Optimal performance assessment of intelligent controllers used in solar-powered electric vehicle

Introduction. Increasing vehicle numbers, coupled with their increased consumption of fossil fuels, have drawn great concern about their detrimental environmental impacts. Alternative energy sources have been the subject of extensive research and development. Due to its high energy density, zero emissions, and use of sustainable fuels, the battery is widely considered one of the most promising solutions for automobile applications. A major obstacle to its commercialization is the battery's high cost and low power density. Purpose. Implementing a control system is the primary objective of this work, which is employed to change the energy sources in hybrid energy storage system about the load applied to the drive. Novelty. To meet the control objective, a speed condition-based controller is designed by considering four separate math functions and is programmed based on different speed ranges. On the other hand, the conventional/intelligent controller is also considered to develop the switching signals related to the DC-DC converter's output and applied the actual value. Methods. According to the proposed control strategy, the adopted speed condition based controller is a combined conventional/intelligent controller to meet the control object. Practical value. In this work, three different hybrid controllers adopted speed condition based controller with artificial neural network controller, adopted speed condition based controller with fuzzy logic controller, and adopted speed condition based controller with proportional-integral derivative controller are designed and applied separately and obtain the results at different load conditions in MATLAB/Simulink environment. Three hybrid controller's execution is assessed based on time-domain specifications. References 19, table 2, figures 40.

Key words: solar power, proportional-integral-derivative controller, artificial neural network controller, fuzzy logic controller.
energy management strategy should differ from that of a traditional battery [12]. The main purpose of this system is to provide sufficient energy to different loads and minimize the energy deficit and the loss of power supply probability (LPSP) [13]. For energy storage to provide multiple grid services effectively and safely, Energy Management Systems (EMSS) and optimization methods are essential [14]. With five parameters, the fractional-order controller is more flexible and robust for microgrid perturbations than the classical Proportional-Integral derivative (PID) controller. A new optimization technique called Krill Herd is used to optimize the parameters of the fractional order PID controller. Compared with other optimization methods like Particle Swarm Optimization (PSO), this is a suitable optimization method [15, 16]. For reducing the effects of PV power intermittency on the stability of the electric grid, a novel algorithm for EMS is proposed, which is combined with a storage system. EMS controls power flow from the PV generator to the grid based on the predetermed PV power level in the simulation model. The PV system and energy storage system are connected to the same DC bus [17].

**Description of Photovoltaic Array (PVA).** Figure 1 illustrates [18] the PVA model which is obtained from several PVA modules. The PVA includes series Rs, shunt Rs, and load RL resistance. In the same way, the photon IPV, the diode I0, and load Ipv currents are represented by their flowing direction.

![Fig. 1. Representation of PVA including source, diode, and load](image)

The current from the input of the circuit is characterized by IPV

\[ I_{PV} = \left[I_{scr} + I_K \cdot (T - 298) \right] \cdot \lambda / 1000, \]

where IPV is the short-circuit current of cell at 25 °C and 1000 W/m²; T is the junction temperature, K; \( \lambda \) is the solar irradiation, W/m².

The reverse saturation current of the module is given by

\[ I_{rs} = I_{scr} \cdot \left[ \exp(q \cdot V_{oc} / N_S \cdot k \cdot A \cdot T) - 1 \right]. \]

Module saturation current is represented with I0 and is given as

\[ I_0 = I_{sc} \left[ \frac{T}{T_c} \right]^3 \exp \left[ q \cdot E_g \cdot \frac{1}{B \cdot k} \cdot \frac{1}{T_c} - \frac{1}{T} \right]. \]

The total current of the PVA module is given as

\[ I_{PV} = N_p \cdot I_0 \left[ \exp \left[ q \cdot V_{pv} + I_{pv} \cdot R_s \right] - 1 \right], \]

where I0, Ipv, Voc, Vpv, I0, Rs are the reverse saturation current, short circuit current, open circuit voltage, cell voltage, cell current, and resistance of the circuit; \( k \) is the Boltzmann’s constant; \( q \) is the electron charge; \( T_c \) is the nominal temperature (298.15 K); \( E_g \) is the band gap energy of the semiconductor; \( N_p, N_S \) are the number of cells connected in series and in parallel, respectively; \( A, B \) are the ideality factors.

