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Modeling, Control and Optimization of a Small Scale CHP System in Island operating Mode based on Fuzzy logic controller

M.F. Elsied[1,2], A. Oukaour[1], H. Gualous[1], Y. Slamani[1], R.Hassan[2] and A.Amin[2]

[1] Lusac laboratoire –, BP78 Rue Louis Aragon (Cherbourg-France)
Université of Caen Basse- Normandie, Caen, France
Phone:0033 986 812685, e-mail: hamid.gualous@unicaen.fr
[2] *Electrical Power and Machines Department*
Helwan University, Faculty of Engineering
Helwan, Cairo, Egypt
Phone: 0033 689 326 447, e-mail: moataz.elsied@unicaen.fr

Abstract. This paper presents the modeling, control scheme and optimization of a small scale combined heat and power (SSCHP) in island operating mode. A thermo dynamic model is carried out for SSCHP engine using Carnot machine method, while an optimization technique is formulated to identify CHP engine parameters. In addition, a dynamic model is built based on a system identification toolbox for SSCHP engine to study the dynamic behavior of the SSCHP during operating mode. In island mode, the Fuzzy logic controller (FLC) is used to regulate the inputs of SSCHP, and to match electric load demand. The complete system was represented and simulated in Matlab/Simulink.

Key words

Small Scale CHP, Synchronous Generator, Thermodynamic Model, FLC, PI.

1. Introduction

Recently, combined heat and power (CHP) is considered an important form of the distributed power generation units (DGs), where the generation unit is placed at or near to users. CHP systems can potentially reduce operational cost, emissions in domestic, commercial, and primary energy consumption associated with power production [1]. The interest in CHP has widened to encompass systems in the Small Scale CHP (SSCHP) which its output power ranges from a few hundreds of kW up to 5 MW.

SSCHP system technology is gaining popularity among the distributed power generation unit due to their several advantages as listed in [1]. SSCHP systems are a relatively proven technology and they have demonstrated the capability to save resources in a variety of applications. Some of these applications include; district heating, hospitals, agriculture industry, and heavy industrial [2]-[5]. A number of researchers have developed thermodynamic models that can be used to predict the thermal and electrical energy outputs of different types of SSCHP engine [6]. Many optimizations techniques with different objective functions in terms of energetic performance are used in engine model. These techniques are used to achieve the optimum design conditions for SSCHP engine thermodynamic model [7].

In order to define the problematic clearly and to perform a suitable analysis of a regulation strategy, a simulation environment is required. A dynamic model of the distributed resource and the electrical load are required for performing the transient simulation and achieving the control design purposes. Roughly there exist two kinds of models for dynamic systems: the first one is based on natural laws, and it is built by differential equations which can describe the basic laws of conservation, and the second one is a data-based model where the measured data are reproduced by parameter fitting using an assumed system structure [8].

By studying the different controlled schemes which used in data-based model, it is clear that the nonlinear methods cannot solve the various control problems of the SSCHP system [9]. Therefore, other advance control methods have been applied such as fuzzy logic controller (FLC), fuzzy PID controller (FPID) and neural network controller (NNC). The main advantage of using these methods is that it allows a model-free estimation of the system. In other words, the designer does not need to state how the outputs depend mathematically upon the inputs [10]. A FLC can be developed by encoding the structured knowledge of the system [11].

The main aim of this paper is to develop and validate a dynamic model for SSCHP engine based on Lagrangian multipliers method. This method is used to identify the CHP engine parameters, where the input exergetic has been used as objective cost function. This model is able to predict the fuel consumption, the generated heat and electricity accurately and total cost. Moreover, the paper presents a FLC for voltage regulator and speed regulator of SSCHP generator. The proposed methodology of control scheme is also compared to the conventional PI which is already used in standalone mode.

2. System description

Fig.1. shows the system configuration to fulfill the load requirements in an isolated mode. Voltage and speed control schemes are aimed to verify the electric load demand variation and supply load with a constant voltage and frequency without using power electronics systems.

