1+PI and PID controllers. To obtain optimal gain parameters of above implemented controllers an Improved- Moth Flame Optimization (I-MFO) technique has been proposed for this study. To justify viability of proposed I-MFO algorithm its performances have been compared with original MFO algorithm. Finally it has been noticed that to obtain robust frequency control in an islanded AC microgrid system, proposed I-MFO optimized tilt multistage controller exhibits outstanding performance under wind, solar and tidal energy uncertainties.

Index Terms: Distribution Generation (DG); Microgrid; Tidal Power Plant (TPP); Tilt multistage TDF/1+TI Controller; Improved-Moth Flame Optimization (I-MFO) algorithm; Integral of Time multiplied Absolute Error

I. INTRODUCTION

In power generation point of view, the power system basically depends on conventional energy sources and renewable energy sources (RES). Conventional energy sources (coal, water, nuclear etc.) have been focused as primary energy source for generation of electrical power since few decades. However, limited stock and scarcity of different conventional energy sources motivate power engineers for renewable energy sources as alternative for generation of

electrical power. In this regard research has been focused on different renewable energy sources i.e. wind, solar, tidal, biomass, fuel cells etc. The low capacity based small grids are referred as microgrid[1-4]. Microgrid comprises different distributed generations (DG) where all DG systems are integrated with proper control mechanism. In view of this distributed generations like Wind Turbine Generator (WTG), Photo Voltaic Cell (PV Cell), Micro-turbine (MT), Fuel Cells (FC), Tidal Power Plant (TPP), Diesel Engine Generator (DEG) etc. have been integrated with common microgrid [5-6]. In operational point of view microgrid may be categorized as grid connected mode and off-grid (island) mode [7-8]. Microgrid in grid connected mode does not undergo any frequency deviation under any uncertainty arisen in the system as presence of utility grid strongly supports system frequency to maintain steady and stable. However microgrid in islanded mode of operation faces huge frequency control problem under any uncertainty that has been arisen in the system. It has been remarked through different research articles that most of uncertainties have been occurred in the system with WTG, PV and Tidal Power Plant [9-10]. To improve reliability and power quality of microgrid system, verities of energy storage equipments (ESE) have been interpreted with microgrid system [11].

In response to microgrid control aspects, numerous controllers have been implementing as secondary frequency control loop for islanded AC microgrid system. In view of this controllers like conventional PID controller, Fuzzy controller, adaptive neuro-fuzzy controller etc. have been successfully implemented for frequency control of an islanded AC microgrid system under unpredictable generation uncertainties. In this regard Bevrani et. al. have been proposed fuzzy controller for an islanded AC microgrid control especially frequency and voltage control [12]. To monitor frequency and power of an islanded AC microgrid system P.C.Sahu et.al. have been proposed fuzzy controller as secondary control loop of the system [13]. To optimal design various proposed controllers, researchers have been implementing different optimization tools to fine tune the gain values of proposed controllers. In this regard I Pan et.al. proposed jaya algorithm to optimize gain parameters of fuzzy controller for frequency control of an islanded AC Microgrid system [14]. Khadenga et.al. proposed hybridized pattern search algorithm for optimizing gain values of multi-stage controller for frequency control of an islanded AC microgrid system [15].

Revised Manuscript Received on November 30, 2019.

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Apart from TPP, few additional DG systems like WTG, PV etc. have been integrated with the microgrid system [16-18].

1.1 Contribution

The research article highlights on modeling of a Tidal Power Plant and robust frequency control of Tidal Power Plant based off-grid (Islanded) AC microgrid system under load, wind, solar and Tidal energy uncertainties which holds following steps.

- A tidal energy based Tidal Power Plant has been modelled to generate required electrical power for supplying to an AC microgrid system.
- The microgrid is configured with some distribution generations (DG) like Diesel Engine Generator (DEG), Micro Turbine (MT), Photo Voltaic Cell (PV), Wind turbine Generator (WTG) and Fuel Cell (FC) along with Tidal Power Plant (TPP). To provide continuous power supply few energy storage devices (ESD) i.e. Battery Energy Storage system (BESS) and Flywheel energy storage (FES) have been penetrated with microgrid.
- In regard to robust frequency control of Islanded AC microgrid system under wind, PV and tidal energy uncertainties, the article has proposed a multistage tilt TDF/(1+TI) controller as secondary frequency control loop and to obtain optimal gain parameter of proposed

controller, an Improved- Moth Flame Optimization (I-MFO) technique has been proposed for this study.

