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ANFIS-Based Maximum Power Point Tracking for Current-Controlled Charging of Electric Vehicle Batteries from Solar Photovoltaic Arrays

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Abstract
Charging an electric vehicle (EV) battery directly from a solar photovoltaic (PV) array is complicated by the highly variable voltage, current and power delivered by the array under changing irradiance, which, if left uncontrolled, can degrade battery performance, response time and service life. Conventional hill-climbing maximum power point tracking (MPPT) methods, such as Perturb & Observe, respond poorly to fast-changing irradiance and cannot guarantee that the charging current stays within a safe band for the battery. This paper proposes a current-controlled charging scheme in which an Adaptive Neuro-Fuzzy Inference System (ANFIS) is used for MPPT, together with a de-rating mechanism, to hold the battery charging current close to a safe reference value of 14 A regardless of irradiance fluctuations. The ANFIS controller takes the PV array power–voltage (P–V) error and its rate of change as two inputs, each represented by seven membership functions, and combines them through a 49-rule Sugeno-type fuzzy inference system to generate the duty-cycle control signal for a DC-DC boost converter. When the array current is below the 14 A reference, the ANFIS-MPPT block drives the converter to operate the array at its maximum power point; when the array current exceeds the reference, a de-rating action reduces the converter duty cycle to pull the operating point back within the safe band. The proposed scheme is implemented and validated in MATLAB/Simulink and compared against a conventional Hill-Climbing (Perturb & Observe) MPPT controller under identical, time-varying irradiance profiles (600–1000 W/m²) and a fixed cell temperature of 25°C. Simulation results show that the proposed ANFIS-based scheme delivers panel output voltage and power that track irradiance changes smoothly (reaching about 390 V and 8000 W under 1000 W/m² irradiance) with markedly reduced oscillation compared with the Hill-Climbing method, keeps the array and battery current confined to a narrow 15–20 A and 0 to −12 A band respectively, and produces a smoother battery state-of-charge (SOC) trajectory than the conventional method.
Keywords— Maximum power point tracking, ANFIS, electric vehicle charging, solar photovoltaic array, DC-DC boost converter, Hill-Climbing, Perturb and Observe, battery state of charge.

I. INTRODUCTION

Road transport is one of the largest contributors to greenhouse-gas (GHG) emissions and urban air pollution, and the transition from internal-combustion vehicles to electric vehicles (EVs) is widely regarded as central to meeting climate commitments such as the Paris

Agreement. Charging the battery of an EV directly from a solar photovoltaic (PV) array, rather than solely from the utility grid, offers an attractive route to further reduce the carbon footprint of electric mobility and to provide charging facilities at locations such as parking lots and workplaces where solar panels can be conveniently installed.

The principal technical difficulty in PV-fed EV charging is that the power delivered by a PV array is a strongly nonlinear function of solar irradiance and cell temperature, and it varies continuously and often rapidly over the course of a day. A charging controller must therefore extract the maximum available power from the array at each instant — a task performed by a Maximum Power Point Tracking (MPPT) algorithm — while simultaneously ensuring that the current delivered to the battery does not exceed the safe charging limit set by the battery chemistry and construction. Conventional MPPT techniques such as Perturb & Observe (P&O, also called the Hill-Climbing method) and Incremental Conductance are simple to implement but are known to oscillate around the maximum power point (MPP) under steady conditions and to track poorly, or even in the wrong direction, under rapidly changing irradiance, both of which translate into fluctuating charging current that can shorten battery life and degrade charging efficiency.

Intelligent MPPT techniques based on fuzzy logic control (FLC) and artificial neural networks (ANN) have been proposed to overcome these limitations, since both can, in principle, track the MPP without requiring an explicit mathematical model of the (highly nonlinear) PV array. FLC, however, requires careful, often manually tuned, design of its membership functions and rule base, while a trained ANN must be retrained whenever the characteristics of the PV array change, for example due to ageing or partial shading. The Adaptive Neuro-Fuzzy Inference System (ANFIS), which combines the rule-based interpretability of fuzzy logic with the learning capability of a neural network, offers a way to combine the advantages of both approaches while mitigating their individual drawbacks. This paper investigates the use of ANFIS for MPPT in a solar PV-fed EV battery charging application, with the specific objective of keeping the charging current close to a safe reference value under continuously varying solar irradiance.

II. RELATED WORK

Perturb & Observe (P&O) remains the most widely used MPPT technique in commercial PV charge controllers because of its simplicity and low sensing requirement (a single voltage or current sensor). However, its fixed perturbation step size forces a trade-off between tracking speed and steady-state oscillation around the MPP, and the algorithm can lose track of the true MPP altogether under rapidly changing irradiance, mistaking the change in power due to irradiance for a change due to its own perturbation. The Incremental Conductance (INC) method removes the steady-state oscillation of P&O by tracking the point at which the incremental conductance equals the negative of the instantaneous conductance, but it is more computationally demanding and can behave erratically during transients.