The integrated SSCHP system under investigation presents a visual representation of the main components .This system aimed at fulfilling the electric and thermal energy demand of a certain load in standalone system, comprises: (I) a SSCHP prime mover subsystem, (II) Synchronous generator (SG), (III) Heat recovery system (HRS), (IV) Control system, (V) Electric grid and load demand. The synchronous generator transforms the mechanical energy that is transmitted through the engine shaft into an electrical energy. The amount of active (P_L) and reactive power (Q_L) is provided to the load according to the load demand profile. The output heat from combustion chamber is used for preparation of the heating process. The combustion exhaust gases are used a heat source for the boiler that delivers heat to a heating network.

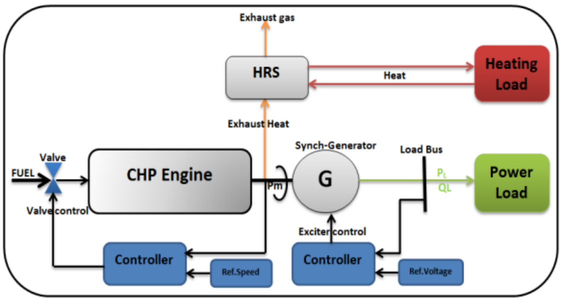

Fig.1. System configuration

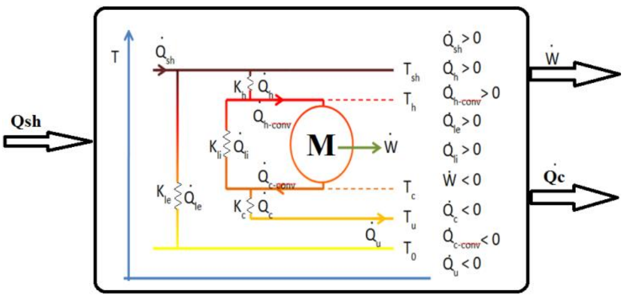

Fig.2. engine inputs and outputs

3. System Modelling

Studies of the dynamic behavior of a SSCHP system before and after sudden changes in electric load should be considered in system modeling regarding to voltage, frequency and power limits violations. A system capable of holding stable operation under steady and transient conditions can be defined as a robust system.

In this section, Matlab/Simulink is employed for simulation of the SSCHP unit as well as for synchronous generator, control system and load representation.

A. SSCHP model

The detailed model of CHP engine is considered in this part. The SSCHP unit is treated and modeled as a compact block where the input is the fuel power and the output is electric and thermal power.

1) Engine thermodynamic model

To develop a practical and simple thermodynamic model of CHP engine, a steady-state regime of the system is introduced here and Carnot cycle engine is also used. The advantages of Carnot cycle engine model are listed in [12], but this model neglects all heat losses such as heat internal losses and heat external losses. The purpose of this paper is to present the analysis for any type of engine using a Carnot cycle model after taking into account all heat losses.

Fig.2. shows the real operation of the engine located between the input heat supply and the output response. Where the SSCHP engine parameters and variables are described as follows:

T_0 : The ambient air temperature.
$\dot{Q}_{sh}$: The heat source which supply which supply the SSCHP at the temperatureT_{sh}.
$\dot{W}$: The mechanical power delivered by the engine.
$\dot{Q}_u$: The exhaust heat at temperature T_u where the engine operates between the temperatures T_c andT_h.
K_c : The cold thermal conductance between T_u , T_c while $\dot{Q}_c$ the associated heat.
K_{li} : The internal loss thermal conductance between T_c , T_h while $\dot{Q}_{li}$ is the associated heat.
$\dot{S}_i$: The internal entropy generation term corresponds to irreversible heat.