- To show effectiveness of proposed multistage tilt TDF/(1+TI) controller for robust frequency control, its performance has been compared with general PDF/(1+PI) and PID controllers and in technique level the performance of proposed I-MFO technique has been compared with original MFO algorithm to justify viability of proposed technique. The robust performance of proposed tilt controller has been carried out with wide variation of system parametric conditions.
- Finally, it has been noticed that for robust frequency control of an islanded AC microgrid, proposed I-MFO optimized multistage tilt TDF/(1+TI)controller holds superior performance over other approaches for this study.

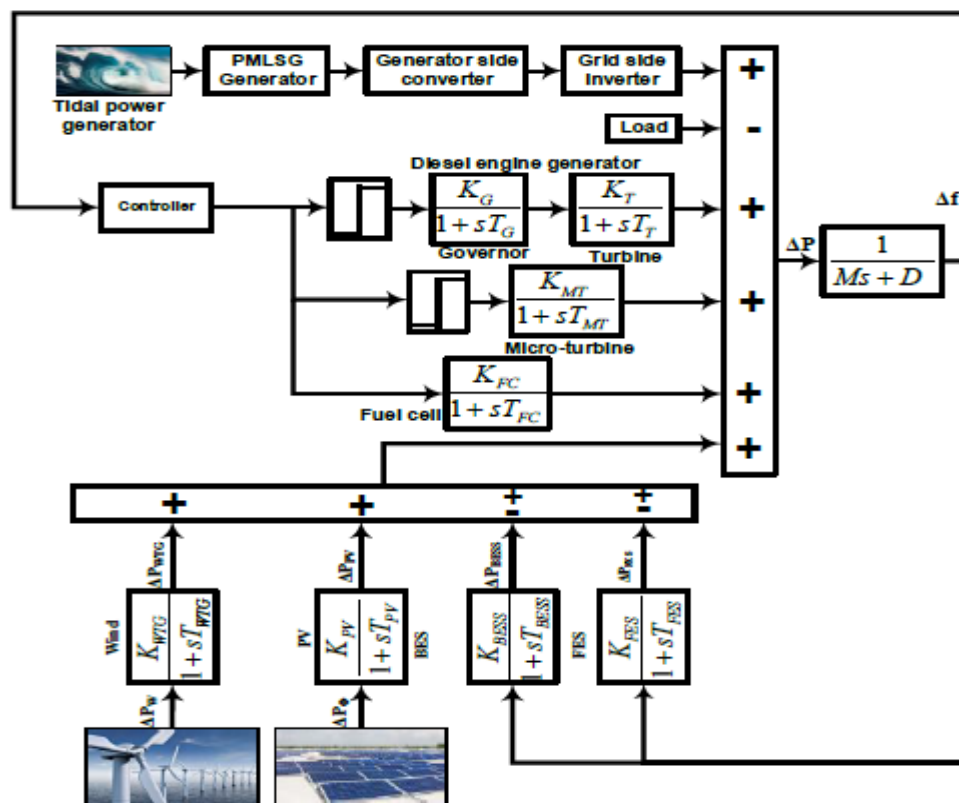


Fig. 1 Transfer function model of proposed AC microgrid system

II. SYSTEM MODELLING

In this research study the proposed off-grid (island) AC microgrid system comprises RES based different distribution generations i.e. Wind Turbine Generator (WTG), Photo Voltaic Cell (PV Cell) and Tidal Power Plant (TPP) along with other conventional micro sources like Diesel Engine

Generator (DEG), Micro-turbine (MT) and Fuel Cells (FC). However, to improve power quality and response time of system under sudden load deviation verities of energy storage equipments (ESE) like Battery Energy Storage

System (BESS) and Flywheel Energy Storage (FES) have been penetrated with common microgrid system. Each micro sources and ESE are modeled with equivalent transfer function expressions. The transfer function model of islanded AC microgrid system is illustrated in Figure.1.

2.1. Wind Turbine Generator (WTG)

The wide dynamic velocity of wind largely affects the power generation of a wind power plant. In this regard to obtain stability in power generation, advanced control mechanism has been implementing in wind power plant [19]. The power generation in wind power plant basically relies on velocity and density of that particular wind.

The wind power plant is modeled with equivalent transfer function expression while integrating with microgrid system and is expressed through equation (1)

$$G_{WIND}(s) = \frac{\Delta P_{WIND}}{\Delta P_{WIN}} = \frac{K_{WTG}}{1 + s.T_{WTG}} \quad (1)$$

K_{WTG} = Gain of wind power plant, T_{WTG} = Time constant of wind power plant.

2.2. Photo Voltaic Cell (PV Cell)

The huge inexhaustible solar energy can be easily converted to an equivalent electrical energy through suitable PV arrays. In reference to [20] the empirical expression given in equation (2) resembles that ambient temperature and intensity of solar radiation largely affects the net power generation of PV Plant.

$$P_{Solar} = \eta \cdot A \cdot \Phi \cdot T_A \quad (2)$$

Where, η = Transmission efficiency

A = PV array surface area in m^2

Φ = Solar Power in Kw/m^2

T_A = Ambient temp.

