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Neuro-fuzzy Control on a Permanent Magnet Synchronous Generator for a Vertical Tidal Turbine to Improve Output Voltage

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Abstract— This article aims to improve the output voltage efficiency of a Permanent Magnet Synchronous Generator (PMSG) with the benefit combination of Neural Networks and Fuzzy Logic. The previous both give a Neuro-fuzzy system tool. The PMSG is associated with a vertical-axis tidal turbine to produce electrical energy. PMSG and the vertical tidal turbine make up the studied system. Regarding the regulation and control of the Pulse Wave Modulation (PWM) rectifier at the output of the system, two controllers are explained and their performance is tested and compared: Maximum Power Point Tracking (MPPT) at Tip Speed Ratio (TSR) and MPPT Neuro-fuzzy.-The two control algorithms were simulated for a turbine operating at maximum mean efficiency with a flow of 1.5 m/s. It is shown that when an unregulated generator feeds a resistive and inductive load, the amplitude of the output voltages is more undulating compared with a tidal turbine equipped with MPPT-TSR and MPPT Neuro-fuzzy control systems. It shows that the optimal MPPT-TSR improves and stabilizes voltages by seeking the reference rotational speed as a variable to minimize the error between the measured and reference rotational speeds. The MPPT Neuro-fuzzy controller, on the other hand, offers a clear improvement and better stabilization of voltages by providing the reference rotational speed as instantaneous to minimize the error between the measured and reference rotational speeds. As for the MPPT Neuro-fuzzy controller, it offers a clear improvement and better stabilization of voltages by providing the reference speed of rotation as instantaneous to minimize the error between the recorded rotational speed and the specified reference speed.

Keywords— Tidal Turbine, Vertical Axis Turbine, PMSG, MPPT, Neuro-fuzzy, Lambda optimal, Output Voltage, Stability Energy system

ACRONYMS

DMST	– double multiple stream tube
HDR	– harmonic distortion rate
IGBT	– insulated gate bipolar transistor
MPPT	– maximum power point tracking
PI	– proportional integral
PMSG	– permanent magnet synchronous generators
PWM	– pulse wave modulation
TSR	– tip speed ratio

I. INTRODUCTION

An alternate technique to harness the energy of the tides is the development of tidal stream devices. This type of tidal

power technology is more practical for producing electricity because it doesn't have the same environmental risks or capacity constraints as tidal barrage plants. Big businesses are showing interest in this new power source for insular environments or underdeveloped countries. Research and development on this new source of energy are moving quickly. While engineers are working to create environmentally safe turbines, marine scientists are investigating the extent to which these may impact the environment.

So, hydropower is a candidate as one of the most interesting sources of renewable energy. These turbines harness the kinetic energy of river or marine currents, the equivalent of wind turbines. To produce energy, they require a water current speed of more than 1m/s on average [1],[2]. Horizontal-axis tidal current turbines have higher efficiency and have been developed by many renewable energy companies around the world. Nevertheless, vertical-axis tidal current turbines demonstrate contrasting conditions. The vertical type possesses some advantages that are cheaper in production, and easier to install because the generator can be placed on top, suitable for floating systems and others [3] (Figures 1 and 2).

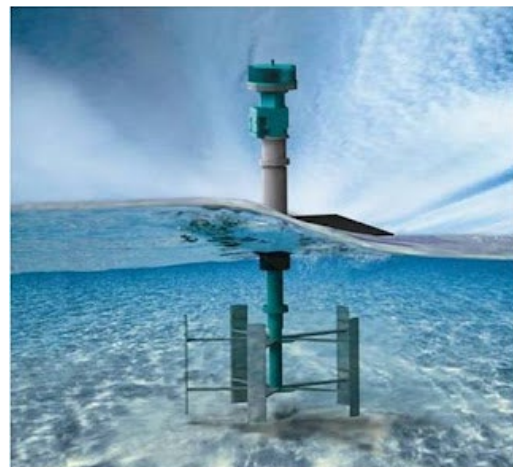


Fig. 1. Vertical axis turbine topology [4].

Tidal turbine applications use permanent magnet synchronous generators (PMSG) because of their excellent mechanical/electrical conversion efficiency of close to 99%

compared with asynchronous machines [5] and because they could be coupled or uncoupled with a speed multiplier [6].

