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Iranian Journal of Electrical and Electronic Engineering

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Variable Step-size Hill-Climbing Search (VS-HCS) MPPT Algorithm for Hydrokinetic Energy Harnessing

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Abstract: Hydrokinetic energy harnessing has emerged as a promising renewable energy that utilizes the kinetic energy of moving water to generate electricity. Nevertheless, the variation and fluctuation of water velocity and turbulence flow in a river is a challenging issue, especially in designing a control system that can harness the maximum output power with high efficiency. Besides, the conventional Hill-climbing Search (HCS) MPPT algorithm has weaknesses, such as slow tracking time and producing high steady-state oscillation, which reduces efficiency. In this paper, the Variable-Step Hill Climbing Search (VS-HCS) MPPT algorithm is proposed to solve the limitation of the conventional HCS MPPT. The model of hydrokinetic energy harnessing is developed using MATLAB/Simulink. The system consists of a water turbine, permanent magnet synchronous generator (PMSG), passive rectifier, and DC-DC boost converter. The results show that the power output achieves a 28 % increase over the system without MPPT and exhibits the lowest energy losses with a loss percentage of 0.9 %.

Keywords: Hill-Climbing Search, Hydrokinetic Energy Harnessing, MPPT Algorithm

1 Introduction

RECENTLY, renewable energy has become attractive worldwide, and many are slowly transitioning from fossil-fuel electric generation to renewable energy [1]. Additionally, most countries offer incentive programs such as tax exemptions, rebates, grants and subsidies to encourage the adaptation of renewable energy technology [2]. Despite having no access to power, one-third of the world's population does have access to flowing water [3], [4]. Most remote areas near flowing water are impoverished, with poor living conditions and limited access to modern infrastructure [5]. Typically, they prefer diesel-powered generators for electricity generation [6]. Unfortunately, this remains unsustainable due to rising gasoline prices and logistics challenges in remote locations. As a solution, renewable energy is the most suitable option for delivering electricity to rural areas due to clean and stable energy sources[7].

Even though wind energy, biomass, hydro, solar, and geothermal energy are types of renewable energy sources, hydropower is the ideal choice for contributing to global energy generation. It is constantly available, has high energy density, is robust and reliable, and is independent of random weather conditions. Additionally, it has less impact on the environment and human activity than solar and wind energy [8] . Furthermore, hydropower as a renewable energy source is a viable option for electrifying islands and remote areas using hydrokinetic devices, thereby reducing the country's high reliance on fossil fuels [9].

Nevertheless, conventional electricity generation using fossil fuels leads to greenhouse gas emissions and environmental problems. Additionally, natural gas and crude oil sources are rapidly depleting. Therefore, to reduce the effects of global warming and dependence on fossil resources, renewable energy is the best choice to

Iranian Journal of Electrical & Electronic Engineering, 2025.
Paper first received 05 Dec 2024 and accepted 23 Feb 2025.
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preserve the environment and is considered a viable solution to electricity demands due to its natural replenishment and sustainability [10] . Furthermore, in rural areas, access to electricity is limited. The location and geographical structure of these areas restrict their access to current developments. Hence, renewable energy resources based on hydrokinetic technology are a viable option for remote communities [11].

Hydrokinetics utilizes the kinetic energy from flowing water from the river stream, waves, tides and ocean current [12]. This form of energy depends on the water velocity profile to ensure the turbine can produce electricity consistently. The variation and fluctuation of water velocity in the river are one of the challenging issues, especially in extracting energy with high power output. Thus, the MPPT algorithm is employed as a control strategy to extract the maximum power under variations in water flow [13].

Several MPPT algorithm for hydrokinetic energy harnessing have been discussed in [14]–[18]. In [14]–[16] the Hill-Climbing Search are proposed to improve the energy extraction of the power output. The conventional MPPT algorithm, such as Hill-Climbing Search (HCS), is commonly used due to its simplicity and easy implementation [19]. Nevertheless, the conventional HCS has a limitation in terms of efficiency and response time. To improve the tracking efficiency the soft computing based MPPT have been introduced such in [17] where the fuzzy logic controller was implemented. Besides, the hybrid MPPT algorithm such as combination of conventional HCS and fuzzy logic controller also could be considered such in[18].