Fractional open-circuit-voltage and fractional short-circuit-current methods approximate the MPP voltage or current as a fixed proportion of the array's open-circuit voltage or short-circuit current, respectively; both are computationally inexpensive but rely on a proportionality constant that must be characterised experimentally for the specific PV array and that introduces a periodic, momentary loss of generated power while the array is briefly open- or short-circuited to re-measure the reference quantity.

Fuzzy logic control (FLC)-based MPPT has been shown to track the MPP robustly under nonlinear and noisy conditions without requiring an explicit array model, typically using the array's power error and the rate of change of that error as inputs to a rule base that outputs a change in duty cycle. Artificial neural network (ANN)-based MPPT can likewise estimate the optimal reference voltage for a given irradiance and temperature once trained, but requires a representative training data set for the specific array and must be periodically retrained as the array characteristics change with age. ANFIS was proposed as a hybrid technique to combine the rule-based structure of fuzzy logic with the adaptive learning capability of a neural network, and has been reported to track the MPP of a PV array effectively while reducing the manual tuning burden associated with a purely fuzzy-logic controller. The present work builds on this line of work by applying an ANFIS-based MPPT scheme specifically to the problem of keeping EV battery charging current within a safe reference band, and by benchmarking its performance directly against the conventional Hill-Climbing (P&O) method under identical irradiance conditions.

III. PROPOSED ANFIS-BASED CURRENT-CONTROLLED CHARGING SCHEME

A. System Overview

The proposed system consists of a solar PV array, a DC-DC boost converter, an ANFIS-based MPPT/current-control module, and the EV battery. Sunlight incident on the PV array is converted into electrical energy, which is delivered to the battery through the boost converter. Because the array's output current and voltage vary continuously with irradiance, the ANFIS module continuously adjusts the duty cycle of the boost converter so that the current delivered to the battery is held close to a safe reference value of 14 A, this value being adopted as the maximum charging current that the battery can accept without degradation.

B. ANFIS-Based MPPT/De-Rating Control

The ANFIS module takes two inputs: the power–voltage error (P&V error) between the instantaneous operating point and the reference operating point, and the rate of change of this error (P&V change rate). Each input is represented over the range −5 to +5 by seven triangular/Gaussian membership functions, labelled VL, L, ML, M, MH, H and VH (very low to very high), and the two inputs are combined through a Sugeno-type fuzzy inference system governed by 49 rules to produce a single crisp output f(u), which is used to adjust the duty cycle of the boost converter.

Two complementary control actions are implemented around the 14 A reference current:

MPPT operation: $I_{array} < 14$ A $\Rightarrow$ duty cycle increased to raise array power toward MPP

De-rating operation: $I_{array} > 14$ A $\Rightarrow$ duty cycle decreased to reduce array power below the reference

When the charging current generated by the array falls below the 14 A reference, the ANFIS-MPPT block increases the duty cycle so that the array is driven toward its maximum power point, thereby raising the current delivered to the battery. Conversely, when the array current

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rises above the 14 A reference — for example, when irradiance rises sharply — the de-rating action reduces the duty cycle, and hence the power drawn from the array, until the current returns within the safe operating band. In both cases the adjustment is achieved purely through the duty cycle of the boost converter, without disconnecting the array from the battery.

C. DC-DC Boost Converter

The DC-DC boost converter receives the duty-cycle command generated by the ANFIS controller and uses it to raise the PV array voltage to the level required by the battery while damping oscillations in the delivered power. For continuous-conduction-mode operation, the steady-state relationship between the converter's output voltage Vo, input voltage Vin and duty cycle D is

$$V_o = V_{in} / (1 - D)$$

A higher duty cycle therefore corresponds to a higher boost ratio, and the ANFIS controller manipulates D directly to track the array's MPP or to de-rate its output as required.

IV. SIMULATION PARAMETERS

The proposed scheme was implemented in MATLAB/Simulink using the parameters summarised in Table I (PV array and irradiance/temperature conditions) and Table II (EV battery). The PV array was subjected to a time-varying irradiance profile stepping through 850, 900, 600, 1000 and 700 W/m² at a fixed cell temperature of 25°C, to exercise the controller over a representative range of operating conditions.

