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Enhanced and speedy energy extraction from a scaled-up pressure retarded osmosis process with a whale optimization based maximum power point tracking

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ABSTRACT

This paper proposes a novel maximum power point tracking scheme for efficient and speedy extraction of maximum power from a pressure retarded osmosis process subject to rapid salinity variation. The scheme is designed using the Whale Optimization with Differential Evolution algorithm, a nature-inspired metaheuristic technique. The algorithm has facilitated the developed maximum power point tracking controller with features that have helped overcome limitations such as lower tracking efficiency and steady state oscillations as encountered in the conventional methods. Previously, a number of widely used algorithms including perturb & observe, incremental mass resistance and mass feedback controller were used to design maximum power point control schemes for a PRO process to reduce power loss due to rapid salinity variation. However, in using these techniques, a trade-off between the oscillations and the respond time was required to adjust the operation. The proposed scheme is used to solve this problem and is implemented in simulation on a scaled-up PRO system. The performance of the scheme is compared with some popularly used maximum power point tracking controllers. It is observed from results that the proposed method not only outperforms other widely used methods but is also more robust.

1. Introduction

Due to the high demand of the sustainable power production, the renewable energy resources such as solar, wind and ocean have attracted considerable interest from the energy industry over the last decade. However, wind and photovoltaic energy have a few limitations owing to the variation of wind speed and solar irradiance, resulting in restricted operational time frames. Thus, Scientists have been investigating alternative renewable energy harvesting methods including pressure retarded osmosis (PRO) using saline water. Energy generation from osmotic pressure difference between low salinity feed solution and high salinity draw solution using PRO was first proposed by Sedney Loeb [1] in 1975. Since then the PRO has been investigated increasingly as a promising source of clean energy by several researchers [2–7]. This osmotic pressure gradient based energy extraction method is easy to scale-up and is capable of harvesting free energy using membrane-based technologies spontaneously without being affected by factors like wind variations or solar irradiation as in the cases of wind and solar energy respectively. In a typical PRO process, fresh water or comparatively less saline water such as river water forms the feed solution on one side of a semi-permeable membrane. The draw solution such as seawater flowing on the other side of the semi-permeable membrane, is of higher saline concentration and provides a natural salinity gradient across the membrane. When two solutions with different salt concentrations are present, the less saline water diffuses across the membrane and the differential pressure energy can be extracted [2]. For example, with the seawater and the river water as the draw and feed solutions respectively, the potential pressure from the two sides of the membrane is equivalent to a 270 m waterfall [3]. The amount of power that can be tapped by the PRO is estimated to be equivalent to be 1.4–2.6 TW [4], - a significant amount of renewable power [5].

However, to make energy generation from a PRO process practically feasible, its production cost needs to be comparable with that of the other renewable energy sources such as wind, hydro and solar. This will require increasing the efficiency of a PRO process through a number of developments including inexpensive

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membrane design and fabrication tailored for a PRO process, novel PRO process design, such as multi-stage PRO, and the design of appropriate control methodologies to extract maximum power from a PRO process. However, while a significant number of state-of-the-art MPPT techniques exist for wind and solar energy, very limited work has been carried out to design novel control techniques to extract maximum power from a PRO process with comparatively faster speed.

The MPPT strategies that have been proposed to improve the efficiency of the PRO module include the Perturb & Observe (P&O), the Incremental Mass Resistance (IMR) and the Mass Feedback Controller (MFC) methods [6]. Similar to the P&O methods for the PV system, the P&O for PRO system introduces a perturbation in the draw solution pressure of the PRO system. However, it results in oscillations at the maximum power point (MPP) due to the variations in the perturbations around the MPP. The IMR was subsequently proposed to reduce the oscillation as well as the power loss by calculating the slope of the PRO power curve. The idea was inspired by the Incremental Conductance (IC) technique for the PV system [7]. The performance of the PRO system using IMR depends on the incremental pressure. The merit of the IMR method is that it is more flexible and stable compared to the P&O method. Yet the accompanying oscillations persist. Furthermore, a feedback control based technique, the MFC was proposed to improve the efficiency of energy extraction from a PRO system. Inspired by the PID controller, the MFC is implemented to minimize the error of the power slope. The weighted sum of both the slope and the change of the slope is utilized to determine the error, resulting in fast convergence and lower power loss. The challenge is to balance three designed PID gains under the disturbances and uncertainties from the system. When the system encounters the variation in the operating environment such as salinity and temperature, the IMR method may present low robustness. Therefore, there is a need for a novel and robust MPPT controller for a PRO process that can offer (i) no or very limited oscillations at the maximum power point, (ii) more flexibility and stability in the face of disturbance and uncertainties, and (iii) faster convergence and less power loss. The controller also needs to be easy to design and implement for a scaled-up PRO system. It is noted that in a PRO based osmotic power plant, under rapidly changing salinity and operation conditions, the need for a trade-off between oscillation and the tracking speed is an unavoidable complication that reduces the efficiency of the overall system significantly. Therefore, the MPPT method will require to find the global maximum power point as fast as possible.

