*Int. J. Electrochem. Sci.*, 16 **(2021)** Article Number: 211123, doi: 10.20964/2021.11.10

International Journal of
ELECTROCHEMICAL
SCIENCE
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# Optimization of Controller for Microbial Fuel Cell: Comparison between Genetic Algorithm and Fuzzy Logic

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*Received:* 17 July 2021 / *Accepted:* 3 September 2021 / *Published:* 10 October 2021

Microbial fuel cell (MFC) has attracted more and more attention as a kind of efficient and green power source. Due to its own complexity, the precise control of MFC is still difficult to achieve. The output voltage of MFC has large overshoot and shock under traditional PID control, and it is difficult to adapt to the changes in operating conditions. So, a genetic algorithm optimized fuzzy PID control is proposed to improve the controller effect and realize the constant voltage output control of the MFC. Simulation results show that compared with the traditional PID, the genetic algorithm optimized PID, and the fuzzy tuning PID, the genetic algorithm optimized fuzzy PID control shows smaller overshoot, better stability and stronger anti-interference ability. Optimizing the conventional PID through fuzzy logic and genetic algorithm is a simple, easy, low-cost but effective method to solve the problems of unstable power generation and poor anti-interference ability of MFC system.

**Keywords:** microbial fuel cell(MFC); genetic algorithm; fuzzy control

## 1. INTRODUCTION

With the aggravation of environmental pollution and energy crisis, it is more and more urgent to find and develop green energy [1-3]. As a new type of bio-power generation technology, microbial fuel cell (MFC) can simultaneously solve the problems of environmental pollution and energy crisis for mankind [4], it has gradually become a research hotspot in the fields of environment and energy [5-7].

MFC system is a kind of complex system with multivariable, nonlinear, strong coupling and time- delay characteristics, which brings great difficulty to its precise control, conventional PID control methods often cannot meet the requirements of the system [8,9].

Fuzzy control is a kind of intelligent control method which imitates human logical thinking. It is suitable for the control of complex systems with nonlinear, time-change, time-delay, and uncertainty characteristics, and has the advantages of strong anti-interference and good real-time ability. But the control precision of conventional fuzzy control largely depends on "expert experience", there is no completely accurate method to design the quantization factors and scale factor of fuzzy controller.

Genetic algorithm (GA) is a metaheuristic algorithm with global optimization ability [10,11]. When solving complex combinatorial optimization problems, it can usually obtain better optimization results compared with some conventional optimization algorithms. In recent years, many researches have tried to solve various optimization problems with genetic algorithm [12-14]. In this paper, the genetic algorithm is used to optimize the quantization factors and scale factors of the fuzzy controller, and the parameters of PID controller are self-adjusted by the fuzzy controller, so as to improve the performance of MFC.

## 2. MODEL OF MFC

Modeling of a MFC includes representing the complex bio-electrochemical system and related mechanism into a simpler form for better understanding and representation of the system. The model for a dual-chamber MFC developed by Zeng [15] was used in this research to model the MFC. Based on Zeng's model and MATLAB simulation software, an comprehensive simulation platform of MFCs has been established in the previous work, which can effectively test the real-time operation status of MFCs under different conditions [16, 17]. All the proposed control schemes in this paper were tested on this self-developed simulation platform.

## 3. DESIGN THE CONTROLLERS

### *3.1 GA-optimized PID controller*

The results of relevant literature show that, the feed flow of the anode chamber is one of the key factor affecting the power generation capacity of MFC [18], so the feed flow of the anode chamber is chosen as the manipulated variable to control the output voltage of MFC.

When designing a conventional PID controller, parameter tuning is really a difficult process. Generally, the most commonly used method is the trial and error method, which can get relatively satisfactory parameters after repeated experiments. Once the actual operation process encounters the change of operating conditions, the parameters obtained by this off-line method often do not adapt to the operating conditions, so they can no longer achieve the satisfactory design effect. In order to solve the problem of automatic setting of PID parameters, GA was used to optimize the parameters of PID controller.

GA imitates the phenomena of selection, crossover, and mutation in nature, and uses each iteration to select the excellent individuals in the population for retention to realize the process of survival of the fittes. The specific steps for GA optimization are as follows:

① Determine the number of iterations, population number and individual length in the population, the upper and lower limits of the population parameters are obtained according to the PID parameters obtained by the trial and error method, and the population is generated randomly.