The needed relations for describing SSCHP operation are presented in Eq.1.

$$\begin{cases} \dot{Q}_h = K_h(T_{sh} - T_h) \\ \dot{Q}_c = K_c(T_u - T_c) \\ \dot{Q}_{le} = K_{le}(T_{sh} - T_0) \\ \dot{Q}_{li} = K_{li}(T_h - T_c) \end{cases} \tag{1}$$

$\dot{E}x_d$ is defined as the input exergy and summarized in the following equation.

$$\dot{E}x_d = \dot{Q}_{sh}\left(1 - \frac{T_0}{T_{sh}}\right) \tag{2}$$

The cogeneration system using the first and the second laws of thermodynamics can be written as [19].

$$\dot{Q}_{h\_conv} + \dot{Q}_{c\_conv} + \dot{W} = \dot{Q}_h + \dot{Q}_c + \dot{W} = 0 \tag{3}$$

$$\frac{\dot{Q}_{h-conv}}{T_h} + \frac{\dot{Q}_{c-conv}}{T_c} + +\dot{S}_i(T_c, T_h) = \frac{\dot{Q}_h}{T_h} + \frac{\dot{Q}_c}{T_c} + K_{li}\frac{(T_h - T_c)^2}{T_c T_h} + \dot{S}_i(T_c, T_h) = 0 \tag{4}$$

By applying the energy balance to the source and the sink, the input and output heat are described as follow:

$$\dot{Q}_{sh} = \dot{Q}_h + \dot{Q}_{le} \quad (5)$$

$$\dot{Q}_c = \dot{Q}_u \quad (6)$$

Finally, the total thermal conductance can be defined as:

$$K_t = K_c + K_h \quad (7)$$

2) Optimization method

This part presents how to develop and to validate a model based on Lagrange multipliers method. This model is able to investigate the heat source according to the heat and power demands. By knowing the exhaust heat and electric power demand which defined as $\dot{Q}_0$ and $\dot{W}_0$, the optimization statement can be expressed formally as follows:

- Minimize: $\dot{Ex}_d$ as a function in $(T_{sh}, T_h, T_c, K_h, K_c)$ is given by submitting Eq.1 and Eq.5. in Eq.2.

$$\dot{Ex}_d = \left(K_h(T_{sh} - T_h) + K_{le}(T_{sh} - T_0)\right)\left(1 - \frac{T_0}{T_{sh}}\right) \quad (8)$$

After performing a program based on Lagrange multipliers optimization in Matlab software, all variables and parameters of the input heat have been calculated. The input heat can be given as follow:

$$\dot{Q}_{sh} = K_h(T_{sh} - T_h) + K_{le}(T_{sh} - T_o) \quad (9)$$

- Subject to: Eq.10, Eq.11 and Eq.12 were given by submitting Eq.1 in Eq.3, Eq.4, Eq.6 and Eq.7.

$$K_h(T_{sh} - T_h) + K_c(T_u - T_c) + \dot{W}_0 = 0 \quad (10)$$

$$\frac{K_h(T_{sh} - T_h)}{T_h} + \frac{K_c(T_u - T_c)}{T_c} + K_{li}\frac{(T_h - T_c)^2}{T_c T_h} + \dot{S}_i(T_c, T_h) = 0 \quad (11)$$

$$K_c(T_u - T_c) = \dot{Q}_0 \quad (12)$$

$$K_t = K_c + K_h \quad (13)$$

Where $T_{sh}, T_h, T_c, K_h, K_c$ are CHP variables and T_o, K_{li}, K_{le}, K_t are CHP parameter.

3) Model Validation

The data were obtained from Turboden10, Turboden18 and Turboden22 CHP, manufactured by Pratt and Whitney power Systems Company, as a practical case study to develop and validate the engine model [13]. The contents of Table I show the practical data of the manufacture $\dot{Q}_0$, $\dot{W}_0$ *and* $\dot{Q}_{sh}$ compared with the calculated values ($\dot{Q}_{sh}cal$). The calculated values based on Matlab optimization program gives a good agreement with the practical one regardless the type of SSCHP engine used.