Studies show that the vertical axis turbine provides a pulsating torque [7].

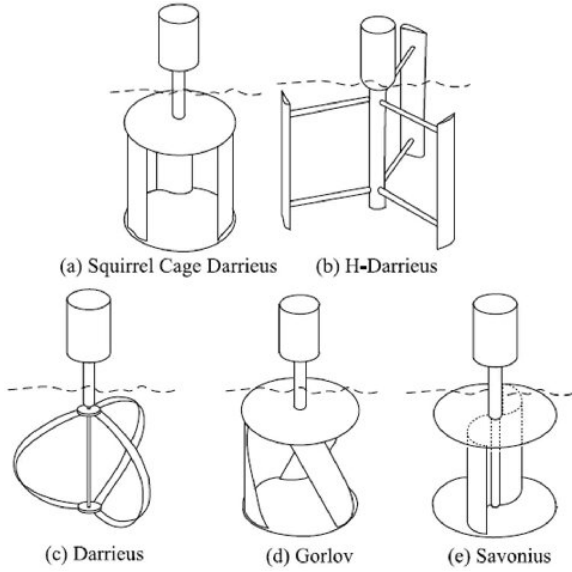


Fig. 2. Vertical axis turbine arrangements [5].

From this, the voltage/current or power output is unstable and oscillates. This oscillation of the voltage output is linked to the mechanical vibration induced by the water flow. So how can we reduce the time taken for the output power to become unstable in the transient phase? Is it possible to make the output power stable in the steady-state phase when producing electrical energy?

The solution most often proposed is to add a control system. There are several such systems, including PI, PID, neural networks, genetic algorithms, fuzzy logic, etc. [8],[9]. However, we propose here to use the Neuro-fuzzy algorithm for the system under study. Neuro-fuzzy systems [9],[10] are a type of artificial intelligence that combines the benefits of both fuzzy logic [11],[12] and neural networks [13],[14]. Neural networks excel in pattern recognition, whereas fuzzy logic is adept at managing imprecise or incomplete data.

In this study, a tidal turbine with a vertical axis of rotation coupled to a synchronous generator with direct drive permanent magnets is considered because of its pulsating torque [15], [16]. PMSG and the vertical tidal turbine constitute the system (figure 3).

Thus, our objective is firstly to observe the impact of the oscillation of the torque of the vertical axis turbine on the voltage at the output of the PMSG. And, secondly to test the best energy optimization for the whole system with the Neuro-fuzzy in comparison with the TSR. Harmonic distortion rate (HDR) and output voltage value are used as criteria to measure and analyze the performance of the tidal system controller for a given resistance and inductance load (R-L).

This article is organized into six sections. In section 2, the system under study is defined and is described as well as its architecture. Then, the two algorithm controllers are explained in section 3 for the MPPT-TSR and in section 4 for the MPPT Neuro-fuzzy. Simulation results are presented followed by discussions to assess the contribution in section 5. Finally,

Section 6 presents the conclusions derived from the preceding sections.

II. SYSTEM UNDERSTUDIED

The basic architecture of the system (without tuning) is formed by a vertical axis turbine coupled with a PMSG and supplying an RL load (Figure 3-a). Tidal turbines are somehow equivalent to wind turbines but they recover kinetic energy from river or sea currents. To produce energy, they will need a 1 m/s average of a current speed. The choice of PMSG is justified by its good performance

Thus it is used to attack directly without a speed multiplier compared to other existing generators such as asynchronous generator cage (AGC), dual-feed asynchronous generator (DFAG), synchronous generator (SG). The RL branch symbolizes the load equipped with three-phase voltage and current measurement systems.