② The appropriate fitness function is set, and the variables such as adjustment time and error generated by model simulation are introduced into the fitness function to calculate the value of the fitness function.

③ According to the value of the fitness function, the selection, crossover, and mutation operations are carried out to update the new population. The iteration continues until the overall stability of the population, and the optimized PID parameter values are output.

The flow chart of the optimization process is shown in Figure 1.

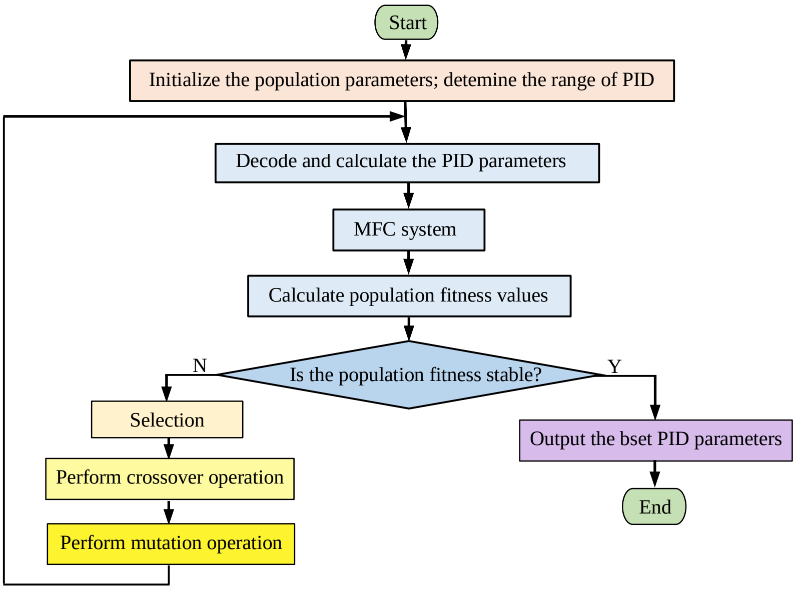


**Figure 1.** Flow chart of GA-optimized PID

Selection is regeneration or replication, and it is a process of selecting individuals with good fitness from the population to generate a new population. The higher the fitness, the higher the probability of the individuals being selected to inherit to the next generation. In the process of selection, the strategy of roulette is adopted to retain excellent individuals. Crossover is to select two individuals from the parent generation population after the selection operation and exchange some bits with each other in a specific way to form a new individual. The new individual formed retains some characteristics of the parent generation individual, which improves the search performance of the algorithm. The mutation is the process of randomly selecting individuals in the population and changing some genes of the individual to produce new individuals. Mutation ensures the diversity of the population and improves the ability of local search [19].

Some output indexes of the system are used as the objective function, which is defined as

$$f = \int_0^{\infty} w_1 |e(t)| \mathrm{d}t + w_2 t_s + w_3 m, (m \le 0) \quad (1)$$

$$f = \int_0^{\infty} w_1 |e(t)| \mathrm{d}t + w_2 t_s + w_3 m + w_4 m, (m > 0) \quad (2)$$

in which $e(t)$ is the error between the set value and the actual output value, $t_s$ is the adjustment time, $m$ is the overshoot, and $w_i$（$i$=1, 2, 3, 4）is the weight. To reduce overshoot, the penalty coefficient $w_4$ is set. When the overshoot is greater than 0, $w_4$ is made much greater than $w_3$. It can be seen from the formula of the objective function that when the value of error, adjustment time, and overshoot are larger, the value of the objective function is larger and the system performance is worse. Therefore, the reciprocal of the objective function is taken as the fitness function, and the minimum value of the fitness function is obtained through iteration to obtain the parameters of the optimal system performance.

After many simulation operation experiments, the number of individuals in the population was set to 50 in the genetic optimization of PID, which can be stabilized after 10 iterations, and the crossover probability was set to 0.6. The single-point crossover was adopted. When the random number was smaller than 0.6, the crossover operation was carried out; and the mutation probability was set at 0.005, when the random number smaller than 0.005, a point of randomly selected individuals on variation.

