Innovative Fuzzy Controller on Island Power Systems with Energy Storage and Renewable for Minimum Fuel Consumption

Invited Paper

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***Abstract*— Isolated areas are usually located a distance away from the main power grids where supplies of electricity rely on diesel generators. Although the initial investment cost of diesel generators is usually low, the fuel cost can be very high over a period of time. Consequently, renewable energy sources such as photovoltaic systems (PV) and micro-hydro generators are used in conjunction with diesel generators to reduce fuel costs. However, poor management and coordination of the energy sources may not solve the issue of high fuel consumption. In order to address this effectively, an innovative energy storage system has been developed to coordinate with various energy sources to reduce the fuel consumption to a minimum. The energy storage system is controlled by a fuzzy controller, which is able to extend the shutdown period of diesel generators and hence minimize fuel consumption. The performance of the energy storage system, as verified in MATLAB/Simulink, indicates that the fuel consumption is reduced by 8%.**

***Index Terms*—diesel generator, energy storage, fuel consumption, fuzzy controller, micro-power systems, renewable energy sources.**

I. Introduction

Rural electrification has been one of the key national agendas in the policies of many developing countries such as Malaysia, to drive the development of scattered islands and isolated areas. A few examples of the islands in Malaysia are Pulau Perhentian Pulau Tioman, Pulau Redang, and Pulau Layang-layang [1], [2]. A few rural areas are Kemar in Perak [3], Kalabakan in Sabah [4], Kampung Denai in Pahang and Kampung Opar in Sarawak [5].

At present, the islands and rural areas are powered using diesel generators. The capital cost of diesel generators is usually low. However, the operational cost may be high due to the high fuel cost over a period of time. In the context of rural and isolated areas, the fuel cost can be four times more expensive than the retail price because of the high transportation expenses incurred for supplying the fuel to the remote destinations [6]. In an effort to reduce the reliance on fuel, governments and utility companies have diversified the energy sources by including renewable energy sources such as photovoltaic systems (PV) and micro-hydro generators [7]–9]. However, the power outputs of even the most renewable energy sources are intermittent. Therefore, an energy storage system is applied because it allows excess power from the different energy sources to be stored [10]. However, without appropriate coordination and implementation, the application of energy storage and energy sources will still lead to high fuel consumption. Hence, an innovative fuzzy controller was developed to coordinate the energy storage system, generator and renewable energy sources on a micro-power system so that the shutdown period of the generator can be prolonged as much as possible while maintaining the balance between generation and demand.

This fuzzy controller is an improved version of the existing control strategies such as load following and cycle charging strategies [11]. The load following strategy does not cut down fuel consumption because the generator is used to supply power to the load at all times, and will only shutdown on the occasion when excess power is made available from the renewable energy sources [12]. This means that the shutdown period of the generator could not be prolonged. On the other hand, the cycle charging strategy is slightly better than the load following approach because it reduces energy wastage from the generator by maintaining the generator as efficiently as possible at all times [13]. However, the shutdown period of the generator is the same as that of the load following approach. Comparatively, the cycle charging strategy requires lower fuel consumption than the load following strategy.

This paper presents details of the fuzzy controller in terms of its role in managing the operations of the energy storage, generator, and renewable energy sources on a micro-power system so that the fuel cost of the generator can be reduced without causing power interruptions to the customers. A number of case studies have been carried out and are presented in this paper to show the performance of the fuzzy controller when compared to the load following and cycle charging strategies. The

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results indicate that the fuzzy controller is able to reduce the fuel consumption of the generator by 8%. This paper will begin with the modeling of various items such as the generator, energy storage, and photovoltaic system in a micro-grid. Following that, details of the fuzzy controller are described before moving on to the case studies and conclusions.

II. Modeling of the Generator, PV, Energy Storage, and Load in Matlab/Simulink

The generator, photovoltaic system, and energy storage system were modeled in MATLAB/Simulink, as shown in Fig. 1.

The diesel generator is modeled using a three-phase voltage source in wye connection. The fuel consumption curve of the generator against the loading factor is modeled in MATLAB/Simulink. The photovoltaic system (PV) is modeled in MATLAB/Simulink using all the relevant solar cell equations expressed in terms of the solar irradiance, efficiency, and temperature coefficient. As a result, the power output and the efficiency of the PV system will vary in accordance with the solar irradiance and the cell temperature.