**System model with proposed control configuration.** The main block diagram with different sources and the solar panel is represented in Fig. 2 [5]. The major source battery is rechargeable and gets charged from the solar panel during the daytime. Here battery can discharge the energy to the load during sunlight is unavailable time. The two controller’s output signal is compared at the circuit breaker block, to produce controlled switching pulses. The electric drive is connected across the DC bus, which is a combination of two DC-DC converters’ outputs. The control switches shown in the block diagram are used to control the flow from the PVA to the battery and unidirectional converter (UDC). Here bidirectional converter (BDC) is used to do the two-directional operations.

**About controllers used in recommended method.** In this work total, four controllers were used based on the proposed control strategy. Those are Speed condition-based (SCB), Artificial Neural Network (ANN), Fuzzy Logic Controller (FLC), and PID controllers. In this section description of all controllers is given.

**SCB controller** is the main controller utilized in the projected control approach. This controller design is always related to the motor’s speed. This will develop 4-outputs SCB controller for obtaining the output signal is represented in Fig. 4 [19]. Here the required output of the controller always depends upon the delayed output and delayed inputs of the ANN controller. Here back propagation method is adopted to...
obtain the desired output from the applied converters. The z-inverse model is utilized here to send the signals from the output to the input of the network.

![Diagram of ANN controller](image)

**Fig. 4. The ANN controller diagrammatic representation**

**PID controller.** The mathematical equation related to the PID controller (Fig. 5) has been represented with the below equation

\[
y(t) = y(t) + e(t) dt + \frac{de(t)}{dt}; \quad (5)
\]

\[
y(t) = k_p e(t) + k_i \int e(t) dt + k_d \frac{de(t)}{dt}; \quad (6)
\]

where \( k_p, k_i, k_d, e(t) \) represent the proportional, integral, derivative gains and error value.

**Fuzzy Logic Controller (FLC).** Figure 6 [9] illustrates how FLCs are typically structured. For the output of the fuzzy logic controller to be rectified, separate mathematical modeling need not be performed. The type of membership function selected depends on the requirements of the system. Most commonly, triangular, or trapezoidal shapes are used. Afterward, the inference was performed using a rule base. Here, the output variables were managed using a rule base. The fuzzy logic controller considered each rule base to determine the result. This FLC system measures error (E) and change in error (CE) as inputs, which means FLC output is the result of error and change in error.

**Main circuit with proposed technique.** The main circuit operation is divided into four modes based on a load applied. In mode one, the total power demanded by the motor is supplied from the UC due to a heavy load, in mode two of operation battery, and UC combined to meet the load requirement. During mode three, the battery only supplies the load requirement, in the fourth mode of operation battery can supply power to UC as well as load. Figures 7-10 are corresponding to different modes of operation of electric motor [15].

**Presentation of proposed control strategy technique.** Figure 11 is representing how the measured signals are generated related to the motor's speed in four modes of operation.

The SCB generates the four different output pulses as per the speed range of an electric motor as follows

1. If the \( N \leq 4800 \) rpm then math function \( U_1 \) only is in an active state and remaining all math functions are disabled.
2. The speed range is $4600 \leq N \leq 4800$ rpm then math functions $U_1$, and $U_2$ are in the active state and the remaining two-math function disabled state.

3. If speed is $4801 \leq N \leq 4930$ rpm then math function $U_3$ is in the active state and remains all are disabled.

4. The $N \geq 4931$ rpm the math function $U_4$ is in the active state and remain math functions are disabled.

Fig. 11. Three converter pulse signal production of flow chart model

Figures 12-14 demonstrate the development of the regulated pulses to the switches $S_1$, $S_2$, and $S_3$ and which are obtained as per the outputs of the SCB as follows. If the output sign of the SCB is whichever $U_2$, or $U_3$, or $U_4$ then the regulated pulse is produced to the switch $S_1$. When the output of the SCB is only $U_4$, the regulated pulses are developed to $S_2$. If the output of the SCB is whichever $U_1$ or $U_2$ then the regulated pulses are offered to $S_3$.

Fig. 12. Switch-1 normalized signals representation

Fig. 13. Switch-2 normalized signals representation

Fig. 14. Switch-3 normalized signals representation

Simulations outcomes and considerations. The outcomes after successful simulation are presented in this section. The SCB with ANN controller’s speed, current, and switching signals generation plots are shown in Figures continuously 15, 21, 27, 33 and 18, 24, 30, 36. Similarly, SCB with PID output responses of a motor is represented in Figures 16, 22, 28, 34 on the other hand, Figures 19, 25, 31, 37 are indicating the switching signal delivered to a particular switch existing in BDC and UDC. Finally, SCB with fuzzy logic controller’s output responses is shown in Figures 17, 23, 29 and 35 similarly. Figures 20, 26, 32, and 38 are the switching signals formed to BDC and UDC.