The individuals in the population are encoded in binary form, with each parameter represented by a code with a length of ten, so the number of the individual representing the three parameters of the PID was 30, and the upper and lower limits of PID parameters $K_p$, $K_i$, and $K_d$ were [0, $2\times10^{-6}$], [0, $2\times10^{-6}$], [0, $4\times10^{-6}$], respectively.

The PID parameters were obtained through repeated simulation, here $K_{p0}=2\times10^{-6}$, $K_{i0}=3\times10^{-6}$, and $K_{d0}=5\times10^{-6}$. After optimization by genetic algorithm, the optimized PID parameters were $K_p=1.6129\times10^{-6}$, $K_i=1.9707\times10^{-6}$, $K_d=1.0479\times10^{-6}$, respectively.

### *3.2 Fuzzy PID controller*

In many cases, the electrical equipments require a power supply that can provide constant voltage power supply capacity. However, because the generation process of MFC involves complex biological, chemical and physical processes, it is difficult to ensure the constant output voltage without control. The traditional PID control usually can not guarantee to achieve the ideal control effect because of the complexity of MFC power generation process, especially when load or system parameters change. Fuzzy control can make use of expert experiences to obtain appropriate control quantity by reasoning according to real-time information of the system and fuzzy rules, thus has good real-time and dynamic performance [20-21].

A fuzzy tuned PID controller was designed to make the PID parameters can be adjusted timely according to the working conditions, so as to overcome the influence of the change of the working conditions on the control effect. The schematic diagram of fuzzy tuning PID control system is shown in Figure 2 [22]. The fuzzy logic controller adopted the structure of a two-inputs and three outputs. The error $e$ and its change $ec$ between the set voltage and the actual output voltage were selected as the inputs of the fuzzy controller, and the fuzzy domain for $e$, $ec$ was designed as [-1, 1]. The three outputs of the fuzzy controller, namely $\Delta K_p$, $\Delta K_i$ and $\Delta K_d$, were used as the adjustment increments of the parameters of the PID controller, and their fuzzy domain were set as [$-2\times10^{-6}$, 0], [$-3\times10^{-6}$, 0], [$-5\times10^{-6}$, 0], respectively. In addition, the input quantization factors of the fuzzy controller were designed as $g_e$=1.5 and $g_{ec}$=2.5; the output scale factors were set as $g_p$=1, $g_i$=0.5, $g_d$=1, separately.

The fuzzy set for inputs and outputs was chosen as the consistent fuzzy set {NB, NM, NS, ZE, PS, PM, PB}. The membership functions were set to triangles, and the sentence expression used by the fuzzy rules was as follow：

If $e$ is ... and $ec$ is ... then $\Delta K_p$ is ... and $\Delta K_i$ is ... and $\Delta K_d$ is ...

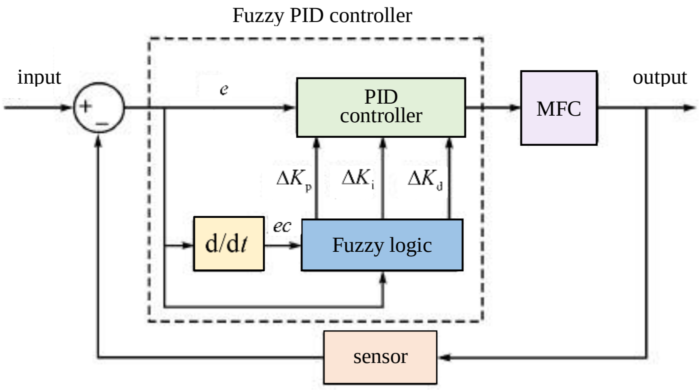


**Figure 2**. The structure diagram of fuzzy PID control

All the fuzzy rules were based on the Mamdani inference mechanism, and the outputs of the fuzzy controller were obtained by using the center of gravity method to de-fuzzify the fuzzy rules. The table of fuzzy control rules for $\Delta K_p$, $\Delta K_i$, $\Delta K_d$ are shown in Table 1.

