Fuzzy Control Based Design and Implementation of Energy Management for DC Microgrid Systems

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Abstract - Most of the electricity in India comes from fossil-fuels like coal, oil and natural gas. Today the demand of Electricity in India is increasing and is already more than the production of Electricity whereas the reserves of fossil-fuel are depleting every day. There is strong need to shift for other sources and the best option is renewable energy sources. In this paper, a DC micro grid system is proposed in order to decrease the transmission charges and increase the efficiency of the system. This system consists of a fuzzy controller to improve the performance of the energy management system (EMS). The fuzzy logic controller has two input signals, and one output signal.

Keywords: Energy management system (EMS), fuzzy control, microgrid.

1. INTRODUCTION

There is an increased awareness of the running down of customary energy sources and environmental damage caused by increased carbon dioxide discharges from coal-fired power generation, the use of renewable energy has become the goal for energy development. Current green energy used in power generation includes: solar, wind, geothermal, biomass, and tidal [1]. Many countries have fixed a goal of increasing the usage of renewable energy above 20% of their total power consumption by the year 2020. In addition, distributed power systems are subject to the effects of environmental factors and constraints of nature. In general power system uses battery energy storage to avoid a power outage or power surges caused due to various natural environmental factors. The recent trend of renewable energy development is to combine the distributed power sources and energy storage subsystems to form a small microgrid [2],[3] that reduces the loss of energy which usually occur during power transmission over long distances. Renewable energy is converted into dc and buffered with energy storage elements, and then it is inverted to ac and fed into the utility grid. This approach can readily adapt to contemporary electrical facilities and accelerate use of renewable energy. However, existing high efficiency and compact appliances and equipment are powered by dc, which is converted by rectifying an AC source with power factor correction. To use renewable energy more efficiently, DC electricity should be directly supplied to these loads. Such a supply scheme is far different from that of the conventional AC distribution and supply system.

In this system there will be a reduction of power loss by around 7%, area which is used for the production is saved by 33%, charges for the installation are reduced by about 15% and the reliability of the system increased by about 200%[1], [5]. Low voltage applications especially for lightening can easily be developed. This proposed system includes renewable energy i.e. green power generation, energy storage element, energy management system (EMS) with a fuzzy controller. This fuzzy controller helps to optimize energy distribution of microgrid system.

The system configuration consists of four major blocks: power generator, energy storage equipment, DC load and EMS. In this power generation includes PV panels, wind turbines and fuel cells. The fuel cells provide base power during a power failure for the emergency loads. The PV panels and the wind turbines are associated with maximum power point tracking, which are later fed into the DC grid. If there is power failure, the Li-ion battery will be first discharged to supply power for a short-time interval and if the failure lasts longer (e.g., 2 min), the fuel cell will start supplying power. If there is power shortage, the bidirectional inverter will take power from the DC grid. The battery discharger will be also responsible for dc-grid voltage regulation if the bidirectional inverter is not in operation. If the bidirectional inverter is in operation, the battery can be charged.

The proposed fuzzy control is to optimize energy distribution and to set up battery state of charge (SOC) parameters. This fuzzy controller consists of a fuzzy logic controller. The fuzzy logic controller has two input signals, and one output signal. The design motion of this study helps to increase the useful life of lithium batteries and to include charge and overdischarge protection mechanisms.
2. MODELING OF GREEN ENERGY COMPONENTS

The modeling of dc microgrid distributed energy and an energy storage component is built by MATLAB simulink mathematical modules, based on equivalent circuits of the components. The following describes the model of each subsystem in detail.

2.1 Modeling of Solar Cell

![Diagram of solar cell equivalent circuit]

\[ I = I_L - I_D \]  \hspace{1cm} (1)

Where \( I_L \) refers to the light current and \( I_D \) is the diode current. Using Shockley equation, the diode current can be expressed as

\[ I_D = I_0 \left[ \exp \left( \frac{q(V + I_R)}{n k T} \right) - 1 \right] \]  \hspace{1cm} (2)

Where

\[ \gamma = A . N CS . NS . \]  \hspace{1cm} (3)

\[ I_L = \left( \frac{G}{r_p} \right) \left( I_{LR} + \mu_{HS} (T - T_{CR}) \right) \]  \hspace{1cm} (4)

And

\[ I_0 = I_{0R} \left( \frac{T_{EC}}{T_{CR}} \right)^2 \exp \left( \frac{q E_{g}}{k B} \left( \frac{1}{T_{EC}} - \frac{1}{T_{CR}} \right) \right) \]  \hspace{1cm} (5)