While integrating PV system with common microgrid, it has been modeled with equivalent transfer function expression and is illustrated in equation (3).

$$G_{PV} = \frac{\Delta P_{PV}(s)}{\Delta P_{\phi}(s)} = \frac{K_{PV}}{1 + s.T_{PV}} \quad (3)$$

K_{PV} = Solar system gain, T_{PV} = Time constant of solar system.

2.3. Tidal Power Plant (TPP)

The tidal energy resumes high energy density which makes it more viable to generate electrical energy through suitable Tidal Energy Conversion System (TECS). The current research article has presented Archimedes Wave Swing (AWS) principle to convert high density tidal energy to electrical energy [21-22]. This idea has been originated by F. Gardener and H.VanBreugel in year 1993. AWS is a cylindrical chamber which is completely filled with air and is illustrated in Figure.2. The top lid of this chamber is referred as floater which moves in vertical way due to high tidal energy and bottom part of chamber is fixed with Sea bay. Whenever the high pressure tide is above the AWS, it exerts high pressure due to which floater moves downwards. Likewise, tidal trough above AWS creates upward motion of floater due to air presence inside AWS. In this regard a vertical linear motion has been generated in the floater which may be

extracted to convert useful electrical energy. In view of this for better understand a Pilot plant with peak rated 2MW has been depicted in Figure.3. A floater with approximated diameter 9m is placed at the centre of the Pilot Plant along with prescribed velocity 2.2m/s and stroke of 7m. The rotating motion that has been converted from linear floater motion is fed to respective generator for generation of electrical power. The generator terminals are connected to utility grid through suitable Voltage Source Inverter (VSI).

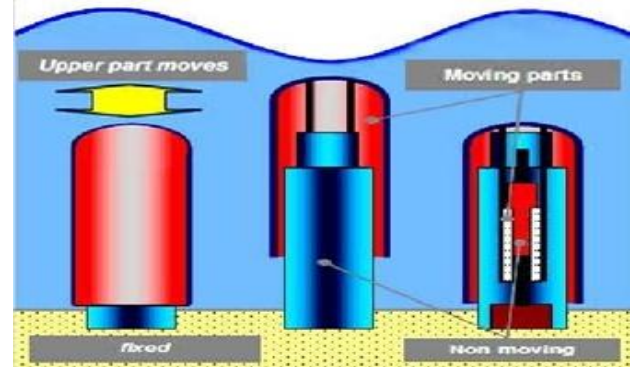


Figure.2 Structure of AWS principle

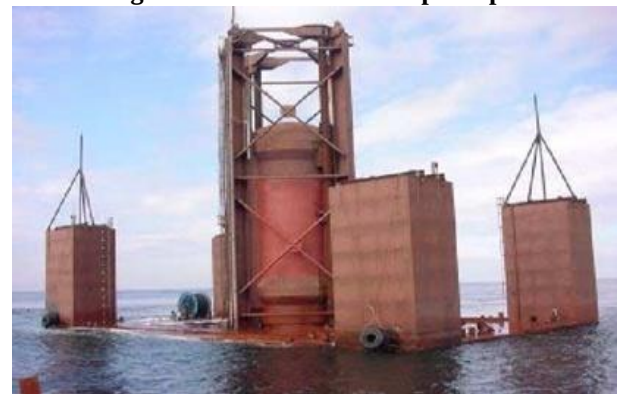


Figure.3 View of Pilot Plant of TPP

2.3.1. Generator Design

The generator requires to be installed for Tidal Power Plant (TPP) is a Permanent Magnet Linear Synchronous Generator (PMLSG) which carries Permanent magnets in its translator. In response to integration of tidal plant with common micro grid system, the generator (PMLSG) is modeled with equivalent transfer function expression and is depicted in equation (4)

$$G_{PMLSG} = \frac{\Delta P_{ELECT}}{\Delta P_{MECH}} = \frac{K_{TPG}}{1 + sT_{TPG}} \quad (4)$$

Where K_{TPG} = Gain of PMSLG, T_{TPG} = Time constant of PMLSG.

2.3.2. Power Electronics Converter (PEC)

The rectifier (VSC) is designed to facilitate maximum power tracking condition in the system. However, the grid side inverter (VSI) is primarily responsible for controlling magnitude and nature of voltage to be injected with micro grid system through suitable controlled switches. Both converters are modeled with single time constant based transfer function and is depicted in equation (5).

$$G_{TPC} = \frac{\Delta P_{OUT}}{\Delta P_{IN}} = \frac{K_{TPC}}{1 + sT_{TPC}} \quad (5)$$

Where K_{TPC} = Gain of Converter, T_{TPC} = Time constant of Converter.