Table I. - Practical and calculated data for SSCHP engine

Engine type	$\dot{W}_0$ (KW)	$\dot{Q}_0$ (KW)	$\dot{Q}_{sh}$ (KW)	$\dot{Q}_{sh}cal$ (KW)
Turboden10	1016	4081	5140	5138,5
Turboden18	1863	7834	9790	9799,78
Turboden22	2304	9601	12020	12020,037

4) Engine Dynamic Model

Turboden18 is selected to be a case study to develop a dynamic modelling for SSCHP engine. The practical data can be fitted using Matlab system identification toolbox for developing a relation between SSCHP inputs and outputs. The main idea for system identification is to build a transfer function that can represent the relation between the input supply and the output response [14-15].Fig.3 shows transfer function for electrical power system after using system identification tool box.

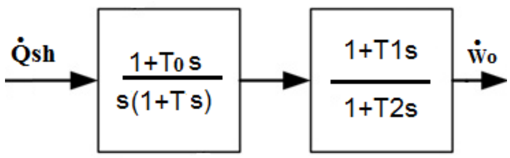

Fig.3. SSCHP Engine transfer function

B. Synchronous generator model

The synchronous machine used in the simulations is based on Matlab Simulink synchronous machine block set. The machine parameters are given in Table II.

Table II.-Synchronous machine data

Rated Power (KW)	Rated Voltage (V)	Rated Speed (rpm)	No.of poles	F_s (Hz)	Inertia (Kg.m^2)	Stator resistance (mΩ)
2000	400	1500	4	50	49.81	0.76

C. Voltage and speed control based on FLC

FLC is a model-free approach, and it does not depend on a model of the system being controlled. Model-free approaches make the controller design simpler, since obtaining a mathematical model of the system is sometimes a very complicated task. The configuration of FLC can be divided into three parts they are, Fuzzification, Knowledge Base, and Defuzzification as listed in [16-17].

1) FLC voltage control

The design of FLC is based on two inputs signal: the first input is the error signal (u), while the second input is the rate of change in the error signal ($\frac{du}{dt}$). FLC voltage regulator (FLCVR), the first input is the voltage error (Vref-Vabc) between the desired value of the generator voltage and its immediate value. The exciter control signal

(ECS) will determine whether the field current needs to be increased or decreased to bring the voltage back to its desired value. The second input to FLCVR is the rate of change of voltage error, which will determine how fast the output voltage is changing as shown in Fig 4. This is an important actor in a real-time control strategy for increasing the time response of the system.

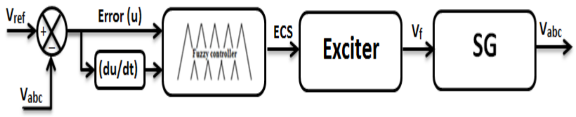

Fig.4. SSCHP voltage control based on FLC

2) FLC speed control

FLC speed regulator (FLCSR), the first input to fuzzy speed controller is the speed error (wref-wmech) between the desired value of the generator speed and its immediate value. The error signal will determine whether the fuel flow needs to be increased or decreased in order to bring the speed back to its desired value. The second input to FLCSR is the rate of change of speed error, which will determine how fast the output speed is changing as shown in Fig.5.

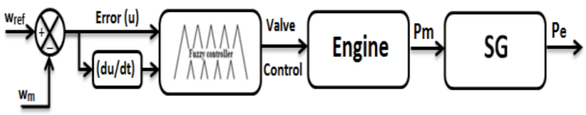

Fig.5 SSCHP speed control based on FLC

3) FLC linguistic variables

The inputs and output are transformed into linguistic variables as, LN: Large negative, MN: medium negative, SN: Small negative, ZE: zero error, SP: small positive, MP: Medium positive, LP: Large Positive, respectively. All the variables are considered in a symmetrical triangular membership function. The rules matrix relating the linguistic input variables to the output variable are given in Table III.