In this paper, the variable step-size Hill-climbing Search (VS-HCS) MPPT algorithm is proposed to improve the steady-state oscillation, response time and efficiency of the power output for hydrokinetic system. The proposed algorithm can intelligently observe the distance between the operating and maximum points based on the curve's region defined in the computational algorithm. Therefore, the appropriate step size will make it an efficient technique for rapid MPP tracking.

2 Methodology

2.1 Modelling of Hydrokinetic System

The modelling of hydrokinetic system consists of water turbine that captures the kinetic energy from the river stream as shown in Figure 1. Due to unpredictable water fluctuates, the input water velocity is considered from 0.2 m/s to 2.0 m/s. This is a typical water speed variation for river streams, especially in Malaysia [4], [20], [21]. Further, the mechanical energy from the hydrokinetic turbine a used to drive the permanent magnet synchronous generator (PMSG). Three-phase rectifier mainly converts the AC to DC before boosting it to a higher level in the DC-DC boost converter.

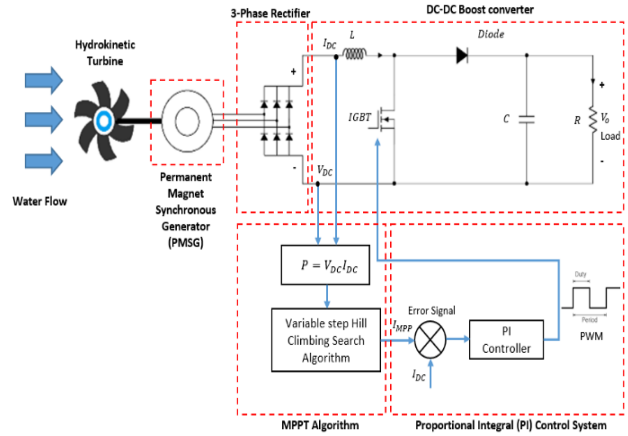


Fig 1. Modelling of hydrokinetic energy harnessing

2.2 Turbine Model and Characteristics

The mechanical power Pm generated by a water turbine can be calculated using the Eq.(1)

$$P_m = \frac{1}{2}\rho A V^3 C_p(\beta,\lambda) \tag{1}$$

Where, ρ is water density (1000 Kg/m3), A is the cross-sectional area of the turbine (m^2), V is the water current velocity (*m/s*) and C_P is the power coefficient of the turbine. The pitch angle (β) is fixed for the small-size turbine. Thus, the C_P is merely a function of the Tip Speed Ratio (λ) which is the ratio of the linear speed of the blade to the water current velocity. Besides, C_P is represented the turbine's characteristic and given by Eq. 2 [22]

$$C_P(\lambda) = -0.022\lambda^6 + 0.04\lambda^5 - 0.26\lambda^4$$
$$+0.72\lambda^3 - 0.77\lambda^2 + 0.27\lambda - 0.011 \tag{2}$$

In practical applications, the *Cp* usually falls within the range of 0.4 to 0.45, although its theoretical maximum value is approximately 0.59 [23]. The tip speed ratio (TSR) is a parameter that quantifies the ratio between the linear speed of the blade tips and the rotational speed of the turbine. Mathematically, it can be represented as Eq. (3):

$$\lambda = \frac{\omega_m R}{V_w} \tag{3}$$

2.3 Modelling of Permanent Magnet Synchronous Generator (PMSG)

The PMSG is widely favored as an electric generator due to its exceptional attributes, including high efficiency, power density, reliability, gearless construction, lightweight design, and self-excitation capabilities [15]. In this study, we adopt a simplified model of the PMSG as stated in [24]. In order to make analysis more accessible, the model represents the generator and rectifier through an analogous circuit seen from the DC side of the rectifier.

Figure 2 presents an equivalent circuit of PMSG under open circuit condition. Where, an electromotive force (EMF) denoted as e_w and its equivalent resistance is labeled as R_w.The EMF is directly proportional to the generator speed (ω_m) as in Eq. (4) , while the R_w is set to twice the per-phase resistance of the generator.