III. PROPOSED STATEMENT

3.1. Proposed tilt based Multistage TDF/(1+TI) Controller

The transfer function expression of two-stage PID controller is

$$T/F = \left[K_P + K_D \left(\frac{NS}{N+S} \right) \right] \left[1 + K_{PP} + \frac{K_I}{S} \right] \quad (6)$$

The mathematical function 'fractional order calculus' inspires to build tilt controller. The order of integral and differentiation is not required to be an integer which may be any fractional value. In tilt based Integral and Derivative (TID) controller the proportional component is replaced with a tilt component (K_T) along with a transfer function component $1/s$. The improved concept of TID controller motivates to design proposed tilt multistage TDF/(1+TI) controller for this study [23]. The unnecessary appearance and adverse effect of controller gain parameter are eliminated with actuating gain parameters at proper instant of time. This can be facilitated with a multistage controller. In tilt based multistage controller the proportional gain parameters are replaced with tilt gains i.e. K_T and K_{TT} respectively. The tilting behavior of proposed controller especially improves tuning process, disturbance rejection ratio and least effect on wide variation system parameter. The tilt based multistage TDF/ (1+TI) controller is mathematically modeled through transfer function expression.

$$TF_{TDF} = \left[\frac{K_T}{S^{\frac{1}{n}}} + K_D \left(\frac{NS}{S+N} \right) \right] \left[1 + \frac{K_{TT}}{S^{\frac{1}{m}}} + \frac{K_I}{S} \right] \quad (7)$$

The controller is actuated with an error signal which is referred as Area Control Error (ACE). In this proposed Microgrid system, deviation in system frequency due to dynamics in load and generation uncertainty is assigned as ACE.

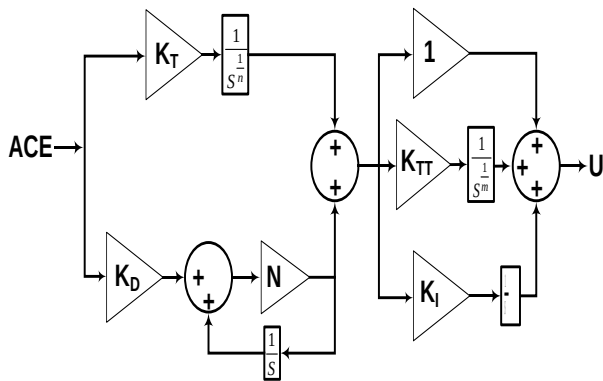


Figure.4 Structure if multi stage TDF/ (1+TI) Controller

3.2. Objective Function

In response to improve system performances, the present article proposes ITAE as objective function for all optimization purposes and is expressed through equation (8).

$$ITAE = \int_0^T |\Delta f| .tdt \quad (8)$$

3.3. Improved Moth Flame Optimization (I-MFO) Algorithm

In this modified technique, to update position of last moth ($Q-Q_K$) the required flames are taken randomly. Hence the effect of best result (best flame) to develop exploitation in search space is also random. With the progress of iteration, the respective position of moth is updated in response to best global solution (best position of flame). At the end of searching process, the above characteristic results exploitation of best result [24]. In this regard with respect to Q_K^{th} flame the worst fitness oriented last moth ($Q-Q_K$) position is updated.

Pseudocode of I-MFO: 1

Data input- Present iteration (i) and iteration numbers (100)

Output – Selection of flame.

Start

In K^{th} iteration compute number of flames

for $a = (Q-Q_K) : Q$

$b = (Q_K-1)*\text{rand} + 1$

$r_a = \text{round}(b)$

$U_K = U(r_a, :)$

$a = a + 1$

end

end

The improved version of MFO combines the principle of three flame observation to improve exploitation of the process. Dynamically or randomly flame of every last ($Q-Q_K$) moth is chosen. The approach provides a proper balance between exploitation and exploration of the moths.

Pseudocode of I-MFO: 2

Data input- Present iteration (i), Iteration numbers (100)

Output – Selection of flame.