The energy storage system is modeled using the model of lead–acid batteries connected in series to produce an output voltage of 48 V. The state of charge of the batteries (SOC) is calculated using the following equation.

$$\mathrm{SOC} = 100\int P_B \frac{1}{E_R} dt \tag{1}$$

where P_B is the power input and output of the batteries and E_R is the total energy capacity of the batteries. The state of charge of the batteries should be within the range of 90% and 30% in order to avoid any premature reduction in the batteries lifespan.

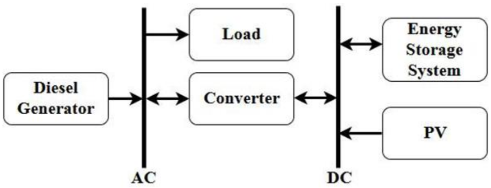


Figure 1. The modeling of the §generator-PV-ESS micro-grid.

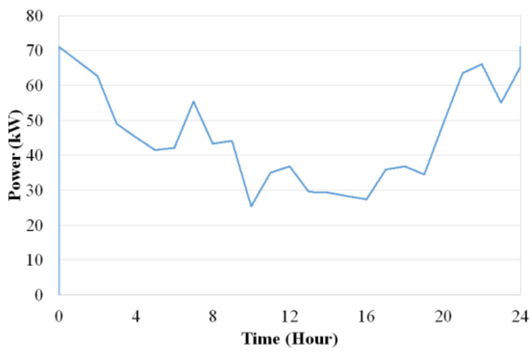


Figure 2. The daily load demand curve of the micro-grid.

The load profile of the micro-grid is modeled based on the data gathered from residential customers located in the rural areas. The maximum demand is 71 kW and the minimum load is 26 kW, as shown in Fig. 2.

III. Fuzzy Controller

The fuzzy controller was developed to reduce the fuel consumption of the generator in a micro-power system with renewable energy sources and energy storage system. The controller uses the latest load profile and PV output profile to predict the amount of power available throughout the following day. The energy storage system will then kick in to supply power on the actual day of power delivery so that the generator can be shutdown at a much earlier time and hence, reduce the fuel consumption and the cost of energy. In addition, any excess PV power can be stored in the energy storage system, which is otherwise wasted under the cycle charging controller system. Fig. 3 shows the power profiles of the PV, generator, and energy storage system in matching with the load. As shown, the shutdown time of the generator takes place for a much longer period than before while the PV output is stored in the energy storage system without any wastage.

Fig. 4 shows the flow chart of the fuzzy controller. The state of charge (SOC) and the solar irradiance are the two inputs to the fuzzy controller, which will generate the output of P_{SOC_PV} for the following day. The output shows the amount of power available from the energy storage as well as the PV system. This information is used together with the load demand to determine whether there is sufficient power from the PV and energy storage to meet the load. If there is sufficient power from PV and energy storage, then the generator will shutdown to avoid unnecessary fuel wastage. The conditions and corresponding actions for shutting down the generator are described in Table I.

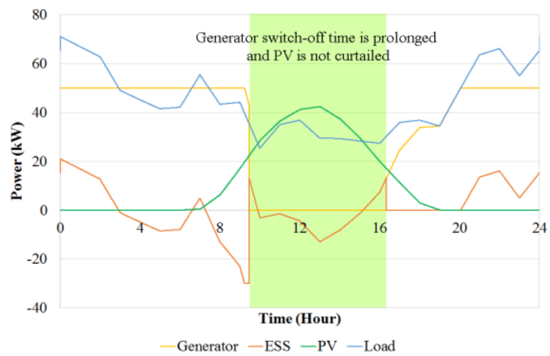


Figure 3. The shutdown time of the generator being prolonged under the fuzzy controller.

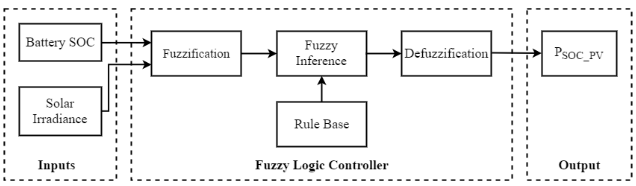


Figure 4. The fuzzy logic controller.