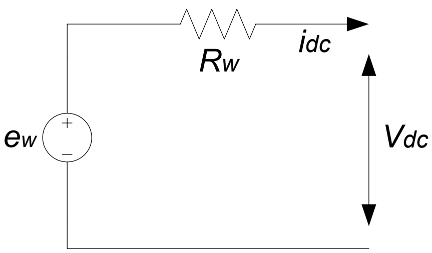


Fig 2. Equivalent circuit of PMSG model

$$e_w = k_w \omega_m \tag{4}$$

By disregarding the effects of damping and friction, the mechanical dynamics can be simplified as in Eq. (5)

$$J\frac{d\omega_m}{dt} = T_m - T_e \tag{5}$$

While T_e is equal to,

$$T_e = \frac{P_e}{\omega_m} = \frac{e_w i_{dc}}{\omega_m} = K_w i_{dc} \tag{6}$$

where K_w represents the EMF generator constant, T_m represents the mechanical torque, and T_e denotes the generator torque.

2.4 Modelling of Boost Converter

Boost converters consist of several components, including inductance, a power switch, a diode, and an output capacitor. Additionally, the incorporation of a few sensors is essential to enable the function of MPPT. Boost converters exhibit two operational states during continuous conduction mode: the switch-on and switch-off conditions. In the switch-ON state, the inductor's current rises linearly until a driving signal is interrupted. The input voltage of the boost converter is denoted as V_{in}. When the switch is turned ON, the output capacitor acts as the voltage source in the circuit. Eq. (7) and (8) can be formulated to describe the switch-on state, assuming negligible forward voltage drop across the diode. T_p represents the switching period in these equations.

$$V_L = L\frac{dI_L}{dt} \Rightarrow L = V_{in}\frac{dt}{dI_L} \tag{7}$$

Equation (7) can be written as

$$L = V_{in}\frac{dt}{dI_L} = \frac{DT_p}{\Delta I_L} \tag{8}$$

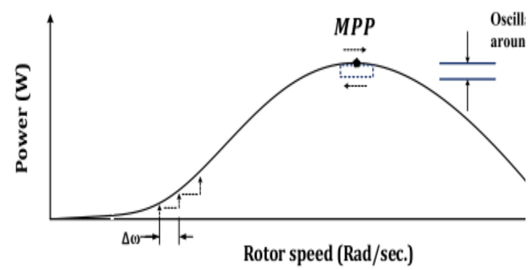
During the switch-OFF phase, the energy stored in the inductor is transferred to a load via a diode. The combined voltage of the input and inductor is applied to the load, leading to the formulation of the Eq. (9) and Eq. (10) respectively.

$$V_{out} = V_{in} + V_L \tag{9}$$

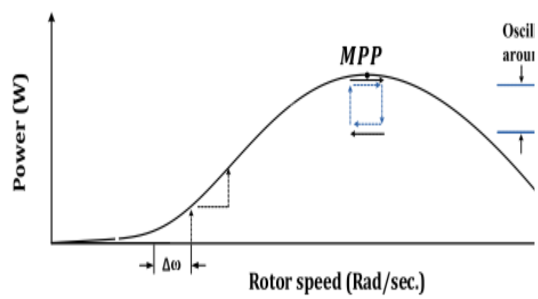
$$V_L = L\frac{dI_L}{dt} \Rightarrow L = \left(V_{out} - V_{in}\right)\frac{dt}{dI_L} \tag{10}$$

Where, V_{out} represents the voltage at the output, while V_L refers to the voltage across the inductor. The increase and decrease in voltage across the output capacitor are identical, and the output voltage value can be determined using Eq. (11). In this equation, V_{out} represents the output voltage of a boost converter, and I_{out} corresponds to the output current.

$$V_{out} = \frac{1}{C}\int I_{out}dt \Rightarrow C = \frac{DI_{out}T_p}{\Delta V_{out}} \tag{11}$$



(a) Small step-size HCS



(b) Large step-size HCS

Fig 3. A comparison between small step-size and large step-size for the conventional HCS MPPT algorithm.