TABLE I. PV ARRAY / NETWORK INITIALIZATION PARAMETERS

Parameter	Value
Input irradiance (W/m²)	850, 900, 600, 1000, 700
Input temperature (°C)	25
Parallel strings	5
Series-connected modules per string	12
Maximum power (W)	129.94
Open-circuit voltage Voc (V)	36.3
Cells per module	60
Short-circuit current Isc (A)	4.82
Current at MPP, Imp (A)	4.45
Voltage at MPP, Vmp (V)	29.2
Temp. coefficient of Voc (%/°C)	−0.3651
Temp. coefficient of Isc (%/°C)	0.045996

TABLE II. EV BATTERY PARAMETERS

Parameter	Value
Type	Lithium-Ion
Nominal voltage (V)	500
Rated capacity (Ah)	7
Initial state of charge (%)	80

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Parameter	Value
Battery response time (s)	0.00013

V. RESULTS AND DISCUSSION

A. Solar Panel Output Voltage, Current and Power

Under the applied irradiance profile, the proposed ANFIS-based scheme drove the PV array output voltage to approximately 390 V at 1000 W/m² irradiance and to below 300 V at 600 W/m², tracking the irradiance changes with comparatively little oscillation. The conventional Hill-Climbing controller, by contrast, reached a peak voltage of about 340 V and thereafter fluctuated continuously below this value, reflecting its known sensitivity to rapidly changing irradiance. In terms of current, the proposed scheme confined the array output current to a narrow band of approximately 15 A to 20 A, whereas the Hill-Climbing method exhibited large, sustained current fluctuations capable of stressing the battery. The array output power under the proposed scheme peaked at approximately 8000 W for a short interval at 2 s, settling to around 7000 W thereafter, and to approximately 6550 W at 850 W/m² irradiance; the Hill-Climbing method, in comparison, produced power that fluctuated so heavily during both the MPPT interval (1.5–2 s) and the de-rating interval (2–2.5 s) that it could not be considered controlled.

B. DC-DC Boost Converter Output

The DC-DC boost converter output voltage produced by the two schemes was of comparable magnitude, but the converter driven by the proposed ANFIS controller exhibited markedly lower oscillation than that driven by the Hill-Climbing controller. The converter output current showed an even more pronounced difference: under the Hill-Climbing scheme the current fluctuated heavily even during nominal MPPT and de-rating operation, whereas under the proposed ANFIS scheme the converter delivered a stable, near-static current with minimal fluctuation, confirming that the proposed current-control approach is materially more effective at protecting the downstream battery from current transients.

C. Battery State of Charge and Terminal Quantities

With an initial battery state of charge (SOC) of 80% in both cases, the proposed ANFIS scheme charged the battery to a maximum SOC of approximately 80.07% over the simulated interval, compared with only marginally above 80% for the Hill-Climbing scheme, reflecting the more consistent delivery of charging current under the proposed method. Battery terminal voltage was broadly similar for the two schemes, with only slight divergence during the 1.5–2 s and 2.5–3 s intervals, but battery current differed substantially: under the proposed scheme the battery current remained within a 0 A to −12 A band, while under the Hill-Climbing scheme it reached as low as −18 A with heavy, sustained fluctuation, a pattern known to accelerate battery degradation.

D. Discussion

Taken together, the voltage, current, power and SOC results show that the proposed ANFIS-based MPPT and current-control scheme achieves two objectives simultaneously that the conventional Hill-Climbing method does not: (i) it tracks the PV array MPP effectively under a realistic, stepped irradiance profile, and (ii) it holds the array and battery current within a materially narrower, and hence safer, operating band. The improvement is attributable to the ANFIS controller's use of both the instantaneous P–V error and its rate of change, processed through a 49-rule inference system, which allows the controller to anticipate and smoothly respond to changes in irradiance rather than reacting only after a fixed perturbation step, as in the Hill-Climbing method.

VI. CONCLUSION

This paper has presented an ANFIS-based current-controlled MPPT scheme for charging electric vehicle batteries directly from a solar PV array, in which the ANFIS controller processes the PV power–voltage error and its rate of change to regulate the duty cycle of a DC-DC boost converter, performing MPPT when the array current is below a 14 A safety reference and de-rating the array output when the current exceeds this reference. Simulation results under a realistic, time-varying irradiance profile show that the proposed scheme delivers smoother panel voltage, current and power than a conventional Hill-Climbing (P&O) controller, confines the array and battery current to a narrower and safer operating band, and produces a more consistent battery state-of-charge trajectory. These results indicate that ANFIS-based MPPT is a promising approach for protecting EV batteries from the current fluctuations inherent in direct solar-PV charging, and motivate the extension of the scheme, presented in a companion paper, to include a fuel-cell backup source for continued charging when solar irradiance is unavailable.

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