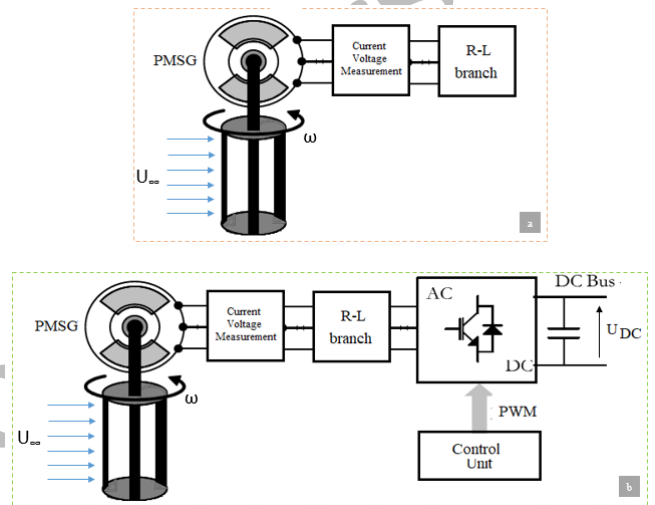


Fig. 3. a) Vertical tidal turbine studied with the R-L load, b) The system with rectifier and control unit.

For regulation, the system complete is illustrated in Figure 3-b. The release of the R-L branch was rectified for use on, the DC bus side. The Control Unit contains all adjustment systems: control of the tidal turbine, control vector of the PMSG as well that the generation of the PWM signal for the rectifier based on power transistors.

The tidal turbine under consideration uses, firstly, the MPPT method with optimum TSR [17] combined with a Proportional Integral (PI) corrector to control the turbine [18] and secondly, an MPPT Neuro-fuzzy strategy. Moreover, a vector control of the PMSG is combined with a PI corrector and the PWM rectifier is based on an insulated gate bipolar transistor (IGBT).

The mechanical power P_m produced by a water turbine represents a fraction C_p of the hydrodynamic power of a fluid from equation (1) [18]:

$$P_m = \frac{1}{2} C_p \rho A U_\infty^3 \quad (1)$$

with ρ is the density of the water in kg.m^{-3} , A is the cross-sectional area of the rotor in m^2 and U_∞ is the free stream velocity of the current in m/s.

The previous equation shows that the power and hence, the energy capture are highly dependent on the velocity. It increases quite rapidly with the current speed.

In understanding how turbines function in water, one important factor is the advance ratio. It measures how fast the turbine blades move relative to the upstream flow velocity.

The advance ratio λ , is given by equation (2)[18]:

$$\lambda = \frac{\omega r}{U_\infty} \quad (2)$$

with ωr is the peripheral velocity of the blades in m/s.

III. THE MPPT-TSR CONTROLLER

A turbine is characterized by its maximum power coefficient C_p corresponding to the optimum value of the advance ratio λ_{opt} . The reference rotation speed is obtained by exploiting equation (3) and replacing the value of the specific speed with its optimum value.

$$\omega_{ref} = \frac{\lambda_{opt} U_\infty}{r} \quad (3)$$

Firstly, the turbine is controlled using the MPPT control method with optimum TSR [17] [18]. It is to extract maximum mechanical power from the water flow at the level of the turbine. Figure 4 explains the MPPT-TSR algorithm.

It consists of setting up a PI regulator at the output to compare the reference rotation speed defined previously with the mechanical speed measured at the system output. This regulator will take the measurement error at its input to generate an electromechanical torque serving as a reference for the PMSG control.

Secondly, the PMSG control will in turn ensure the generation and regulation of the electromagnetic torque on the PMSG shaft before being compared to the mechanical torque coming from the turbine.

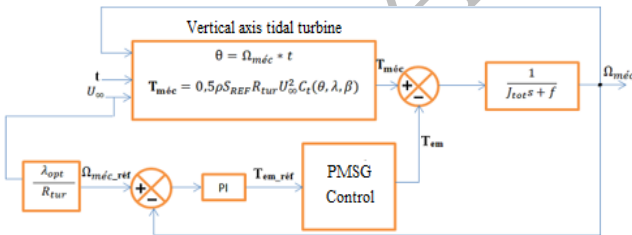


Fig. 4. Simplified MPPT-TSR schematic diagram.

This controller promotes the optimal exploitation of tidal energy. Still, such a strategy is based on MPPT with knowledge of the characteristics of the advanced parameter C_p (λ) of the tidal turbine [18], [19]. This is why, subsequently, we will use MPPT based on artificial intelligence.

IV. THE MPPT NEURO-FUZZY CONTROLLER

At this stage, the same electrical chain structure is used and the control of the turbine will be done by MPPT Neuro-fuzzy shown in Figure 5. By adopting fuzzy logic ensemble rules [12], such a fuzzy device handles the variation in extracted power ΔP_t and rotational speed at the turbine that results in a

change in the mechanical speed set-point of the tidal turbine. ΔP_t and $\Delta \omega_t$ are the variation power and rotational speed respectively at time n-1 and at time n.