Table III. –FLC linguistic variables

u / du/dt	*LN*	*MN*	*SN*	*ZE*	*SP*	*MP*	*LP*
LN	LN	LN	LN	LN	MN	SN	SN
MN	LN	LN	LN	MN	SN	ZE	ZE
SN	LN	LN	MN	SN	ZE	ZE	SP
ZE	LN	MN	SN	ZE	SP	MP	LP
SP	SN	ZE	ZE	SP	MP	LP	LP
MP	ZE	ZE	SP	MP	LP	LP	LP
LP	SP	SP	MP	LP	LP	LP	LP

4. Simulation results

In this section, the simulation has been implemented using Matlab/Simulink to investigate the performance of the control systems in standalone connected operating modes. The performance of the control systems is investigated based FLCVR and FLCSR in order to verify electric load requirements. The study takes in consideration that the load demand can't exceed the power generation. All parameters of the used engine are validated according to Turboden18.All simulation results are presented in p.u values according to rated conditions of the generator data (Sbase=2MVA&V=380V&1500rpm&50Hz).

A. Load profile

It is well known that residential electricity demand varies according to some factors such as household income, dwelling type and ownership, The availability at home of each household, time of day, time of year, geographical location and climate. [18]-[22].

Fig.6 shows an assumed average daily electricity load profile in p.u for group of houses in winter, the load data is represented in 60 sec by Matlab/ Simulink. The first time interval from 0 to 15 sec represents the electric consumption in the first 6 hours of the day and its load demand is 0.275p.u .The next step is from 15 to 30 sec and it is represents the duration time between 7 till 12 with load demand 0.525p.u.The third step duration is from 30 to 45 sec and it represents the real time between 13 to 18 with load demand 0.38 p.u. Finally the simulation time from 45to 60 sec represents the remaining hours of the day with the maximum load demand (0.77p.u). The total simulation time is 60 sec.

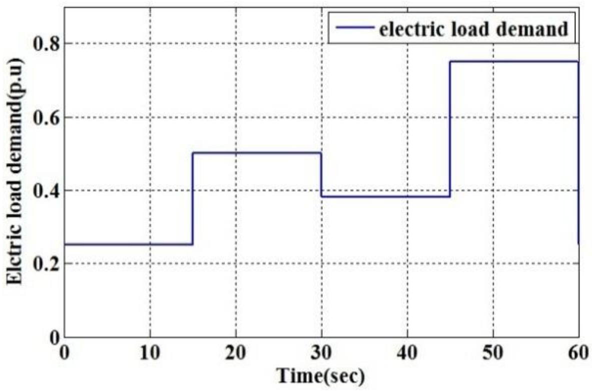

Fig.6. Average daily electricity load profile

B. Engine input and output

For calculating the input heat as a function of electric or heat demand, two approaches are used, the first gives the priority for electric demand (the model is satisfying the electric requirements without considering the heat demand) and the second gives the priority for heat demand without taking into account the electric demand. Fig.7 shows the amount of the input heat required to satisfy the electric demand of the load as well as indicate the exhaust heat according to the first approach. This exhaust heat can be used to satisfy load heat demand after using heat exchange unit.

C. SSCHP performance

Fig.8, Fig.9 and Fig.10 illustrate the generator RMS terminal voltage, excitation current response and three phase instantaneous output voltage after electric load variation. For comparison purposes, two responses are shown: the first with FLC and the second by using PI controller. PI parameters after tuning for voltage controller are [KP=14, Ki=10]. It is clear from this figure that the generator voltage is returned to its desired level faster and with less undershoots by using FLC.

