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# Novel highly accurate universal maximum power point tracker for maximum power extraction from hybrid fuel cell/photovoltaic/wind power generation systems

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All the maximum power point tracking (MPPT) units that are currently used in hybrid systems include several distinct MPPT controllers, so that, each MPPT controller is dedicated to a subsystem. Using a distinct MPPT algorithm and controller for each subsystem of a hybrid system explicitly complicates the system implementation, increases cost, and decreases the accuracy of the MPPT process. This paper addresses this problem by presenting a novel fast and highly accurate universal maximum power point (MPP) tracker for hybrid fuel cell/photovoltaic/wind power generation systems. The tracker is called "universal tracker" because it uses a unified algorithm and controller to concurrently track the MPPs of the photovoltaic (PV), fuel cell (FC) and wind energy conversion (WEC) subsystems of a hybrid FC/PV/wind power system. The proposed universal MPP tracker only uses the output voltages and currents of the PV module, FC stack, and WEC subsystem used in a hybrid power system, i.e., it does not need any expensive sensors such as anemometers and tachometers. Moreover, the technique tracks the MPP of the WEC subsystem, not the MPP of its wind turbine, so it extracts the highest output electrical power from the WEC subsystem. A hybrid FC/PV/wind power generation system has been built to validate theoretical results and evaluate the tracker performances. It is experimentally verified that the universal MPP tracker performs a very fast and highly accurate MPPT process, so that, the MPPT efficiencies are about 99.60%, 99.41%, and 99.28% respectively in the PV, FC and WEC subsystems with the very short tracking convergence times of 12 ms, 33 s, and 25 s, respectively. A comparison between the tracker and the state-of-the-art MPP trackers has been also performed that explicitly demonstrates the better performances of the proposed universal MPP tracker, while it concurrently tracks three MPPs but others track only one MPP.



## 1. Introduction

Recently, there has been a rapid increase in the use of renewable energies, in particular, solar and wind energies, due to the problems such as reduction in fossil fuels availability and environmental issues. In practical applications, renewable power sources are often combined together and other types of power sources such as FC stacks to form a hybrid power generation system [1]. This combination increases not only output rated power but also the system reliability [2]. A MPPT unit used in a PV system increases the energy efficiency by tracking the MPP of the PV module/panel utilized in the system [3]. Different MPPT methods have been reported in the literature [4]. Open-circuit voltage (OCV) method first measures the open-circuit voltage of the PV module while it has been disconnected from the system, and then estimates the voltage of MPP [5]. Temperature method estimates the open-circuit voltage using the PV module temperature [6]. Short-circuit current (SCC) technique uses the short-circuit current of the PV module to estimate its MPP [7,8]. Fuzzy methods convert the voltage and current of the PV module into several fuzzy variables, and then, some fuzzy roles are used to track MPP [9,10]. A modified version of fuzzy algorithms is called "adaptive fuzzy MPPT method" [11]. Artificial neural network (ANN) based MPPT methods use the neural networks trained by a set of data expressing the voltage and current of MPP under different conditions. For instance, in a research, two feed-forward neural networks having two hidden layers were used to track MPP [12]. Perturb and observe (P&O) technique uses the voltage

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and current perturbations to find MPP. Three versions of this technique are available: P&O fixed step-size [13], P&O variable step-size [13], and three-point weighted [14]. An improved P&O method was also reported in Ref. [15]. Two modified methods called "particle swarm optimization adaptive neuro-fuzzy inference system (PSO-ANFIS)" and "P&O-ANFIS MPPT" were compared together [16]. The *P-V* curve slope is used to track MPP in incremental conductance (IC) method [17,18], an improved version of the IC technique is also available [19]. Extremum seeking control (ESC) method uses a nonlinear feedback system to estimate MPP [20–22]. Ripple-based ESC method is a modified version of the ESC technique that is applicable to grid-connected PV systems [23]. Power management (PM) MPPT method is more appropriate for tracking MPP under partially shaded conditions [24]. Scanning method tracks MPP by scanning and comparing the output powers measured during the process [25]. A sensor based MPPT method first measures solar irradiance using a sensor, and then estimates MPP [26]. Prediction-P&O method is a hybrid method that combines the direct-prediction technique with the P&O method [27]. To increase the MPPT efficiency and tracking speed, the cuckoo search (CS) algorithm can be used to track MPP [28]. Field program gate array (FPGA) based MPPT method finds MPP by comparing instant output power with calculated maximum output power [29]. Auto-scaling variable step-size IC MPPT method uses a judgment criterion and auto-scaling variable step-size to enable the PV system to achieve a fast dynamic response [30]. Genetic algorithm (GA) MPPT method applies the GA [31], and predictive MPPT method utilizes a model predictive controller to track MPP [32].