TABLE I. THE CONDITIONS AND CORRESPONDING ACTIONS FOR THE FUZZY CONTROLLER.

Step	Conditions	Actions
1	$D = d + 1$[a]	Predict solar irradiance for the next day (d) and determine the SOC of the batteries. Move to step 2.
2		Calculate $P_{SOC\_PV}(d)$ using the fuzzy logic as described in Fig. 4.
3	$T = 0$[b]	Set the time (t) for the day (d). Move to step 4
4	$P_{PV}(t) > P_{Load}(t) - P_{SOC\_PV}(d)$	If true, move to step 5. If false, move to step 8.
5	$P_{PV}(t) > P_{Load}(t)$	If the condition is true, move to step 6. If it is false, move to step 7.
6	SOC (t) < 90%	If the condition is true, the generator is shutdown, and the ESS is charged by the excess power from the PV because the batteries have extra empty capacity to store more energy. If the condition is false, the generator is switched off, and the PV is curtained because the batteries are too full. Update $t = t + 1$. Move to step 4 if it is not the end of the day. Move to step 1 if it is the end of the day.
7	SOC (t) > 30%	If it is true, the generator is switched off, and the ESS is discharged to the load because the batteries have enough energy. If it is false, the generator supplies the difference ($P_{Load}(t)$ - $P_{PV}(t)$) and the batteries are idle. Update $t = t + 1$. Move to step 4 if it is before the end of the day. Move to step 1 if it is the end of the day.
8	$P_{Load}(t) > P_{GenMax}(t)$[c]	If true, move to step 9. If false, move to step 10.
9	SOC (t) >90%	If true, both the generator and energy storage will supply power to ($P_{Load}(t)$ - $P_{PV}(t)$) as the batteries have enough energy. If false, move to step 10. Update $t = t + 1$. Move to step 4 if it is before the end of the day. Move to step 1 if it is the end of the day.
10	SOC (t) >30%	If true, both the generator and energy storage supply power to the difference ($P_{Load}(t)$- $P_{PV}(t)$). If false, the generator supplies the maximum power to the load and the batteries are idle. Update $t = t + 1$. Move to step 4 if it is before the end of the day. Move to step 1 if it is the end of the day.

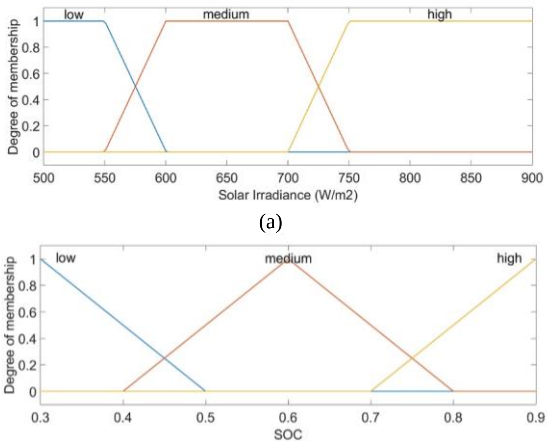
Footnotes:
[a] d is the day of a month. $D = d + 1$ is the next day.
[b] t is the time of the day.
[c] $P_{GenMax}(t)$ is the maximum power output of the generator.

IV. FUZZY LOGIC MEMBERSHIPS

The fuzzy inference system was built on MATLAB Fuzzy Toolbox. The battery SOC and the solar irradiance are the two inputs to the two pre-defined fuzzy memberships. The range of the SOC is from 30% to 90%. The solar irradiance is ranged from 500 to 900 W/m^2. The pre-defined fuzzy membership for the solar irradiance is enclosed by three envelopes of solar conditions, namely low, medium, and high as shown in (b)
Figure 5.

On the other hand, the pre-defined fuzzy membership for the SOC is enclosed by three envelopes of the SOC conditions, namely low, medium, and high. During fuzzification, the input of the solar irradiance to the fuzzy membership generates two solar conditions with their respective linguistic values. The input of the SOC to the membership produces two conditions for the SOCs with their respective fuzzy values. In total, there are four linguistic outputs generated from the fuzzification.