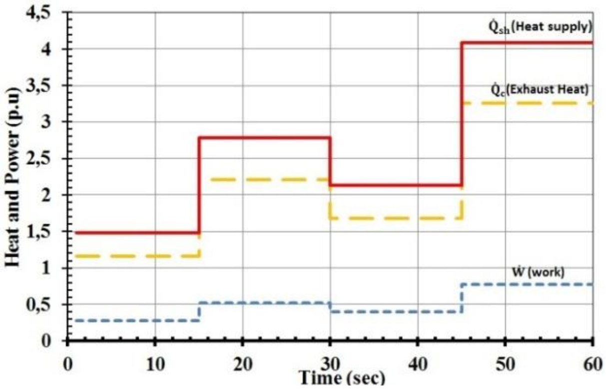

Fig.7. Engine output power according to load profile

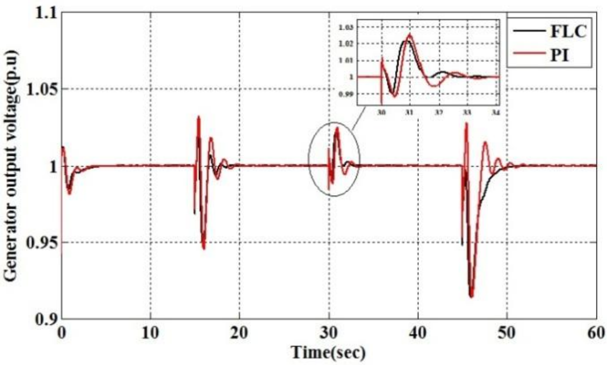

Fig.8. Generator RMS terminal voltage response using PI and FLC

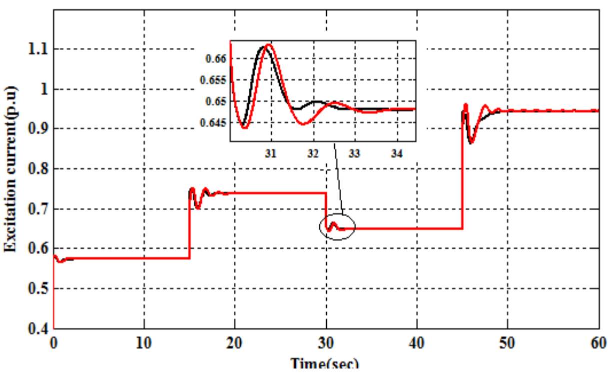

Fig.9. Generator RMS Excitation current using PI and FLC

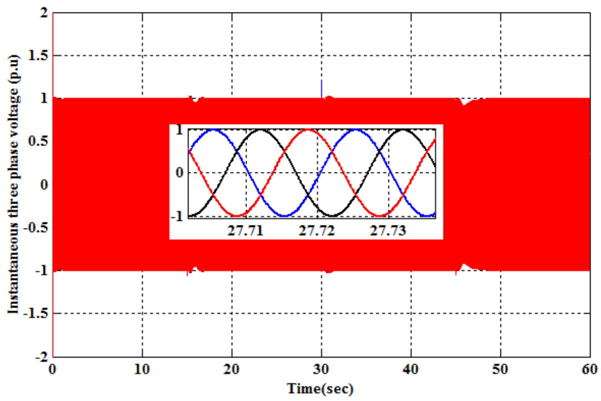

Fig.10. Engine output power according to load profile.

Fig.11 and Fig.12 show the engine mechanical speed and power response using FLC and PI controller [KP=40, Ki=8]. The speed regulator controller has been incorporated with the generator system to maintain the speed constant 1 p.u. it has been found that the engine mechanical power follows the load power demand at constant speed as desired.

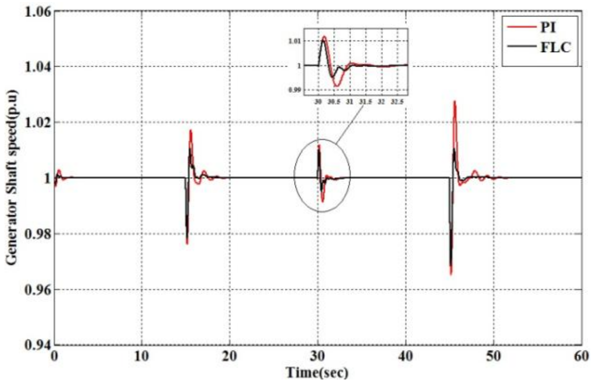

Fig.11. Generator shaft speed response using PI compared to FLC.