Start

Take input data

For K^{th} iteration compute numbers of flame

for $a = Q - Q_K : Q$

$b_1 = (Q_K - 1)*\text{rand} + 1$

$r_a = \text{round}(b_1)$

$b_2 = \text{rand}()$

if $b_2 \leq 0.33$

$U_K = U(Q_K, :)$

elseif $0.33 < b_2 \leq 0.66$

$U_K = U(r_a, :)$

elseif $0.66 < b_2 \leq 1$

$U_K = U(1, :)$

end

$U_K = U(r_a, :)$

$a = a + 1$

end

end

IV. RESULTS AND ANALYSIS

The time domain simulated results of different responses are obtained in MATLAB 2016 simulink environment. In regard to this the proposed model of micro grid system is developed in simulink environment however the required programmes of proposed I-MFO technique is written in .m file. This section focuses on power generation of a distributed generation (DG) especially Tidal Power Plant (TPP) and the demonstration is followed with control and operation of an islanded AC micro grid system under distributed power generation uncertainty. To demonstrate the outcomes of proposed research work this section goes through different case studies. In optimization process the limit of gain parameters of proposed controller has been chosen in the range of $[-2 \ 2]$ except filter coefficient $[0 \ 100]$ and tilt exponent 'n' and 'm' $[0 \ 10]$

Case1. Power Generation in Tidal Power Plant (TPP) and its effect on system frequency.

The modeling of Tidal Power Plant (TPP) is based on AWS principle. Tidal power is the source of energy which to be converted as useful electrical energy in TPP. In regard to this an irregular tide has been considered for this study and the extracted force (N) shown in Figure.5(a) from respective tidal power which helps to drive the floater. The high density oriented tidal power makes linear motion of floater. Through suitable arrangement the linear motion of floater is converted to rotational motion which to be fed to generator for generation of required electrical power. The generated real power (p.u) of TPP is given in Figure.5(b).

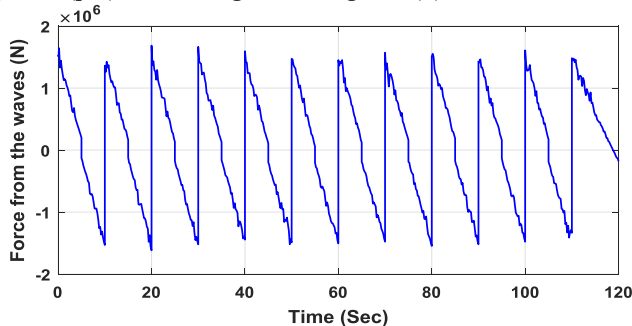


Figure.5(a) Force of tidal water

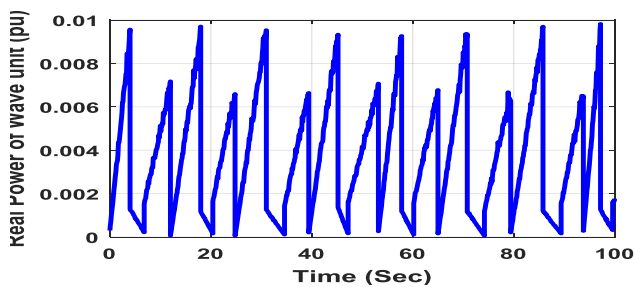


Figure.5(b) Power generation from TPP

The integrated tidal power largely affects the micro grid system frequency due to its wide dynamic nature. So to maintain system frequency within their acceptable region, the present article proposes an I-MFO based optimal PID, PDF (1+PI) and proposed TDF (1+TI) controllers for analysis. To begin with at time $t=0$ the real power shown in Figure.5(b) is effected with micro grid system and the corresponding controlled dynamic responses are illustrated in Figure.6. In view of this the responses of deviation in system frequency and power are depicted in Figure.6(a) and Figure.6(b) respectively. The optimal gain parameters of proposed

TDF/(1+TI) controller under different uncertainties are presented through table1. It has been noticed from responses depicted in Figure.6 that our proposed I-MFO optimized TDF (1+TI) controller is more effective to damp out the dynamic responses which confers supremacy of proposed approach.