In this equations above, \( I_{LR} \) refers to the light current at reference condition, \( I_{0R} \) the reverse saturation current, actual and reference condition respectively, \( T_{EC}, T_{CR} \) the cell temperature, actual and at reference condition respectively, \( G, G_R \) irradiance actual and at reference condition respectively, \( q \) the electron charge, \( r_p \) series resistance, \( \gamma \) the shape factor, \( k \) the Boltzmann constant, \( A \) the completion factor, \( NCS \) the number of cells connected in series per module, \( NS \) the number of modules connected in series of the entire array, \( \mu_{HS} \) the manufacturer supplied temperature coefficient of short-circuit current and \( E_g \) the material bandgap energy.

In this case Sharp NUS0E3E solar modules are used, each with a power rating of 180 W, as the photovoltaic device of the microgrid system. The total capacity of solar power is 5 kW, generated by two photovoltaic arrays in parallel, where each array was built with 14 solar panels in series. The simulated output power versus output voltage of the solar cell is shown in Fig. 2. This study used constant illumination intensity 1 kW/m² and constant temperature with varying \( V \) for simulation verification.

![Simulated output power \( P_{PV} \) versus output voltage \( V_{PV} \) of the solar cell with constant illumination intensity 1 kW/m²]

2.2 Wind Turbine Modeling

The power generated by wind turbine is expressed as

\[ P_W = 0.5 \rho A V^3 C_p (\lambda, \theta) \]  \hspace{1cm} (6)

Where \( P_W \) is power generated by the wind turbine, \( \rho \) is density of gas in the atmosphere (kg/m³), \( A \) is cross-sectional area of a wind turbine blade m², \( V \) is wind velocity (m/sec), and \( C_p \) is the wind turbine energy conversion coefficient.

The density of gas \( \rho \) and energy conversion coefficient \( C_p \) in \( (6) \) are expressed by \( (7) \) and \( (8) \), respectively

\[ \rho = \left( \frac{253.25}{T} \right) \exp^{-0.024 \left( \frac{T}{273} \right)} \]  \hspace{1cm} (7)

\[ C_p (\lambda, \theta) = \left( \frac{116}{\lambda} - 0.4 \times 0 - 5 \right) \times 0.5 \exp^{-\frac{185}{\lambda}} \]  \hspace{1cm} (8)

Where \( Z \) is the altitude, \( T \) is the atmospheric temperature, \( \lambda \) is the tip speed ratio, and \( \theta \) is the blade tilt angle.

Equation \( (9) \) gives the expression of the tip speed ratio \( \lambda \) in \( (8) \) and \( (10) \) is the expression of the initial tip speed ratio \( \lambda \) in \( (9) \).
charge-discharge cycle) capacity but this ambiguity can lead to confusion and errors. It is not usually an absolute measure in Coulombs, kWh or Ah of the energy left in the battery which would be less confusing. The battery voltage is easy to measure and implement in the circuit. There exists nonlinearity between voltage and SOC. Therefore, the SOC parameter of batteries has been selected as the design factor instead of battery voltage in this paper.

2.4 Fuel Cell Modeling

Fuel cells provide a high efficiency clean alternative to today’s power generation technologies. The polymer electrolyte membrane (PEM) fuel cell has gained some acceptance in mediumpower commercial applications such as creating backup power, grid tied distributed generation, and electric vehicles. The output voltage $E$ of the PEM fuel cell is represented as

$$E = E_{\text{nernst}} - (V_{\text{act}} + V_{\text{ohm}} + V_{\text{con}})$$

Where $E_{\text{nernst}}$ is Nernst voltage, $V_{\text{act}}$ is the activation over potential, $V_{\text{ohm}}$ is ohmic over potential, and $V_{\text{con}}$ is concentration over potential.