**Table 1.** Fuzzy control rules

| $\Delta K_p/\Delta K_i/\Delta K_d$ | | *ec* | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | NB | NM | NS | Z | PS | PM | PB |
| *ec* | NB | PB/NB/PS | PB/NB/NS | PM/NM/NB | PM/NM/NB | PS/NS/NB | Z/Z/NM | Z/Z/PS |
| | NM | PB/NB/NS | PB/NB/NS | PM/NM/NB | PS/NS/NM | PS/NS/NMS | Z/Z/NS | NS/Z/Z |
| | NS | PM/NB/Z | PM/NM/NS | PM/NS/NM | PS/NS/NM | Z/Z/NS | NS/PS/NS | NS/PS/Z |
| | Z | PM/NM/Z | PM/NM/NS | PS/NS/NS | Z/Z/Z | NS/PS/NS | NM/PM/NS | NM/PM/Z |
| | PS | PS/NM/Z | PS/NS/Z | Z/Z/Z | NS/PS/Z | NS/PS/Z | NM/PM/Z | NM/PB/Z |
| | PM | PS/Z/PB | Z/Z/NS | NS/PS/PS | NM/PS/PS | NM/PM/PS | NM/PB/PS | NB/PB/PB |
| | PB | Z/Z/PB | Z/ZPM | Z/PS/PM | NM/PM/PM | NM/PM/PS | NB/PB/PS | NB/PB/PB |

In this way, the three parameters of the PID controller can be abjusted in real time through the following relationship:

$$\begin{aligned} K_p &= K_{p0} + \Delta K_p \\ K_i &= K_{i0} + \Delta K_i \\ K_d &= K_{d0} + \Delta K_d \end{aligned} \quad (3)$$

*3.3 GA-Optimized fuzzy PID controller*

The quantization factor and proportional factor of fuzzy controller have great influence on its performance. The design of these factors is generally realized through experience or trial and error.

However, when the actual operating conditions change, the parameters obtained by such methods often do not have the adaptability. Using the powerful optimization ability of genetic algorithm to optimize the scale factor and quantization factor of fuzzy controller, the suitable parameters can be determined quickly, so that the fuzzy PID controller can be further optimized [23]. The schematic diagram of the fuzzy PID controller optimized by the genetic algorithm is shown in Figure 3.

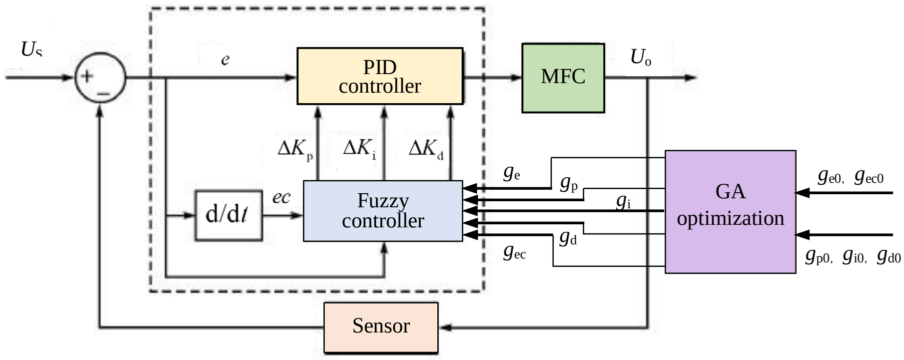


**Figure 3**. The schematic diagram of GA-optimized fuzzy PID control

The implementation process of optimizing parameters using genetic algorithm is similar to the steps mentioned above for optimizing PID parameters by genetic algorithm. However, since there are now five parameters to be optimized, the length of individuals should be changed to 50 accordingly. The upper and lower limits of each parameter were determined as $g_e \in [1,2]$, $g_{ec} \in [1,5]$, $g_p \in [0,1]$, $g_i \in [0.5,1]$ and $g_d \in [0,1]$.

## 4. RESULTS AND DISCUSSION

In order to test the effectiveness of the proposed control schemes and compare their control performance, the four different control schemes proposed in this paper were simulated by MATLAB. During simulation, the set voltage value was $U_s$=0.5 V, external load was $R$=400 Ω, and the sampling time was selected as $T_s$=1 h. The output voltage curves of MFCs with the four different controllers are given in Figure 4.