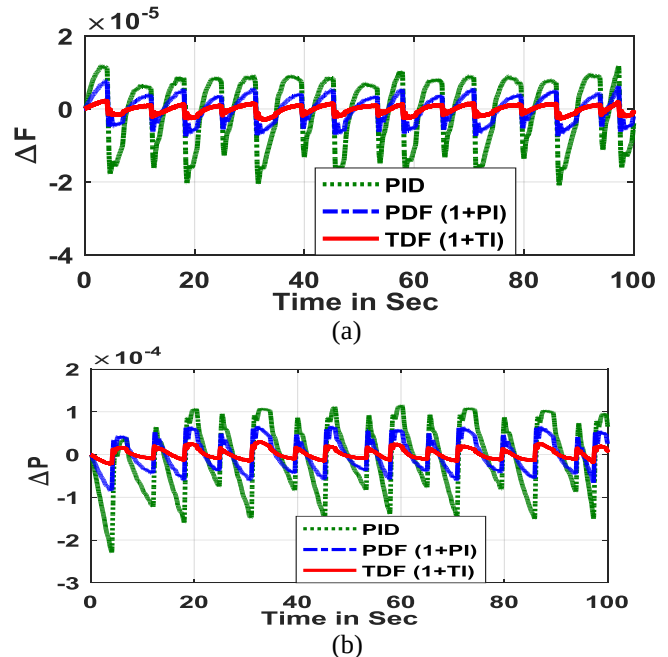
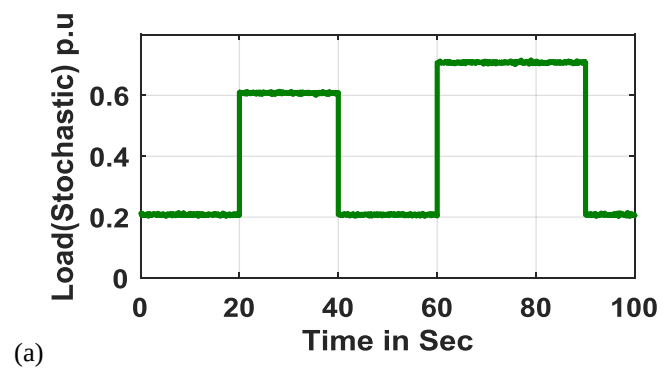


Figure.6. Dynamic responses of (a) frequency deviation (b) Output power deviation due to tidal power uncertainty

Case2. Robust frequency control under Load Uncertainty only

In regard to produce instability in micro grid system frequency a stochastic generated random load shown in Figure.7 (a) has been effected in the system. In view of this the controlled responses of deviation in system frequency and output power are depicted in Figure7 (b) and Figure7 (c) respectively. Owing to damping and settling time of responses, proposed I-MFO optimized TDF (1+TI) controller has an ability to improve dynamic responses significantly.



(a)

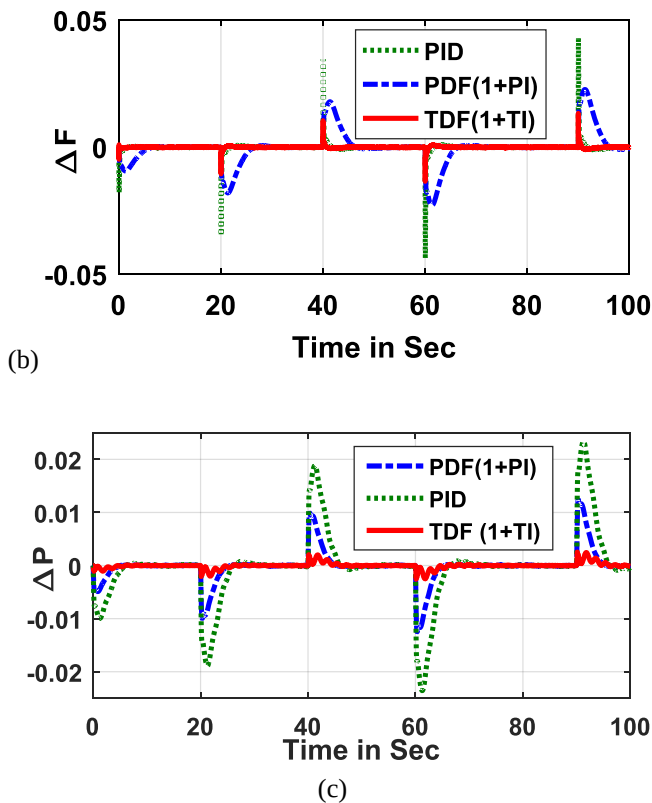


Figure.7. Responses of (a) Stochastic generated random load (b) Controlled dynamic response of frequency under load uncertainty (c) Output power deviation due to applied load uncertainty .

Case3. Robust frequency control underPV and Wind power Uncertainty

In regard to justify improved performance of proposed approach i.e I-MFO optimized TDF (1+TI) controller, the dynamic behavior of the micro grid system has been examined under Photo Voltaic and Wind generated power uncertainties. The stochastic based proposed wind speed (m/s) and generated real power of Wind Turbine Generator (WTG) system are illustrated in Figure8 (a) and Figure8 (b) respectively. To begin with at time $t=0$, the generated power from WTG is injected to micro grid system as an uncertainty and no uncertainty has been found by applied load and generated power from PV system. Under such uncertainty, the controlled responses of deviation in system frequency and power output due to I-MFO optimized different controller i.e PID, PDF (1+PI) and proposed TDF (1+TI) are illustrated in Figure9(a) and Figure9(b) respectively. To simulate the system model, the best set of optimal gain parameters of proposed optimal TDF (1+TI) controller has been taken and are gathered in table1.