$$V_{\text{act}} = -[\xi_1 + \xi_2 \cdot T + \xi_3 \cdot T \cdot \ln(C_{\text{O2}}) + \xi_4 \cdot T \cdot \ln(i)]$$

$$V_{\text{ohm}} = i \cdot R_{\text{M}}$$

$$R_{\text{M}} = \frac{181.6 \left[ 1 + 0.03 \left( \frac{I}{A_f} \right) + 0.062 \left( \frac{T}{100} \right)^2 \left( \frac{A_f}{I} \right) \right] \exp \left[ 4.18 \left( \frac{T}{T_{\text{max}}} \right) \right]}{\lambda_l - 0.634 - 3 \left( \frac{A_f}{I} \right) \exp \left[ 4.18 \left( \frac{T}{T_{\text{max}}} \right) \right] \cdot \lambda_l}$$

$$V_{\text{con}} = -E_{\text{O2}} \cdot \ln \left( 1 - \frac{I}{I_{\text{max}}} \right)$$

where $T$ is operating absolute temperature, $C_{\text{O2}}$ is concentration of oxygen, $I$ is current density, $\xi_{1,2,3,4}$ are reference coefficients, $l_{\text{M}}$ is effective thickness of membrane, $\lambda_l$ is output current of the fuel cell, $j_{\text{A},2,3,4}$ are reference coefficients, $j_i$ is current density, and $I_{\text{max}}$ is maximum current density.

3. INTELLIGENT ENERGY MANAGEMENT SYSTEM

The system configuration of the proposed microgrid system includes four major blocks. To design an accurate controller of the proposed microsystem, the dynamic mathematical models of the power sources (PV, wind turbine, and fuel cell), dc/dc converters (buck-boost, buck, and phaseshifted full-bridge converters), bidirectional converter (symmetrical full-bridge converter), and bidirectional inverter (full bridge inverter) of the integrated micro-system are necessary. However, the modeling, analysis, and design of...
the proposed integrated dc microsystem are not simple. To maintain the battery SOC with EMS, the fuzzy controller is needed to meet design specifications, because the control for EMS is a low response component and the models of dc/dc converters, dc/ac converters of the micro-DC microgrid system are unnecessary.

Fuzzy control theory is designed and implemented in EMS for the dc microgrid system to achieve the optimization of the system. The design criterion requires that both the photovoltaic device and the wind turbine are supplied by a maximum power point tracker to maintain the maximum operating point. The difference between actual load and total generated power is taken into account for Li-ion battery in charge and discharging modes. The life cycle and SOC of the battery are in direct proportion. To improve the life of the Li-ion battery, we can control and maintain the SOC of battery with fuzzy control. Fig 4 shows the Block diagram of fuzzy control to maintain the desired SOC of the battery.

![Block diagram of fuzzy control to maintain the desired SOC of the battery.](image)

**Fig 4:** Block diagram of fuzzy control to maintain the desired SOC of the battery.

### 3.1 Fuzzy Control

Lotfi A. Zadeh, an American scholar of automatic control, suggested fuzzy theory first in 1965, as a tool of computable expression for concepts that could not be clearly defined. A fuzzy control system is based on fuzzy-logic thinking in the design of how a controller works. The so-called fuzzy logic is to establish a buffer zone between the traditional zero and one, with logic segments of none-zero and none-one possible. It allows a wider and more flexible space in logic deduction for the expression of conceptual ideas and experience. A fuzzy controller differs from a traditional controller in that it employs a set of qualitative rules defined by semantic descriptions.

The fuzzy controller is applied in the proposed microgrid power supply system, as shown in Fig. 4. To obtain the desired SOC value, the fuzzy controller is designed to be in charging mode or discharging mode for the proposed microgrid system. The input variables of the fuzzy control are \( \Delta SOC(\%) \) and \( \Delta P(W) \) and output variable is \( \Delta I \). The definition of input and output variables are listed as follows:

\[
\Delta SOC = SOC_{\text{command}} - SOC_{\text{now}} \quad (19)
\]

\[
\Delta P = P_L - (P_{\text{wind}} + P_{\text{pv}}) \quad (20)
\]

The power difference \( \Delta P \) between required power for load and the total generated power of the microgrid. The fuel cell only provide base power for the emergency loads when the system fails. Therefore, the fuel cell is not considered as powersource in (20). The generated power comes from solar power \( P_{\text{pv}} \), wind turbine \( P_{\text{wind}} \) and power load \( P_L \) for the proposed system. The input and output membership functions of fuzzy control contain five grades: \( \text{VN} \) (Very negative), \( \text{N} \) (negative), \( \text{Z} \) (zero), \( \text{P} \) (positive), and \( \text{VP} \) (Very positive), ‘S’ for state of charge, ‘P’ for power and ‘D’ for charge as shown in Figs. 5 and 6. By input scaling factors \( K_1 \) and \( K_2 \), we can determine the membership grade and substitute it into the fuzzy control rules to obtain the output current for charge/discharge variance \( \Delta I \) of the Li-ion battery. If the \( \Delta P \) is negative, it means that the renewable energy does not provide enough energy to the load. Thus, the battery must operate in charging mode; if the \( \Delta SOC \) is negative, it means that the SOC of the battery is greater than the demand SOC. Thus, the battery must operate in discharge mode.