The generator instantaneous load current and fuel consumption are shown in Fig. 13 and Fig. 14 .The results indicate the variation of fuel consumption and current according to load demand all over the day to satisfy load requirements. The control system using FLC is used to optimize the fuel consumption during load variation.

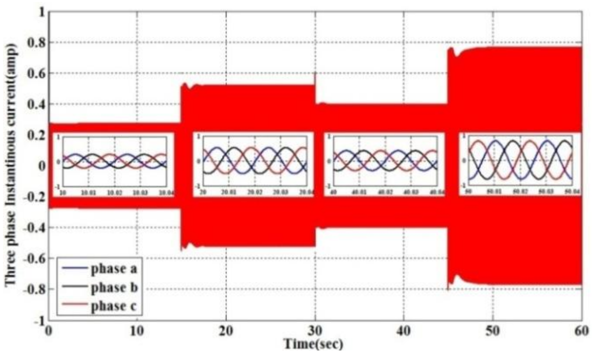

Fig.13. Three phase load current

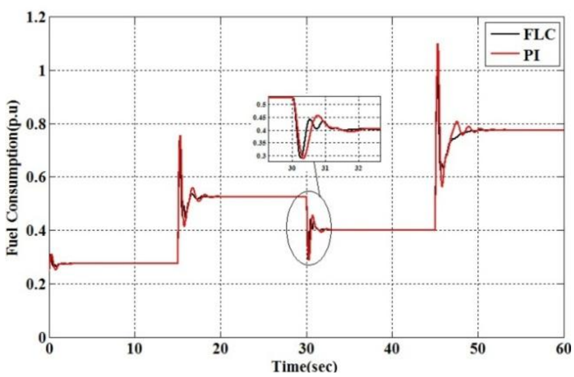

Fig.14. Fuel consumption variation

Fuel consumption during transient period is different for each method of control (FLC and PI controller) as well as accumulated cost. Fig.15 shows the reduction in cost using FLC compared to PI controller over one day. The electricity tariff is assumed to be (0.08C) € per kWh, where C is variable and it changes according to CHP manufacture and CHP rating.

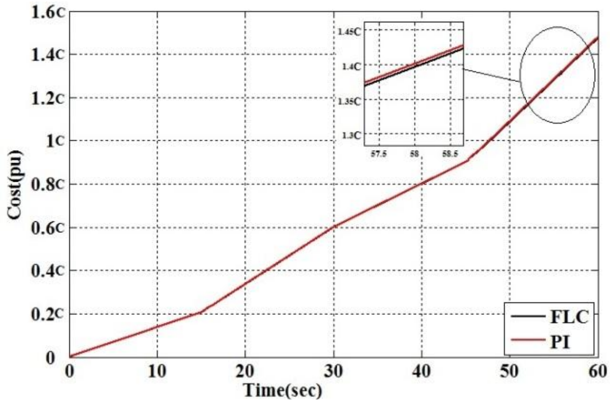

Fig.15. Fuel cost variation

5. Conclusion

This paper has presented a methodology to investigate the performance of a dynamic model of a SSCHP for island mode. The methodology of island operating mode is applied to verify load requirements using FLC, which has been implemented and simulated using Matlab/Simulink. Initially, the SSCHP control system is verified by a PI controller and FLC. From the simulation study, the FLC is preferred over a nominal PI controller in voltage and frequency regulation due to the minimum oscillation and steeling time. Moreover it is simpler than PI controller in mathematical calculation.

References

[1] J. Godefroy, R. Boukhanouf and S. Riffat, “Design, testing and mathematical modeling of a small-scale CHP and cooling system (small CHP-ejector trigeneration,” Applied Thermal Engineering journal 27 (2007) 68–77.