Fuel cell (FC) stacks are efficient electrochemical power sources with low pollution in which electrical power is produced by way of the chemical reaction between oxygen and hydrogen [33]. The MPPT methods used in FC based power generation systems are some of the same MPPT methods used in PV systems that were explained in detail. The MPPT method reported in Ref. [34] regulates load resistance to track the MPP of a microbial fuel cell, while the MPPT technique proposed in Ref. [35] continually detects the MPP of a FC, and then, varies the load to match it with the MPP. Similar to what explained in detail for PV systems, the fuzzy, P&O, ANN, and ESC MPPT methods are applicable to FC systems [36–39]. Varying output impedance to track MPP is another technique [40]. Utilizing potentiometers to maximize output power, and adjusting the voltage of a microbial FC to one third of the open-circuit voltage are the two other methods having very low accuracy [41,42].

A wind energy conversion (WEC) system essentially consists of a wind turbine and an electric generator [43], although for a high-efficient WEC system supplied to a DC load, an AC/DC converter including a three-phase rectifier, and a MPPT controller are also necessary [44]. A wind turbine is the key device of a WEC system which is used to convert wind energy into mechanical energy [45]. Wind turbines are mechanical devices having high price and low energy conversion efficiency [46], so adopting an appropriate scheme to extract as much eclectic power as possible from WEC systems is necessary [47]. It is particularly vital at low wind speeds that the output power of a WEC system significantly decreases [48]. For a certain wind speed, there is an optimum turbine speed at which the turbine output mechanical power reaches its maximum [49,50]. A MPPT controller tracks this optimum turbine speed [51], and then regulates the turbine speed to this optimum speed [52]. There are different MPPT methods reported in the literature that are applicable to WEC systems [53]. These methods such as ESC and optimal torque control (OTC) all can be classified into the three main categories known as tip speed ratio (TSR) control based methods [54], power signal feedback (PSF) control based methods [55], and hill-climb search (HCS) technique [56]. In the TSR control based methods, the wind and turbine speeds both should be first measured by sensors or estimated using different physical parameters. Furthermore, the optimum TSR is also needed to adjust the actual TSR of the turbine to the optimum TSR by the controller [57]. The PSF control based methods need the mechanical power equation or maximum power curve of the wind turbine expressing the relationship between the turbine maximum power and the turbine speed [58]. The maximum power curve should be first obtained from off-line experiments or estimated by simulating. The turbine or wind speed is then used to extract maximum power from the mentioned power equation or curve to provide a reference value for the controller, so that, the turbine output power is regulated to the reference value by varying the turbine speed. The OTC method is a well-known technique which belongs to this category of MPPT methods. The first problem associated with the TSR and PSF control based methods is that they all need speed sensors (anemometer and tachometer) to track the maximum output power of a wind turbine with an acceptable accuracy, otherwise, the accuracy is low. This is the main defect of the TSR and PSF control based sensorless methods reported in the literature [59,60]. Reduction in MPPT accuracy resulted from variations in environmental parameters such as ambient temperature is the second problem [61]. The HCS method is an algorithm originally proposed for PV systems [62], it searches the maximum power of a turbine by perturbing the wind turbine speed. The main drawback of this technique is that the algorithm convergency and convergence time strictly depend on the current position of the system's operating point and the perturbation form [63], i.e., the algorithm may converge to wrong points that causes the wind turbine oscillation or even stall [64]. The MPP of a wind turbine is defined as an operating point of the turbine at which maximum mechanical power is extracted from the turbine. Similarly, the MPP of a WEC system is an operating point of the WEC system at which maximum electric power is extracted from the WEC system. As will be shown, the MPP of a WEC system is different from the MPP of the wind turbine used in that WEC system. As mentioned, all the above-mentioned MPPT methods only regulate the operating point of a wind turbine to its MPP, i.e., they do not track the MPP of a WEC system, so what is actually extracted, is the maximum output mechanical power of the turbine, not the maximum output electrical power of the WEC system [65]. In contrast with, the universal MPP tracker proposed in this study tracks the MPP of WEC systems, not the MPP of their wind turbines.

Hybrid power generation systems currently use several distinct MPPT controllers, so that, each MPPT controller is dedicated to a subsystem. Utilizing several MPPT controllers with different MPPT algorithms in a hybrid system not only increases the system complication and cost but also decreases the MPPT accuracy. This study provides a solution for this problem by presenting a novel fast and highly accurate universal MPP tracker applicable to hybrid FC/PV/wind power system. The tracker only uses the output voltages and currents of the PV module, FC stack and WEC subsystem used in a hybrid power system. The tracker neither needs any sensors such as anemometers and tachometers nor has the drawbacks of the other MPPT methods explained in detail. Furthermore, the technique tracks the MPP of the WEC subsystem, not the MPP of its wind turbine, so it extracts the highest output electrical power from the WEC subsystem. A hybrid FC/PV/wind energy system has been constructed, and the excellent performances of the tracker are experimentally verified. The rest of this paper is organized as follows. The implementation of the hybrid FC/PV/wind power generation system including the proposed universal MPP tracker is explained in Section 2. The performances of the universal MPP tracker are evaluated in detail in three separate sub-sections in Section 3, and Section 4 concludes the paper.