During defuzzification, the four linguistic outputs are mapped against each other in the table, as shown in TABLE to determine the conditions of the instruction. There are four pre-defined conditions for the instruction, namely low, medium, high, and very high. The conditions and the values of the instructions are used to define the area enclosed in the fuzzy membership for the output as shown in Figure 6, given that the smallest degree of the membership of the antecedent is chosen as the true value of the aggregated rule antecedent. Through the center of area defuzzification method, the value of the output $P_{SOC\text{-}PV}$ is determined.



(a)

(b)

Figure 5. The input membership functions for the (a) solar irradiance and (b) battery SOC.

TABLE II: DEFINITION OF THE INSTRUCTION

Battery SOC	Solar irradiance		
	Low	Medium	High
Low	Low	Low	Medium
Medium	Low	Medium	High

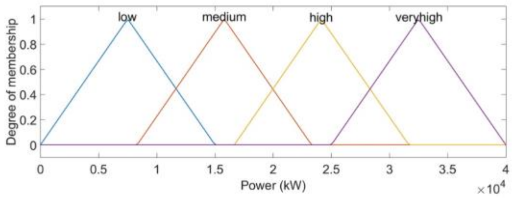


Figure 6. The output membership function of P_{SOC_PV}.

TABLE III: THE PARAMETERS USED FOR THE SIMULATION STUDIES.

Specification of the battery	**Parameters**
Type	Lead–acid
Nominal capacity	1156 Ah (6.94 kWh)
Lifetime	9645 kWh
Number of batteries per string	8 units
Float life	12 years
Roundtrip efficiency	80% [c]
Specifications of the PV	
Sizes considered	30–120 kW with a step size of 10 kW
Operation and maintenance cost	$10/kW/year
Lifetime	25 years
Efficiency	16%
Specifications of the diesel generator	
Fuel cost	$0.46/liter
Fuel Consumption (at 25, 50, 75, and 100%)	4.9, 8.3, 12.1, and 16.1 liters/hour
Specifications of the PV inverter	
Efficiency	90%
Lifetime	15 years
Specifications of the converter	
Efficiency	90%
Lifetime	15 years

V. INPUT PARAMETERS

A number of case studies were carried out to determine the shutdown hours and fuel consumption of the generator. The parameters required for the simulation case studies are listed in Table III.

VI. CASE STUDIES

Case Study 1: A comparison of the fuzzy controller with respect to the load following and cycle charging strategies

TABLE IV. THE SHUTDOWN TIME AND FUEL CONSUMPTION OF THE GENERATOR UNDER THE THREE DIFFERENT STRATEGIES.

Control strategy	Generator switch-off duration (hours/year)	Fuel consumption ($/year)
Fuzzy controller	2630	39,525
Load following	1972	42,702
Cycle charging	1975	43,349

The fuzzy controller was used in a micro-power system comprised of a 50 kW generator, 60 kW PV, and 555.2 kWh energy storage system, serving the load with a peak demand of 71 kW. The results of the three control strategies are shown in Table IV. The fuel consumption of the generator under the fuzzy controller strategy was observed to be the lowest.

Case Study 2: A comparison of the COE and CO_2 avoided under the three different controllers

The fuzzy controller was used in this case study to understand its influence on the COE and CO_2 avoided in a micro-power system comprised of a 50 kW generator, 60 kW PV, and 166.56 kWh energy storage system, serving the load with a peak demand of 71 kW. The results are compared to that of the cycle charging and load following strategies as shown in Table V.

TABLE V. A COMPARISON OF THE COST OF ENERGY (COE) AND CO_2 BEING AVOIDED UNDER THE DIFFERENT STRATEGIES.

Item	Load following strategy	Cycle charging strategy	Fuzzy-based control strategy
Payback (year)	8.8	8.5	8.3
Fuel cost ($USD/year)	42,084	45,336	45,283
Generator runtime (Hour/year)	6367	7369	6235
Generator replacement (units)	10	12	10
COE ($USD/kWh)	0.1986	0.1983	0.1936
CO_2 Emission avoided (kg/year)	320,204	344,948	344,545

VII. CONCLUSIONS

In an islanded network, diesel generators are usually used in conjunction with the PV system and energy storage system in order to ensure a highly reliable electricity supply to the customers. However, ineffective management of the electrical sources and storage can lead to high fuel consumption and hence a high COE. At present, there are two control strategies namely load following and cycle charging strategies used to manage the devices. However, these strategies do not bring down the COE due to the prolonged operation hours of the generators. Therefore, a fuzzy controller was developed to manipulate the generators, PV, and energy storage systems so that the shutdown period of the generator can be prolonged. A number of case studies have been carried out to show that the fuel consumption with the fuzzy controller is reduced by 8% when compared to the cycle charging approach. The fuzzy controller has been proven to be useful for any island network because the customers can cut down their energy consumption, which also brings financial and environmental benefits.