As can be seen from the figure, in the start-up stage, the overshoot of the output voltage of MFC was the largest when conventional PID controller was used and the smallest when GA-optimized fuzzy PID controller was used. Moreover, the adjustment time is the shortest when GA-optimized fuzzy PID controller was used. At the same time, it can be seen that the adjustment times of MFC with GA improved PID and fuzzy improved PID were not as short as that of that with conventional PID control, which indicated that the overall control effect was not particularly satisfactory when GA or fuzzy was used to optimize PID, while the fuzzy PID optimized by GA can make the MFC system achieve satisfactory control effect.

The comparison data of the main performance indicators of the MFC system under the action of several different controllers are shown in Table 1.

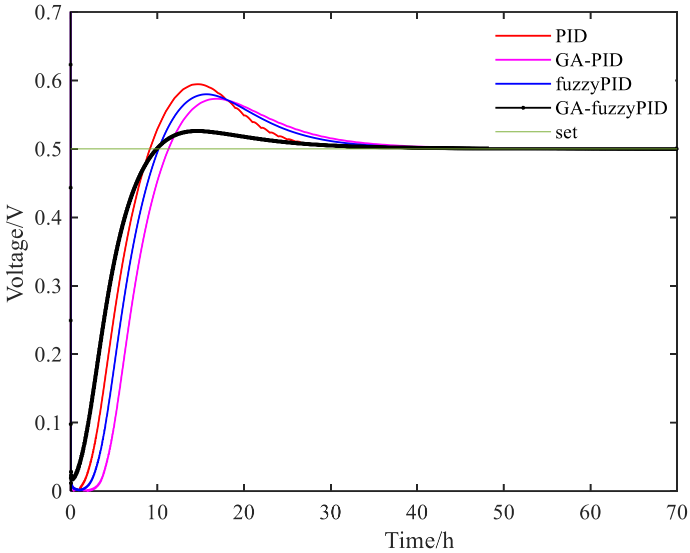


**Figure 4**. The output voltage curves of MFCs with four different controllers

**Table 2.** Comparison of control performance

| Control scheme | Adjust time/h | Maximum overshoot |
|---|---|---|
| PID | 26 | 19% |
| GA-PID | 33 | 15% |
| Fuzzy PID | 31 | 16% |
| GA Fuzzy PID | 23 | 5% |

When the MFC encounter load change, its output voltage will be affected and fluctuate, as shown in Figure 5, where the setting voltage was $U_s$=0.5 V, the initial external load was $R$=300 Ω, and the external load changed every 100 h, that were, when $t$=100 h, $R$=350 Ω; when $t$=200 h, $R$=500 Ω; and when $t$=300 h, $R$=400 Ω.

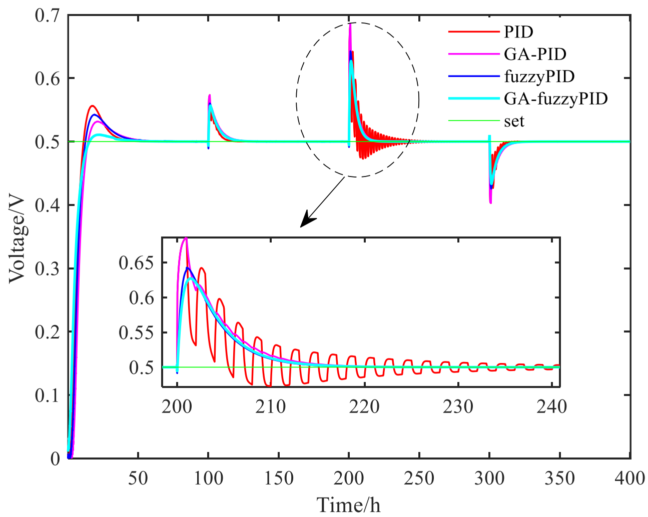


**Figure 5**. The output voltage of MFC when load changed

It can be seen from the voltage curves that whether PID control or fuzzy PID, GA-PID or GA improved fuzzy PID was used, the output voltage of MFC could return to the set point and basically stabilize in case of load change. However, it was obvious that when GA optimized fuzzy PID control was adopted, the adjustment time was shorter and the overshoot was the smallest. The comparison index data is shown in Table 3, in which, $t_d$ represents the time when the load disturbance occurs, and the allowable error range was set at ± 2%.