The MPPT Neuro-fuzzy control consists of modeling the turbine's mechanical power by a neural network as a function of turbine flow and rotation speed, with an MPPT by a fuzzy logic system based on time, rotation speed, and power for the rotation speed's reference generation [13], [14].

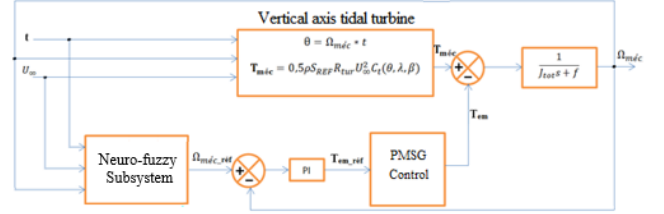


Fig. 5. Simplified MPPT Neuro-fuzzy schematic diagram.

This is interesting because, even at the constant flow velocity, the vertical axis turbine provides an oscillating torque and consequently the power varies according to the positions of the blades [20], [21].

The actual rotational speed of the generator measured by the speed sensor mounted on the rotor shaft is compared to its reference value and then the speed error is corrected by a PI regulator [22].

On the rectifier side, the control of the power transistors is done by Pulse Width Modulation [23].

V. RESULTS AND DISCUSSIONS

The numerical simulation of the water turbine is based on the double multiple stream tube (DMST) method that has been developed at the University of Pisa [24].

In a DMST model, the rotor is segmented into a front half-cycle (upstream) and a rear half-cycle (downstream). The flow passing through a rotor with a radius 'r' is divided into a series of neighboring stream tubes, each containing two actuator plates arranged in sequence [25],[26].

Table 1 summarizes the physical parameters of the tidal turbine for the simulation done with Matlab.

TABLE I. PHYSICAL PARAMETERS OF THE TIDAL TURBINE

Parameters	Symbol	Value
Speed of sea currents	U_∞	1.5 m/s
Rope length	C	156 mm
Turbine radius	r	455 mm
Turbine height	h	824 mm
Wedge angle	β	0 °
Canopy inertia	J_t	1.5 kgm ²
Friction	f_t	0.025 Nms/rad
Torque	T_{mec}	103.5 Nm (min) 197.9 Nm (max)
Advance ratio	λ	0 to 4
Resistance	R	0.3 Ohms

Inductance	L	0.004 Henry
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To find the maximum power coefficient C_{Pmax} , the evolution of the power coefficient C_p over a revolution as a function of the advance ratio λ is plotted in Figure 6-a. Then, the optimal advance ratio is deduced. It forms the typical bell curve like that of a wind turbine [26]. The power coefficient increases from 0 to 55%. 55% corresponds to the maximum power coefficient *for* an optimal advance ratio equal to 2.2.

The evolution of the average power of this turbine is presented in Figure 6-b, with a maximum value of 692 W corresponding to an optimal rotation speed of 7.25 rad/s or 69.25 rpm.

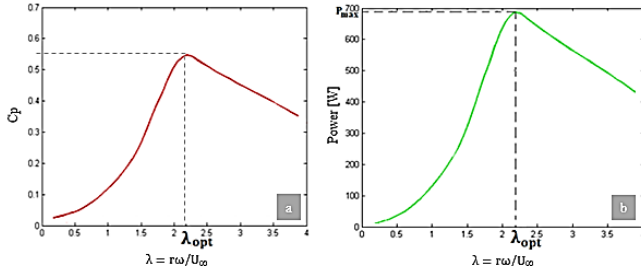


Fig. 6. Evolution, a) of the power coefficient C_p and b) of the average power as a function of the advance ratio λ .

To observe the impact of the oscillated torque on the power generator and to test the best energy optimization for the whole system, simulation of the assembly (turbine and PMSG with or without load control system) is carried out under the following conditions: U_∞ of 1.5 m/s, λ_{opt} of 2.2, C_{Pmax} of 0.55, maximum power of 692 W at the optimal turbine rotation speed of 7.25 rad/s.