2.5 Conventional Hill-Climbing Search (HCS) MPPT Algorithm

The conventional HCS involves two significant problems: decreasing dynamic steady-state performance and increasing total power loss at water velocity fluctuations. The tuning of the perturbation required some computational algorithm for step size to determine the moving tracking point increment. The conventional HCS applied to fix step size in their perturbation execution. Nevertheless, the system takes longer to reach the maximum point when the step size increment is too small. In contrast, if the increment is too large, the system has significant oscillations near the maximum power point as shown in Figure 3 (a) and (b) respectively.

2.6 Proposed Variable Step-size Hill Climbing Search

A variable step-size HCS MPPT algorithm is proposed to create balance tracking controllability and speed tracking to overcome the drawback of conventional HCS MPPT algorithm. It can intelligently observe the distance between the operating and maximum points based on the curve's region defined in the computational algorithm. Therefore, the appropriate step size will make it an efficient technique for rapid MPP tracking.

The concept of variable step-size HCS is based on dividing the optimal P-ω curve into four separation regions as shown in Figure 4. The region 1 until region 4 is determined by comparing the specific ratio, R_k with the synthesized ratio, $\left(\left|\frac{\Delta P_c(n)}{P_c(n)}\right|\right)$. The k is represents the number either in forward or reverse perturbation region while R is comparing ratio where $\varepsilon < R < 1$ as detailed in Table 1. The synthesized ratio is obtained by calculating the optimal mechanical power from Eq. (1). While, the values of R_k is taken from metaheuristic method based on power accuracy variation around the MPP. Here, more than 100 times continuous simulations were conducted, and the power-speed curve pattern have been analysed to estimate the probability value of the R_k.

The computational algorithm used a variable step size that constantly changes depending on the location of the tracking point in which region. For example, the nearest region with a peak point employed a small step size while the far region employed a large. As a result, a small step size makes the output more precise and less oscillation while approaching a maximum point. In contrast, a large step size will affect rapid tracking time. Therefore, it can eradicate conventional algorithms' drawbacks in speed tracking and steady-state oscillation.

Table 1. Value of Specific ratio and respective step size

Region	Specific ratio, R_k	Step size ($\Delta\omega$)
Region 1	0.6	$\Delta_{\omega 1} = 0.2$
Region 2	0.4	$\Delta_{\omega 2} = 0.1$
Region 3	0.12	$\Delta_{\omega 3} = 0.05$
Region 4	$0 < \varepsilon < 0.12$	$\Delta_{\omega 4} = 0.01$

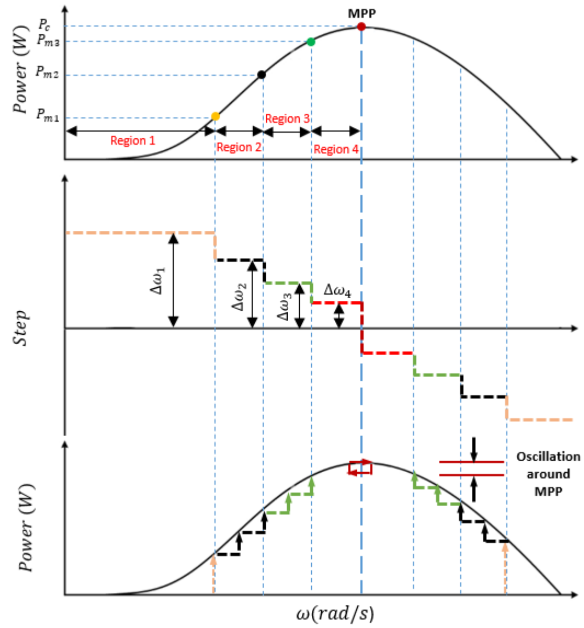


Fig 4. The concept of variable step-size HCS MPPT Algorithm

The following step describes a variable step-size HCS MPPT algorithm. The flowchart of this MPPT algorithm can be referred to Figure 5.