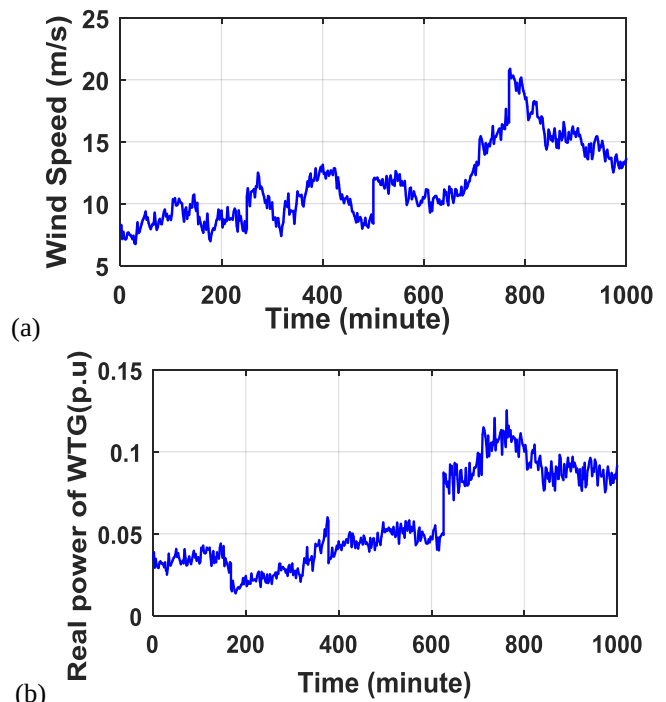


Figure.8. Stochastic generated (a) wind speed (b) generated real power of Wind turbine generator (WTG).

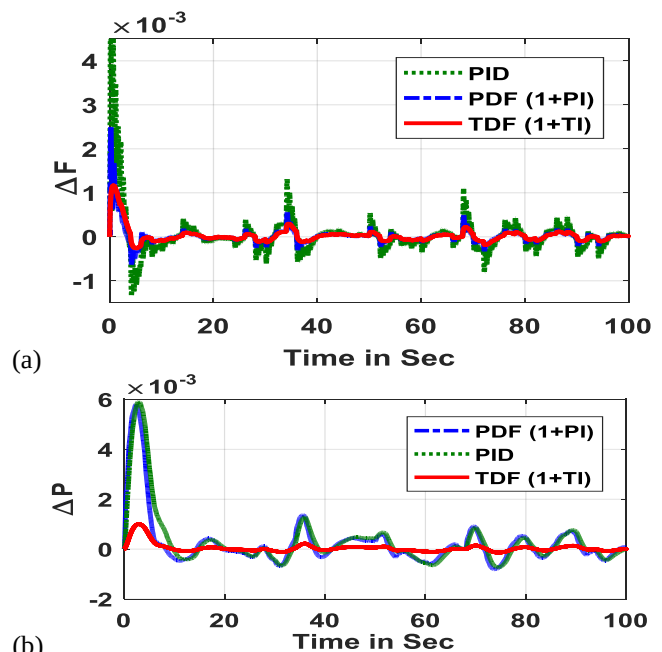


Figure.9 Dynamic responses of deviation in (a) system frequency (b) Output power under wind power uncertainty.

Again the system dynamic performance has been examined under the uncertainties associated with PV generated power. A stochastic based real power generation in Photo Voltaic system during morning 6am to evening 6pm is depicted in Figure10(a). In response to this at time $t=0$ the generated PV power has been effected in micro grid system and simultaneously the controlled response of deviation in system frequency due to I-MFO optimized PID, PDF (1+PI) and proposed TDF (1+TI) is depicted in Figure10 (b).

The dynamic responses those have been depicted in Figure 9 and Figure 10(b) reveal that proposed I-MFO tuned TDF (1+TI) controller exhibits superior performance in response to improved damping and stability of the response.

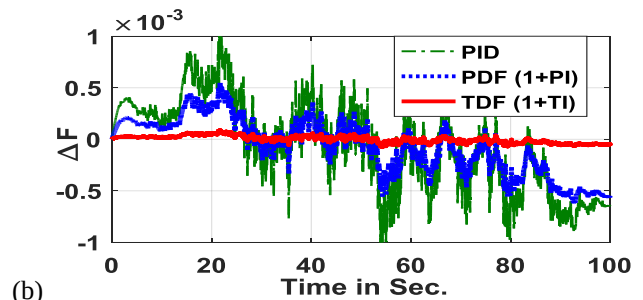
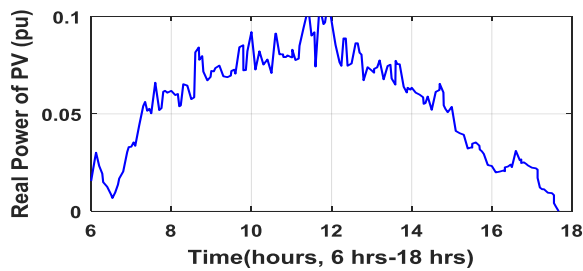


Figure.10. Responses of (a) generated PV power (b) deviation in frequency under solar irradiation power uncertainty.