The harmonic distortion rate (HDR) or the total distortion harmonic (TDH) defines the root mean square (RMS) of the harmonic content, including the harmonic components, up to 50th order and it is expressed as a percent of the fundamental. Inter-harmonics are specifically excluded. The output voltage value and its HDR are used as the measure's criterion to discuss and analyze the performance of the system.

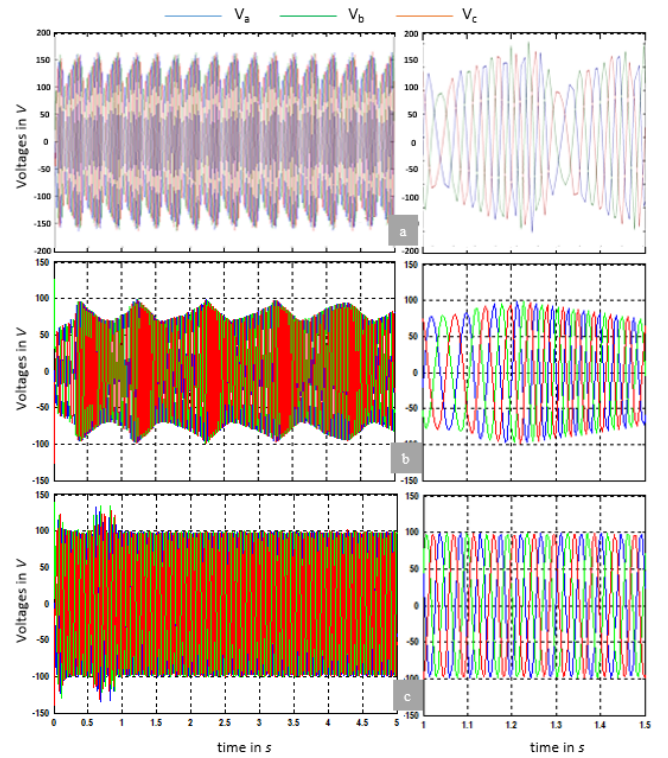


Fig. 7. Output voltage diagram a) without adjustment (No MPPT), b) with MPPT-TSR, and c) with MPPT Neuro-fuzzy.

The curves in Figure 7 show the evolution of the three-phase voltages (V_a , V_b , V_c) at the output of the PMSG in the absence or presence of the regulation. By results found in the literature, the amplitude envelopes have the same shapes as the oscillated torque (Figure 7-a). However, for the voltage evolutions according to the shapes in Figures 7b and 7c, this effect is attenuated in the case of the tidal turbine fitted with a regulation system.

Among these regulations, those based on MPPT-TSR show more disturbed amplitudes. We still observe a slight fluctuation (Figure 7-b)). This is due to the use as a reference of the average speed which must not be a constant value because the torque of the vertical axis turbine is oscillated.

Those with MPPT Neuro-fuzzy which provides an instantaneous reference rotation speed that evolves at the same speed as the torque minimize the error between the measured speed and the reference speed, even with a constant speed flow (Figure 7-c). So, we get results satisfactory with the MPPT Neuro-fuzzy since the impact of torque is no longer displayed on the voltage output from the PMSG.

The mechanical and electrical powers are plotted versus time in Figure 8. In Figure 8-b and 8-c, the duration of the transient phase decreases.