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REFERENCES

[1] M. H. Ashourian, S. M. Cherati, A. A. M. Zin, N. Niknam, A. S. Mokhtar, and M. Anwari, "Optimal green energy management for island resorts in Malaysia," *Renew. Energy*, vol. 51, pp. 36–45, Mar. 2013.

[2] K. Y. Lau, C. W. Tan, and A. H. M. Yatim, "Photovoltaic systems for Malaysian islands: Effects of interest rates, diesel prices and load sizes," *Energy*, vol. 83, pp. 204–216, Apr. 2015.

[3] K. A. Aziz and K. N. Shamsudin, "TNB experience in developing solar hybrid station at RPS kemar, gerik, perak darul ridzuan," *IOP Conf. Ser. Earth Environ. Sci.*, vol. 16, no. 1, p. 012145, 2013.

[4] S. L. Koh and Y. S. Lim, "Meeting energy demand in a developing economy without damaging the environment—A case study in Sabah, Malaysia, from technical, environmental and economic perspectives," *Energy Policy*, vol. 38, no. 8, pp. 4719–4728, Aug. 2010.

[5] M. Fadaeenejad, M. A. M. Radzi, M. Z. A. AbKadir, and H. Hizam, "Assessment of hybrid renewable power sources for rural electrification in Malaysia," *Renew. Sustain. Energy Rev.*, vol. 30, pp. 299–305, Feb. 2014.

[6] K. Y. Lau, M. F. M. Yousof, S. N. M. Arshad, M. Anwari, and A. H. M. Yatim, "Performance analysis of hybrid photovoltaic/diesel energy system under Malaysian conditions," *Energy*, vol. 35, no. 8, pp. 3245–3255, Aug. 2010.

[7] J. Wong, Y. S. Lim, P. Taylor, and S. Morris, "Optimal utilisation of small-scale embedded generators in a developing country–A case study in Malaysia," *Renew. Energy*, vol. 36, no. 9, pp. 2562–2572, Sep. 2011.

[8] J. Wong, Y. S. Lim, J. H. Tang, and E. Morris, "Grid-connected photovoltaic system in Malaysia: A review on voltage issues," *Renew. Sustain. Energy Rev.*, vol. 29, pp. 535–545, Jan. 2014.

[9] L. Y. Seng, G. Lalchand, and G. M. Sow Lin, "Economical, environmental and technical analysis of building integrated photovoltaic systems in Malaysia," *Energy Policy*, vol. 36, no. 6, pp. 2130–2142, Jun. 2008.

[10] K. H. Chua, Y. S. Lim, and S. Morris, "A novel fuzzy control algorithm for reducing the peak demands using energy storage system," *Energy*, vol. 122, pp. 265–273, Mar. 2017.

[11] A. M. Ameen, J. Pasupuleti, and T. Khatib, "Simplified performance models of photovoltaic/diesel generator/battery system considering typical control strategies," *Energy Convers. Manag.*, vol. 99, pp. 313–325, Jul. 2015.

[12] R. Dufo-López and J. L. Bernal-Agustín, "Design and control strategies of PV-Diesel systems using genetic algorithms," *Sol. Energy*, vol. 79, no. 1, pp. 33–46, Jul. 2005.

[13] M. R. Basir Khan, R. Jidin, J. Pasupuleti, and S. A. Shaaya, "Optimal combination of solar, wind, micro-hydro and diesel systems based on actual seasonal load profiles for a resort island in the South China Sea," *Energy*, vol. 82, pp. 80–97, Mar. 2015.

[14] Achievement & Awards. *TNB Energy Services*. [Online]. Available: http://tnbes.com.my/achievement-awards/

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