Step 1: Measure the power output $P_\omega(n)$, rotor speed ω_n, and set reference rotor speed as $\omega_{ref} = \omega(n)$

Step 2: Calculate the power change $\Delta P_\omega = P_\omega(n) - P_\omega(n-1)$, and evaluate the power change $\Delta P_\omega > 0$

Step 3: Calculate the normalized power change i.e synthesized ratio $\left|\frac{\Delta P_c(n)}{P_c(n)}\right|$, and compare with the thresholds R_1, R_2, R_3, R_4 to determine the appropriate step size adjustment

Step 4: the rotor speed depending on the comparison results, adjust the rotor speed using different step size, $\omega(n+1) = \omega(n) + \Delta_\omega$

Step 5: Check the convergence until the change in power output stabilized

Step 6: Update and repeat the process for next iteration

By following these steps, the algorithm efficiently tracks the MPP by dynamically adjusting the rotor speed with variable step sizes, ensuring optimal power extraction from the water turbine. If the power output increases, the rotor speed is adjusted in the same direction using a step size determined by the magnitude of the power change, with larger steps used when power changes significantly and smaller steps for minor changes. If the power output decreases, the direction is reversed. This dynamic adjustment helps in quickly approaching the MPP while fine-tuning the rotor speed to maximize power extraction. The process iterates until the power output stabilizes, indicating that the maximum power point has been reached. This method ensures efficient and adaptive optimization of the turbine's performance under varying flow conditions.