Table.1 Optimal gain parameters of TDF/(1+TI) Controller

Area	Uncertainties	Tilt based TDF (1+TI) Controller						
		K_T	n	K_D	N	K_{TT}	K_I	m
Islanded AC	ΔP_L	1.8202	6.3432	-1.0082	76.0342	1.4854	-1.8800	8.2284
	ΔP_W	-1.6232	5.9802	-0.4242	44.9878	1.8070	0.9868	6.0080
Micro grid System	ΔP_V	-0.6842	2.2200	-1.2322	67.8820	1.2282	1.0122	4.9876
	ΔP_{TP}	1.7676	3.7986	-1.0202	72.0088	0.9988	1.2232	2.1018

Table.2 Optimal gain parameters of TDF/(1+TI) Controller with different Techniques

Uncertainty	Techniques	ITAE	Tilt based TDF (1+TI) Controller						
			K_T	n	K_D	N	K_{TT}	K_I	m
ΔP_L	MFO	21.0862	1.0808	7.6422	1.9822	64.5522	1.4362	-0.9886	3.4986
	I-MFO	6.0042	1.8202	6.3432	-1.0082	76.0342	1.4854	-1.8800	8.2284
ΔP_W	MFO	18.9648	-0.7832	1.8866	-0.9934	58.9844	0.6986	1.2986	2.0066
	I-MFO	12.8028	-1.6232	5.9802	-0.4242	44.9878	1.8070	0.9868	6.0080
ΔP_V	MFO	21.7862	-1.6422	6.9988	-0.9854	59.8764	1.8766	1.3972	7.5454
	I-MFO	8.4632	-0.6842	2.2200	-1.2322	67.8820	1.2282	1.0122	4.9876
ΔP_{TP}	MFO	32.0934	1.5004	6.0022	-1.6868	68.9822	1.1126	1.4128	8.6486
	I-MFO	10.0842	1.7676	3.7986	-1.0202	72.0088	0.9988	1.2232	2.1018

V. CONCLUSION

The article has well addressed on power generation of a Tidal Power Plant and its integration with AC microgrid system. In regards to power generation of TPP the article has specially focused on force of tidal water (N), Floater Speed (m/s) and real power generation (p.u) of TPP through suitable modelling. Secondly the article has focused on robust frequency control of an islanded AC micro grid system with implementing optimal controllers. The frequency control problem in islanded AC microgrid system has been arisen due to large uncertainties in TPP, Wind turbine generator (WTG) and applied loads. In view of this to maintain system frequency within desired values the article has proposed a tilt based multistage TDF/(1+TI) controller as secondary frequency control loop for this study. To obtain optimal gain parameters of proposed tilt controller an improved Moth Flame Optimization algorithm has been proposed and to show effectiveness of proposed optimal tilt multistage TDF/(1+TI) controller, its performances have been compared with general multistage PD/1+PI and PID controllers. In technique level a comparative study has been carried out among original MFO and proposed I-MFO algorithms to justify viability of proposed I-MFO algorithm. Finally, it has been conferred that proposed I-MFO optimized tilt based multistage TDF/(1+TI) controller significantly improves system performance in

response to frequency control of an islanded AC micro grid system.

APPENDIX

K_{DEG} = Gain of DEG = 1; T_{DEG} = Time constant of DEG = 2s; K_{WTG} = Gain of WTG = 1; T_{WTG} = Time constant of WTG = 1.5s; K_{PV} = Gain of PV Cell = 1; T_{PV} = Time constant of PV Cell = 1.8s. K_{MT} = Gain of MT; T_{MT} = Time constant of MT = 2s; K_{FC} = Gain of Fuel Cell; T_{FC} = Time constant of Fuel Cell = 4s; K_{TPG} = Gain of tidal plant Generator = 1; T_{TPG} = Time constant of tidal plant Generator = 0.3sec; K_{TPC} = Gain of tidal plant converter = 1; T_{TPC} = Time constant of tidal plant converter = 10ms; K_{BESS} = Gain of Battery system = 1; T_{BESS} = Time constant of battery system = 0.1s; T_{FES} = Time constant of Flywheel system = 0.1s; D = damping coefficient = 0.012 (pu/Hz); M = Inertia constant = 0.2 (pu/s);

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