The control rules of this study prioritize selling additional electricity generated by the renewable energy in response to the present control strategy of microgrid development for selling electricity and increasing the life of Li-ion batteries. Table I shows the fuzzy rules of the proposed system. For example, the output variable \( \Delta I \) is VP (the degree of discharging current is large) when the input variable \( \Delta P \) is VNP (the amount of electricity to sell is large) and input variable \( \Delta SOC \) is NS (greater than the SOC command and the membership degree is small). However, the output variable \( \Delta I \) is ND (the degree of charging current is small) when the input variable \( \Delta P \) is VPP.

<table>
<thead>
<tr>
<th>( \Delta SOC )</th>
<th>VNS</th>
<th>NS</th>
<th>ZS</th>
<th>PS</th>
<th>VPS</th>
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<tr>
<td>VNP</td>
<td>VPD</td>
<td>VPD</td>
<td>ZD</td>
<td>ND</td>
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<tr>
<td>NP</td>
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<td>ZD</td>
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<td>ZP</td>
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**TABLE I:** FUZZY CONTROL RULES
VNPN (the amount of electricity to sell is large) and input variable $\Delta SOC$ is PS (smaller than the SOC command and the membership degree is small). The output variable is ND instead of VND when the system is operated in the above conditions because selling electricity is the first priority in this case. Thus, the fuzzy control table of the proposed dc microgrid system is not symmetrical. To extend the life of storage batteries in the design of fuzzy control, the fuzzy control rules are set to maintain battery SOC above 50%. Moreover, in the fuzzy control rules the Li-ion battery is forced to discharge as the control strategy when power demand at load was greater than the power generated by the renewable energy.

In many previous studies, the fuzzy controller has been applied to improve control performance and has shown better control performance than conventional linear controllers.

3.2 Illustration

Fig. 7: Dynamic model of the microgrid system using MATLAB simulink

In this, a fuzzy controller with double input is proposed to improve the control performance of the EMS, as presented in Figure 4. This fuzzy controller consists of a fuzzy logic controller with the above described rule base. The input variables of the fuzzy control are $\Delta SOC$ and $\Delta P$ and output variable is $\Delta I$ of the fuzzy logic controller. The output signal from the conventional fuzzy controller, called the control signal ($\Delta I$), is used for stabilizing the battery performance.

The dynamic model of the proposed dc microgrid system using MATLAB simulink is shown in Fig. 7, where the system consists of a 5 kW solar module, a 1.5 kW wind turbine module, a 1.5 kW Li-ion battery module, and a 6.5 kW load.

Fig. 8: Simulation results with initial battery SOC at 10%.

This example verifies the accuracy of the proposed system with fuzzy controller that can maintain the SOC of the battery at a certain level whether initial
value of the SOC is low or high. As shown in Fig. 8, the fuzzy controller Li-ion battery SOC is maintained at 50% with an initial value of 10%. As shown in Fig. 9, the fuzzy controller Li-ion battery SOC is maintained at 50% with an initial value of 10%. To control strategy of this study is to sell electricity as a priority and to maintain battery SOC.

![Simulation result with initial battery SOC at 100%](image1)

**Fig. 9:** Simulation result with initial battery SOC at 100%.

![Simulation results when the bidirectional Inverter rating is over the power rating](image2)

**Fig. 10:** Simulation results when the bidirectional Inverter rating is over the power rating.

Fig. 10 shows that the fuzzy controller forced the Li-ion battery to discharge when ΔP is greater than 5 kW to keep the system in power equilibrium without going over the power rating of the bidirectional invertersubsystem. However, the SOC of the battery is not the first priority to achieve the safety when the inverter is over the power rating.

4. CONCLUSION

In this paper the modeling, analysis, and design of fuzzy controller is done to achieve optimization of an energy management for a dc microgrid system. From the simulation results, it can be concluded that the system achieves power equilibrium, and the battery SOC maintains the desired value for extension of battery life by using the control rules for a dc microgrid. Thus the fuzzy controller for EMS provides better performance than any other controller. The management system takes advantage of the design to control the SOC of the Li-Ion battery and increasing its life and achieves optimal control of the DC microgrid.

REFERENCES