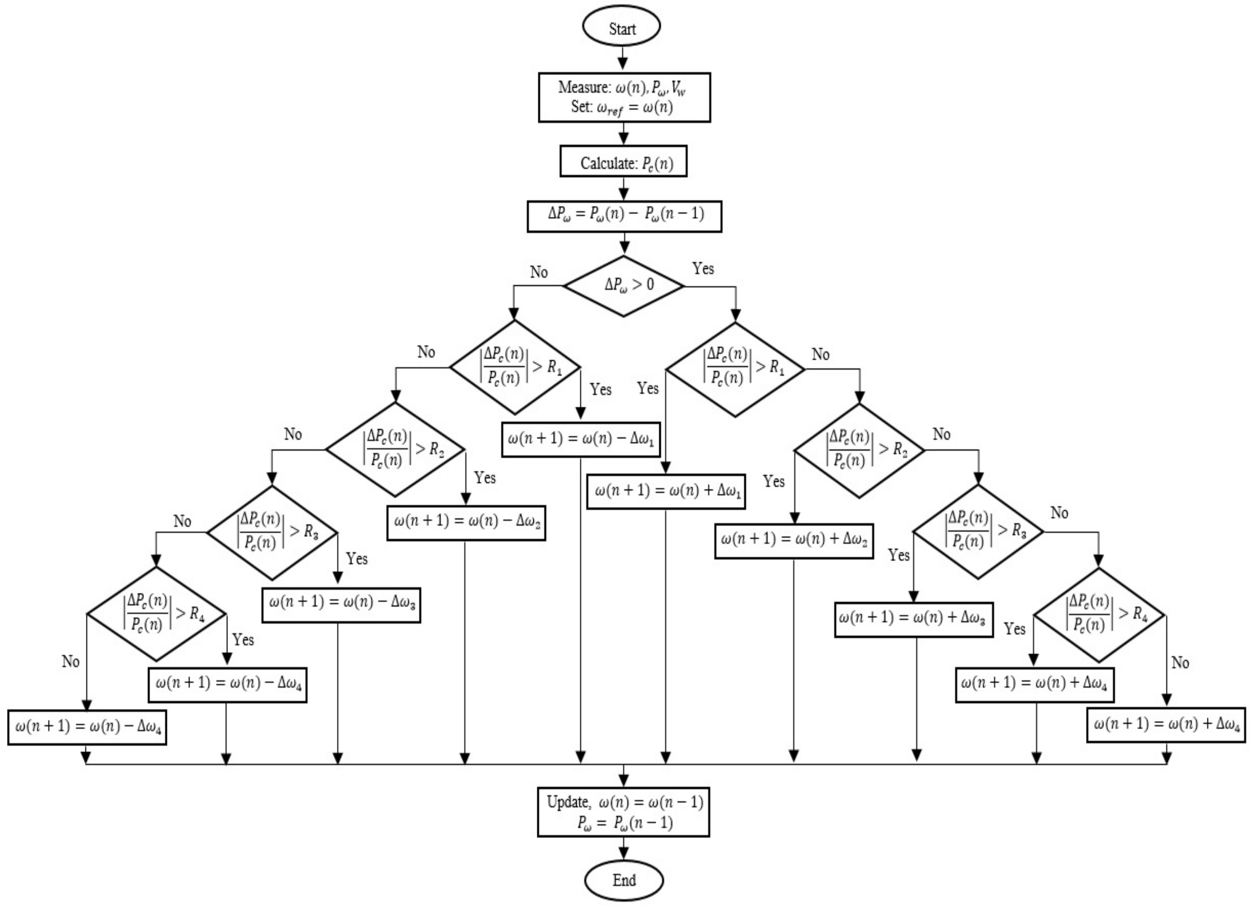


Fig 5. Flowchart for Variable step size HCS MPPT algorithm

3 Results

In this paper, all the simulations were carried out using MATLAB/Simulink on Window 10 notebook-featuring by the AMD Ryzen 7 4800H Processor, 8 Cores, 16 Thread, 2.9 GHz to 4.2 GHz with 16 GB RAM. Table 2 shows the parameter settings that have been applied in this study including the turbine, permanent magnets synchronous generator and boost converter specification respectively. In order to evaluate tracking efficiency and energy losses, multiple simulations were performed to validate the stability of the system and the effectiveness of the metaheuristic MPPT algorithm.

3.1 Maximum Power extraction

The tracking ability of the MPPT algorithms are different depending on their configuration and parameter setup. In this paper, VS-HCS MPPT will be compared with the conventional HCS MPPT and a system without MPPT algorithm. Each system is simulated with input water speed velocity that fluctuated from 0.2 m/s to 2.0 m/s. Figure 6 shows the output power that has been generated during the simulation.

Table 2. Parameter setting used in MATLAB/Simulink

Components	Parameter setting	Values
Water turbine	H-Darrieus	
	Radius	0.3 m
	Height	0.8 m
	Swept Area	0.48 m^2
	Water density ρ	1000 kg/m^3
	Pitch Angle β	Fixed
PMSG	Stator Resistance R_s	2.875 Ω
	Inductance (L_s)	0.0085 H
	Poles	12
	Flux Density	0.175 Wb
Boost Converter	Input Capacitor, C_{in}	100 (μF)
	Output Capacitor, C_{out}	245 (μF)
	Inductance, L	1.85 (mH)
	Load Resistance R_{Load}	10 (Ω)
	Switching Frequency,f_s	20 (kHz)

It is observed that, without the MPPT algorithm, the output power or energy extraction is lower compared with the MPPT algorithm. The result shows that without the MPPT algorithm the system only can generate 547 W. Nevertheless, when the conventional HCS with a fixed step size is applied, the output power is increased to 664 W. According to Mouse et al. [25] the increase of the energy extraction is due to perturbation execution in the HCS MPPT algorithm when the algorithm is trying to locate the optimal maximum power point (MPP).

As a proposed VS-HCS MPPT algorithm is applied, the output power is increased significantly and achieved 701 Watt. The algorithm intelligently established the perturbation direction by calculating directly the distance between operating points and comparing it with optimal varying curves. In addition, the concept of the VS-HCS is by dividing the P-ω curve into several segment using synthesize ratio, $\left|\frac{\Delta P_c(n)}{P_c(n)}\right|$ and compared with the specific ratio, R_k in determining the suitable step-size.

Table 3 shows the comparison of energy extraction at maximum power point during dynamic steady-state conditions with and without MPPT algorithms. Without an MPPT algorithm, the system extracts 547 Watts of power. By implementing a conventional HCS algorithm, the power extraction is increased to 664 Watts, marking a 21% improvement. On the other hand, VS-HCS further enhances the power extraction to 701 Watts, resulting in a 28% increase over the system without MPPT. This comparison highlights the significant efficiency gains achieved through the use of MPPT algorithms, particularly the VS-HCS, which demonstrates the highest improvement in power extraction.