**Table 3.** Comparison of control performance under load change

| Controller | Transient time / h | | | Maximum overshoot | | |
|---|---|---|---|---|---|---|
| | $t_d$=100 h | $t_d$=200 h | $t_d$=300 h | $t_d$=100 h | $t_d$=200 h | $t_d$=300 h |
| PID | 8.9 | 26.5 | 9.0 | 15% | 37% | 19 % |
| GA-PID | 12.5 | 11.8 | 11.0 | 15% | 37% | 19% |
| Fuzzy PID | 10.9 | 10.5 | 9.6 | 12% | 29% | 15% |
| GA-Fuzzy PID | 11.2 | 10.8 | 10.3 | 11% | 25% | 13% |

The comparative analysis shows that the conventional PID control had certain anti-interference ability to load disturbance, and the adjustment time of PID control was the shortest in the first disturbance and the third disturbance but was the longest in the second disturbance, which shows that the control effect of PID is unstable in the face of working condition changes; and under all disturbance conditions, the overshoot generated by PID control was the largest, which further shows that the adaptability of PID controller is poor. When the GA improved PID controller (GA-PID) encounters disturbance different sizes, the adjustment times were basically the same, and the average adjustment time was better than that of conventional PID, but the overshoot had not been improved, which shows that GA optimization makes the operation performance of PID controller more stable, but it can not improve its control accuracy. Compared with the conventional PID and GA-PID controllers, fuzzy improved PID (fuzzy PID) controller has better adjustment time and overshoot, which shows that fuzzy control imitating human reasoning behavior has strong adaptability to disturbances. After the fuzzy PID controller was further optimized by GA, the GA-Fuzzy PID controller further reduced the overshoot, but the adjustment time increased slightly. Compared with fuzzy PID control, the adjustment time of MFC controlled by GA-Fuzzy PID controller was increased by about 4.2% on average, but the overshoot was reduced by 11.5% on average. Overall, the control effect of GA-Fuzzy PID is better than that of fuzzy PID.

The control effect of GA-Fuzzy PID scheme proposed in this paper can also be compared with some previous research results, and its advantages can be found. At present, there are not many literatures on MFC control methods. On the premise of using the same model as this paper to describe a MFC, a conventional fuzzy controller could make the output voltage of MFC gradually follow the given voltage value, but the response speed was slow, especially when the load was disturbed, the output voltage deviated greatly [24]; a model predictive control (MPC) scheme based on Kalman correction could make the MFC system obtain a more stable voltage output and the influence of interference on the system could be effectively suppressed, but the steady-state accuracy was not ideal, and the steady-state oscillation amplitude was about ± 9.5% [25]; an adaptive fuzzy control scheme based on variable universe used a scale factor to adjust the universe of the fuzzy controller in real time, so that it could eliminate the control dead zone and improve the control accuracy, however, the maximum overshoot in case of disturbance exceeded 20% [26]. The comprehensive comparison results show that the GA-Fuzzy PID control scheme proposed in this paper presents smaller steady-state error, smaller overshoot and shorter adjustment time, which significantly improves the dynamic and static performance of the system. This further shows the effectiveness of the control scheme proposed in this paper.

## 5. CONCLUSIONS

Advanced control is an effective way to ensure the reliable and efficient operation of complex systems. The conventional PID control has problems of large overshoot and long-time oscillation. GA can optimize PID parameters offline, which eliminates the long-term oscillation, though the adjustment time is still long and the offset is large. The fuzzy PID control effectively adjusts the parameters of the PID controller in real-time, which reduces the deviation between the actual output voltage and the set voltage value; in addition, the transient time is also greatly reduced, but control precision is a little insufficient. The GA-fuzzy PID controller, in which GA is used to optimize the quantization factor and scale factor of the fuzzy controller, make the system further reduce the offset. From the overall effect, the dynamic and static performance of the GA-fuzzy PID controller is the best. Optimizing the conventional PID through some advanced control methods such as fuzzy and GA is a simple, easy, low-cost but effective method to solve the problems of unstable power generation and poor anti-interference ability of a MFC system.

ACKNOWLEDGEMENTS
This work was funded by the National Natural Science Foundation of China (grant 61143007); the Chinese-North Macedonia Scientific and Technological Cooperation Project of Ministry of Science and Technology of the People's Republic of China (grant [2019] 22: 6-8), and the Plan for Distinguished Professors in Liaoning Province, China (grant [2014] 187).

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