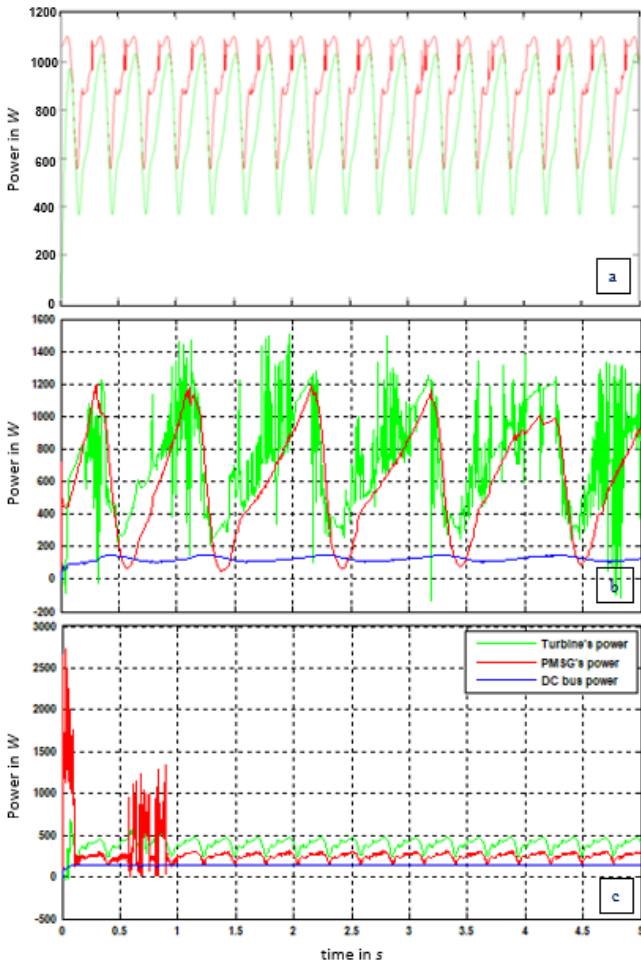


Fig. 8. Mechanical and electrical powers a) without adjustment (No MPPT), b) with MPPT-TSR, and c) with MPPT Neuro-fuzzy.

It goes from 1.5 seconds for the MPPT-TSR to 0.9 seconds for the MPPT Neuro-fuzzy. Said transient phase characterizes the transition of the system toward a stable state.

Table 3 indicates that the MPPT Neuro-fuzzy algorithm becomes stable very quickly after 0.9 seconds compared to the MPPT-TSR algorithm of 1.5 seconds. Also, there is no stability in case of no MPPT adjustment.

On the performance side of the regulation systems, Table 3 summarizes the controller performance analysis between the three algorithms: no MPPT, MPPT-TSR, and MPPT Neuro-fuzzy.

TABLE II. TRANSITION PHASE DURATION

	No MPPT	MPPT-TSR	MPPT Neuro-fuzzy
Transition phase duration (s)	Unlimited	1.5	0.9

TABLE III. CONTROLLER PERFORMANCE ANALYSIS

	No MPPT	MPPT-TSR	MPPT Neuro-fuzzy
I_{max} (A)	2.7	12.5	1.8
V_{max} (V)	170	90	100
P_{DCBus} (W)	0	120	125

η (%)	65	80	95
HDR (%)	45	20	5

The efficiency η in % is defined by the ratio between the power's electric, P_{PMSG} , and P_{DCBUS} compared to the mechanical power P_{MEC} supplied by the turbine, illustrated in Figure 8. It shows that the system with MPPT Neuro-fuzzy controller, with 95% of η , is more efficient than the MPPT-TSR with 80%.

To finish, with an HDR of 5% compared with 20%, the MPPT Neuro-fuzzy regulator continues to demonstrate superior performance compared to the MPPT-TSR. It reliably maintains stable output voltage to power the electrical network.

VI. CONCLUSIONS

A vertical-axis water turbine with a radius of 455 mm and a height of 824 mm is considered, with a flow rate of 1.5 m/s minimum torque of 103.5 Nm, and maximum torque of 197.9 Nm. Moreover, concerning the simulation of the system, the impact of the oscillation of the torque of the vertical axis turbine on the voltage at the output of the PMSG is observed on the trend of the currents and voltages at the output of the system. With the MPPT Neuro-fuzzy, better energy optimization of the whole system is observed. This is justified by a time performance very fast compared to other regulations. Between 45%, 20%, and 5% of HDR, the minimum value is about the use of the Neuro-fuzzy controller.

Comparing the performance of the Neuro-Fuzzy control system with other control methods, such as Optimal TSR control, in terms of voltage regulation and energy production. This research would provide insights into the relative advantages and limitations of Neuro-Fuzzy control for tidal turbine applications. This article demonstrates an integration of adaptive control in which could account for varying tidal conditions and load demands, ensuring stable and efficient voltage output. Modeling tidal dynamics by incorporating accurate tidal flow modeling into the Neuro-Fuzzy control system could enable more precise predictions and proactive adjustments to maximize voltage output under different tidal conditions. This contributes to the overall reliability and performance of the tidal turbine system and to the broader field of control engineering by demonstrating the efficacy of hybrid intelligent control techniques in challenging and dynamic operating environments.

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