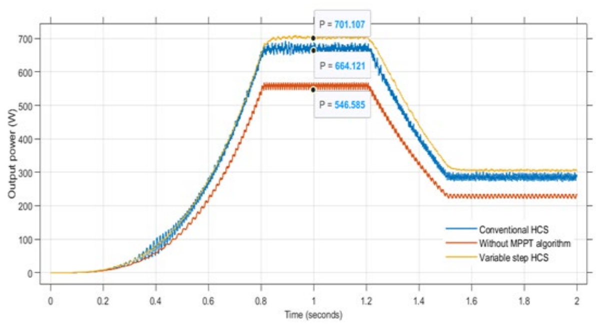


Fig 6. The comparison of the output power based on different water velocity with and without MPPT Algorithm.

Table 3. The comparison of energy extraction at maximum power point at dynamic steady -state with and without MPPT algorithms

Method (%)	Power	Increasing
Without MPPT algorithm	547 Watt	-
Conventional HCS	664 Watt	21 %
Variable step size HCS	701 Watt	28 %

3.2 Steady-state Oscillation and Energy Loss

Figure 7 shows the magnification view of oscillation output power during dynamic steady-state. An oscillation occurs during the perturbation execution due to the reaction system toward water fluctuation. As shown in waveform, the oscillation is higher for conventional HCS and without the MPPT algorithm, which leads to increased power losses from ripple power. Contrastingly, the proposed variable step size HCS tends to reduce the oscillation significantly and diminish the overshoot.

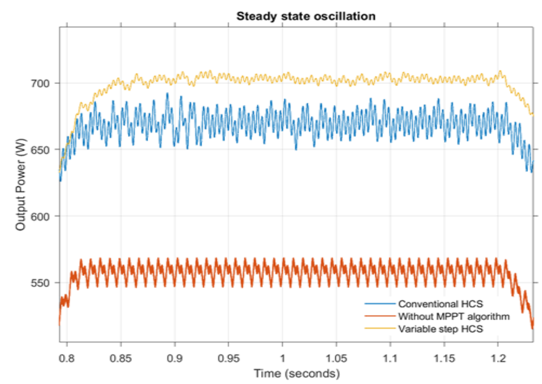


Fig 7. The oscillation at the output power during dynamic steady-state (after zooming)

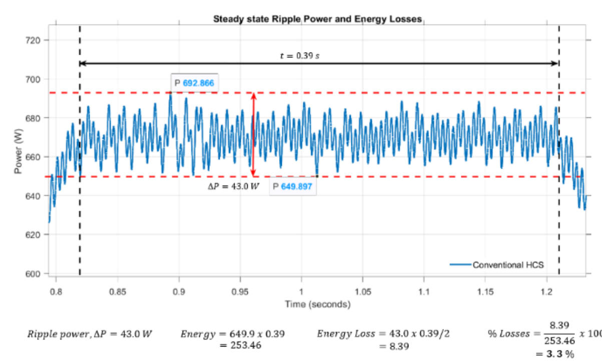


Fig 8. The energy loss calculation for conventional HCS MPPT algorithm during dynamic steady-state oscillation.

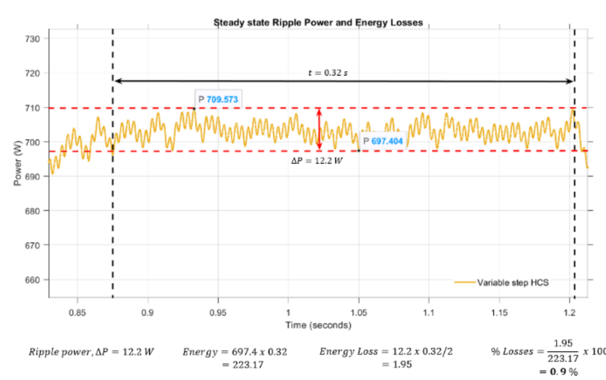


Fig 9. The energy loss calculation for variable step-size HCS MPPT algorithm during dynamic steady-state oscillation.

In other words, the MPPT algorithm is able to improve the energy extraction, but the oscillation rate depends on the computational technique applied to the system. For this reason, we had modified the conventional HCS MPPT algorithm and incorporated variable step-sizes according to different perturbation regions. A variable step-size HCS MPPT algorithm will produce less steady-state oscillation in the output power as well as reduce power losses.