[2] Sanjeev Nayak and D N Gaonkar “Modeling and Performance Analysis of Microturbine Generation System in Grid Connected/Islanding Operation,” International journal of renewable energy research, Vol.2, No.4, 2012.

[3] A.K. Saha, “Study of Microturbine Models in Islanded and Grid-Connected Mode,” Journal of Energy and Power Engineering 5 (2011) 862-869.

[4] X.L. Zhao, L. Fu, S.G. Zhang, Y. Jiang and H. Li, “Performance improvement of a 70 kWe natural gas combined heat and power (CHP) system,” Energy journal 35 (2010) 1848–1853.

[5] M. Bianchi, A. De Pascale and F. Melino “Performance analysis of an integrated CHP system with thermal and Electric Energy Storage for residential application,” applied energy journal (2013) (article in press).

[6] Y. Ust, B. Sahin and A. Kodal “Performance optimization of irreversible cogeneration systems based on a new energetic performance criterion: energy density,” Journal of the Energy Institute 2009 VOL 82 NO 1.

[7] Masood Ebrahimi , “ Energy and exergy analyses of a micro-steam CCHP cycle for a residential building,” Energy and Buildings 45 (2012) 202–210.

[8] Engell and Sebastian, Modeling of dynamic systems, Lecture notes in Process Dynamics and Operations, Department of Biochemical and Chemical Engineering - Technische Universit Dortmund, Germany: 2008.

[9] Ogata, Katsuhiko, Modern Control Engineering, 4th ed, Prentice Hall, 2001.

[10] Sanjeev K Nayak, “ Performance of fuzzy logic based microturbine generation system connected to grid islanded mode, ” International Journal of Fuzzy Logic Systems (IJFLS) Vol.2, No.3, July (2012)

[11] Shijie Yan and Xu Wang, “Active Disturbance Rejection Fuzzy Control of MTG Fuel pressure,” IEEE International Conference on Mechatronics and automation, 9th -12th August (2009), Changchum, China.

[12] M. Feidt, “Optimization of the direct Carnot,” Applied Thermal Engineering journal 27 (2007) 829–839.

[13] “Pratt and Whitney power Systems company data sheet,” standard cogeneration units without SPLIT.Avialable: http://www.turboden.eu/en/products/products-chp.php.06/2012.

[14] Diego Ivan, “Development of a control strategy for mini CHP plants for an active voltage management in low voltage networks,” Master’s Thesis, Faculty of Electrical Engineering Information Technology, Germany,April.2011.

[15] Abdesslam Lokriti , “Induction motor speed drive improvement using fuzzy IP-self-tuning controller,” A real time implementation ISA Transactions (2013) article in press.

[16] Nihat Ozturk, “Speed control of permanent magnet synchronous motors using fuzzy controller based on genetic algorithms,” Electrical Power and Energy Systems journal 43 (2012) 889–898.

[17] R.Kandiban, “Speed control of BLDC motor using adaptive fuzzy PID controller,” Procedia Engineering 38 (2012) 306 – 313.

[18] Amanda D. Smith, “Benefits of thermal energy storage option combined with CHP system for different commercial building types,” Sustainable Energy Technologies and Assessments journal 1 (2013) 3–12.

[19] O.R. Moreton. Smith, “The feasibility of biomass CHP as an energy and CO2 source for commercial glasshouses,” Sustainable Energy Technologies and Assessments journal 1 (2013) 3–12.

[20] Pedro J. Mago, “Analysis and optimization of the use of CHP–ORC systems for small commercial buildings,” Energy and Buildings 42 (2010) 1491–1498.

[21] Pedro J. Mago, “Evaluation of the potential emissions reductions from the use of CHP systems in different commercial buildings,” Building and Environment 53 (2012) 74e82.

[22] Evgueniy Entchev, “Micro-generation technology assessment for housing technology,” Energy and Buildings 36 (2004) 925–931.