Mode-I results.

Fig. 15. Output responses of the electric drive related to Mode-I (SCB+ANN)

Fig. 16. Output responses of the electric drive related to Mode-I (SCB+PID)

Fig. 17. Output responses of the electric drive related to Mode-I (SCB+FLC)
Fig. 18. Pulses of converters by SCB+ANN, Mode-I

Fig. 19. Pulses of converters by SCB+PID, Mode-I

Fig. 20. Pulses of converters by SCB+FLC, Mode-I

Mode-II results.

Fig. 21. Output responses of the electric drive related to Mode-II (SCB+ANN)

Fig. 22. Output responses of the electric drive related to Mode-II (SCB+PID)

Fig. 23. Output responses of the electric drive related to Mode-II (SCB+FLC)

Fig. 24. Pulses of converters by SCB+ANN, Mode-II

Fig. 25. Pulses of converters by SCB+PID, Mode-II

Fig. 26. Pulses of converters by SCB+FLC, Mode-II

Mode-III results.

Fig. 27. Output responses of the electric drive related to Mode-III (SCB+ANN)

Fig. 28. Output responses of the electric drive related to Mode-I (SCB+PID)

Fig. 29. Output responses of the electric drive related to Mode-I (SCB+FLC)
Battery parameters. Figure 39 represents the battery parameters which include state of charge (SOC), voltage, and current corresponding to charge and discharge. Here the positive sign of the current shows the battery charge period and a negative sign is corresponding to the discharge.

About PVA parameters. Different inputs are provided to the solar panel to generate power at different voltage levels. Here the main input parameter of the solar panel is temperature and irradiance, based on the maximum power tracking algorithm a duty cycle is generated to the DC-DC converter of the solar panel. The provided duty cycle of the solar panel converter is always decided on the constant output voltage level corresponding to different input variations of a solar panel.
The controllers’ performance representation based on steady-state time

<table>
<thead>
<tr>
<th>Controller</th>
<th>Time taken by the individual controller based on the load applied, s</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mode-I</td>
</tr>
<tr>
<td>SCB+ANN</td>
<td>0.75</td>
</tr>
<tr>
<td>SCB+FLC</td>
<td>0.25</td>
</tr>
<tr>
<td>SCB+PID</td>
<td>–</td>
</tr>
</tbody>
</table>

Table 2 shows the 3 controller’s performance analyses. Among all the controllers SCB+ANN provides better results in all the aspects except maximum peak overshoot.

Table 2: Representation of three controller’s performance related to time-domain specification

<table>
<thead>
<tr>
<th>Controller</th>
<th>Delay time, s</th>
<th>Rise time, s</th>
<th>Peak time, s</th>
<th>Settling time, s</th>
<th>Maximum peak overshoot, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>MFB+ANN</td>
<td>0.05</td>
<td>0.08</td>
<td>0.1</td>
<td>0.6</td>
<td>12</td>
</tr>
<tr>
<td>MFB+FLC</td>
<td>0.09</td>
<td>0.15</td>
<td>0.18</td>
<td>0.55</td>
<td>8</td>
</tr>
<tr>
<td>MFB+PID</td>
<td>0.15</td>
<td>1.55</td>
<td>1.6</td>
<td>1.65</td>
<td>7</td>
</tr>
</tbody>
</table>

Conclusions. Three different hybrid controllers are designed according to the proposed control approach. The considered speed condition based controller regulated switching signals generated by the artificial neural network/fuzzy logic/proportional integral derivative controllers, which is used to control the output voltage level of bidirectional converter and unidirectional converter related to the motor’s speed. Among all the controllers used in this paper, speed condition based controller played a vital role and salted it as a common controller. Three hybrid controllers, speed condition based controller with artificial neural network, speed condition based controller with fuzzy logic, and speed condition based controller with proportional integral derivative are implemented individually to the main circuit in 4 different modes corresponding to the load applied and attain satisfactory results. Performance and comparative analysis are done among the three-hybrid controller by considering distinct time-domain measurements.

Conflict of interest. The authors declare that they have no conflicts of interest.

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How to cite this article: Kumar R.S., Reddy C.S.R., Chandra B.M. Optimal performance assessment of intelligent controllers used in solar-powered electric vehicle. *Electrical Engineering & Electromechanics*, 2023, no. 2, pp. 20-26. doi: https://doi.org/10.20998/2074-272X.2023.2.04