Figures 8 and 9 illustrate the energy losses at certain time intervals for each MPPT algorithm. Comparatively, systems without MPPT and those using conventional HCS produce high ripple power. Consequently, the power losses are very high, making the system less efficient. This suggests that the VS-HCS MPPT algorithm is particularly effective in enhancing the output power, showcasing it potentials for reducing power losses.

The details feature selection results obtained from simulation provide valuable insight into energy losses of each algorithm, which are presented in Table 4. The VS-HCS exhibits lowest energy losses at 1.95 W with a loss percentage of 0.9 %. This indicates that the VS-HCS algorithm is particularly effective in reducing power losses and enhancing system efficiency. The variable step size adjustment helps in minimizing the oscillations and losses compared to both conventional HCS and systems without MPPT.

Table 4. The energy losses comparison with and without MPPT algorithm during dynamic steady-state oscillation

Method	Energy loss (W)	Losses (%)
Without MPPT algorithm	4.38	2.0
HCS	8.39	3.3
VS-HCS	1.95	0.9

Table 5 shows a detailed comparison of theoretical and output power for a hydrokinetic system during steady-state oscillation at various water velocities, with a specific focus on the performance enhancements provided by MPPT algorithms. The analysis covers a range of water velocities from 0.4 to 2.0 meters per second, examining the system's efficiency with and without MPPT, including the HCS and VS-HCS algorithm

Table 5. The comparison of the theoretical power and output power for the hydrokinetic system during steady-state oscillation at different water velocity

Water velocity (m/s)	Theoretical power (W)	Without MPPT (W)	Eff. (%)	MPPT Algorithm			
				HCS (W)	Eff. (%)	VS-HCS (W)	Eff. (%)
0.4	5.72	2.3	40.18	2.8	48.92	3.4	59.41
0.6	19.32	10.0	51.77	11.8	61.09	14.1	73.00
0.8	45.79	29.1	63.56	37.2	81.25	38.9	84.96
1.0	89.42	56.7	63.41	61.1	68.33	74.8	83.65
1.2	154.53	105.6	68.34	122.5	79.28	143.0	92.54
1.4	245.38	182.3	74.29	217.2	88.52	220.8	90.00
1.6	366.28	261.1	71.28	316.9	86.52	335.2	91.51
1.8	521.52	338.1	64.83	475.1	91.10	479.6	91.96
2.0	715.39	546.6	76.41	664.0	92.82	701.1	95.05

It is observed that, HCS and VS-HCS consistently enhance power output and efficiency. The VS-HCS, in particular, shows superior performance, achieving the highest efficiencies across all tested velocities, with efficiency improvements ranging from approximately 59.41% at 0.4 m/s to 95.05% at 2.0 m/s. This indicates that the VS-HCS is highly effective in maximizing the system's power output and overall performance by outperforms both the conventional HCS and systems without MPPT in terms of energy efficiency, making it the most suitable choice for optimizing the performance of hydrokinetic systems.

4 Conclusion

In this paper, the VS-HCS MPPT algorithm was proposed to improvise the drawbacks of conventional HCS for hydrokinetic energy harnessing in the river. The implementation of VS-HCS MPPT algorithm in hydrokinetic technology significantly enhances their efficiency and power output. Through its dynamic adaptation, rapid convergence, and precise adjustments, VS-HCS consistently outperforms conventional HCS, ensuring that the system operates at or near its maximum power point under varying conditions. The data clearly demonstrates the superior performance of VS-HCS, achieving the highest efficiencies across all tested water velocities. Its ability to adapt to different flow conditions and reduce oscillations makes it a robust and reliable choice for optimizing hydrokinetic systems. Consequently, VS-HCS stands out as a highly effective MPPT algorithm, capable of maximizing the performance and efficiency of hydrokinetic energy systems in diverse environmental settings.

Acknowledgment

The authors would like to thank to Universiti Malaysia Pahang Al-Sultan Abdullah for funding support under UMP RDU230355 and Tabung Persidangan Dalam Negara (TPDN).

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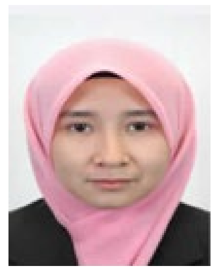

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