With these in view, a novel MPPT control method for a scale-up PRO process is designed in this work based on the Whale Optimization with Differential evolution (WODE) algorithm proposed by Mirjalili et al. [8] and is known as the Whale Optimization Algorithm (WOA). This algorithm uses an evolutionary computing approach inspired by the hunting strategy of humpback whales in the ocean and is able to handle the non-linear objective functions and performs well as an optimizing tool for the design of closed loop control systems. To design the MPPT controller for a PRO plant, based on this algorithm, first the permeation-pressure $(\Delta V - \Delta P)$ relations and the average power density-pressure $\overline{(W - \Delta P)}$ characteristics of the PRO process, including the primary detrimental effects, is studied. Then the WODE algorithm, developed on the basis of hump back whales' unique bubble-net feeding behavior during hunting, is introduced and modelled. Finally, the WODE-based MPPT controller is implemented on a scaled-up PRO process and its performance is assessed through a sequence of simulation based study.

The developed WODE-based MPPT controller is found to be able to track the best-peak position in a few steps with oscillation-free convergence. Additionally, the controller requires fewer iterations, converges faster and has less computational burden owing to fewer search particles being needed to find the best solution. This has resulted in lower steady state oscillation as well as less power loss in the output. The findings are found to be in conformity with that of the WODE-based MPPT methods in the case of PV [9–11]. The developed method is easy to implement on a scaled-up PRO process with various physical constraints and salinity profiles. Moreover, the development of the proposed method for a scaled-up PRO process indicates that the method is suitable to be implemented on PRO processes of different sizes.

2. Characteristics of a PRO system

The complete mechanism of a typical PRO salinity power plant is shown in Fig. 1 [12]. Here, the PRO membrane model is connected to the external devices including an energy recovery device (ERD), a high-pressure pump (HP), a hydro-turbine (HT) and a boost pump (BP). The pressure of the high-pressure pump is controlled by the MPPT controller. The overall PRO process is presented in Fig. 1.

2.1. Pressure retarded osmosis model

In the previous research, various PRO models incorporating detrimental effects (D-PRO) of external polarization concentration (ECP), reverse salt permeation (RSP) and internal polarization concentration (ICP) are studied [13]. In this work, the D-PRO model is implemented and used to derive the MPPT algorithm. This model is analogous to an equivalent circuit model with purely resistive elements in the circuit, albeit nonlinear in general. This implies that we have used purely a quasi-static model. The authors [5] [13] [14] developed the model based on the following assumptions: i) to simplify, a constant density is assumed for both draw and feed solution [13]; ii) the difference of osmotic pressure is assumed based on the van't Hoff law [5]; iii) constant hydraulic pressure difference owing to neglected pressure loss [14]. The mathematical formulation of the power density in a PRO system is described as following [15]:

$$\mathrm{W} = J_w \Delta P \tag{1}$$

In (1) ΔP is the hydraulic pressure and J_w is the water permeation flux. The water permeation flux J_w for the D-PRO model incorporating the detrimental effects of ECP, RSP and ICP is defined as following using experimentally measurable parameters [16]:

$$J_w = A\left(\left\{\frac{\pi_D e^{-J_w/k} - \pi_F e^{-J_w S/D}}{1 + B/J_w\left[e^{-J_w S/D} - e^{-J_w/k}\right]}\right\} - \Delta P\right) \tag{2}$$

In (2) A, B, S and D are the membrane water permeability, salt permeability, substrate structural parameter and the bulk diffusion coefficient, respectively. π_d and π_f are the osmotic pressure of the draw solution and the feed solution, respectively. k is the boundary layer mass transfer coefficient which is represented as $k = D/\delta$,

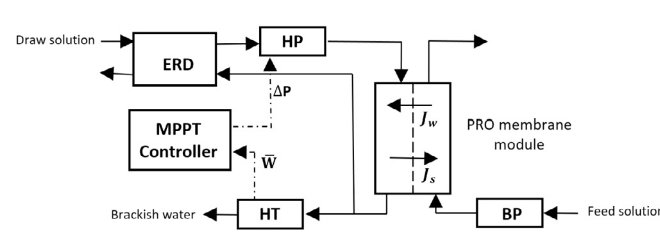

Fig. 1. Block diagram of the PRO system with MPPT controller.