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A Magnetic Levitation Rooftop Turbine Ventilator: A Case Study for Wind Micro-Generation

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Abstract: This case study develops a prototype of a magnetic levitation rooftop turbine ventilator (RTV) through re-designing a standard rooftop ventilator that is typically mounted upon rooftops of factories, constructed to wind micro-generation system. By re-arranging positions of the rotor and the stator and integrating the magnetic levitation system to assisting support weight of turbine body, which can result in a very low starting torque so as to minimize the self-starting speed (m/s). Thus, it could easily turn and be able to rotate in low-speed wind ambient. This can practically improve responsiveness to intermittent wind and its directional change. The testing apparatus was conducted with wind speeds from 0-14.0 m/s, incremented by 0.2 m/s each iteration, where the test results show that the RTV self-starts at a wind speed of 0.4 m/s and minimal charged speed was recorded at 95.8 RPM at a voltage of 12.07 V_{DC} (activated charging voltage via battery bank of two 12 V, 100 A—in parallel connection) at 7.8 m/s. Then, it reaches ceiling voltage of 35.3 V_{DC} and 0.51 A_{DC} at turning approximately 119 RPM in which it produces power output 18 watts. At cut-out speed of 14.0 m/s and also rated output speed, the RTV optimizes the turning at 160.6 RPM while generating 1.02 A_{DC}, in which it produces a maximum power output of 36 watts. For the modes of finance; ROI remarks at 6.21, payback period at 4.03 years, and cost per kWh is as low as 2 cents/kWh, assuming operating at average speed of 14.0 m/s all year long.

Keywords: Rooftop Turbine Ventilator (RTV), Wind Micro-Generation System, Magnetic Levitation, Low Self-Starting Speed

I. INTRODUCTION

Wind micro-generation has gained popularity abroad and is technically feasible for urban and populated areas. As conventional horizontal axis wind turbine (HAWT) installed capacity has been only proven to work well within remote wind zones, working anywhere outside remote wind zones can shift a new paradigm for wind micro-generation. This step forward will enable the generation of electricity right at any point of using, diminishing of transmission and distribution losses, and minimizing investment for grid parity [1], [10]. Thus, a low-speed and cost-effective vertical axis wind turbine (VAWT) which is self-starting and generating electricity at cut-in speed of under 4 m/s (Thailand's average wind speed) [6], is designed and engineered to make this progress.

Particularly, utilizing a type of VAWT that exist upon typical rooftop structures, '*a rooftop ventilator*' (Fig. 1). This type of ventilator exists all over on rooftops of factories in Thailand. For that reason, this case study offers an innovative approach to transform a standard rooftop ventilator, which has been used as an air-ventilation purpose into a cost-effective VAWT. By which, enable to self-start at minimal speed and with minimal cost. This progress can be a viable alternative to generate and supply electricity locally. Generally, this case study illustrates no aerodynamic design's point of view but proposes viability of application.

Fig. 1 Existing rooftop ventilators in Thailand (factory rooftops)

II. BACKGROUND KNOWLEDGE

As ongoing research and development of low-speed VAWT struggle to achieve greater efficiency. Several researchers suggest VAWT has advantages over HAWT in terms of omni-direction of kinetic-energy harnessing [4], [5], [9], [11], [12], [17], as it can collect concentration of wind-flow from any direction. Eriksson et al. suggest VAWT works better than HAWT for such rooftop positions and easier generator arrangement, where it can be arranged underneath its rotor [5]. Mertens recommends that VAWT is suitable and appropriate for roof-mounting upon buildings [14]. As Riegler suggests to use existing elevated structures to mount up the VAWT [12], then this can be retrofitted [18] onto existing instant rooftop structures. Ahmed states that VAWT can be linked to a rooftop ventilator in terms of rotor configuration and capability to accepting wind directly towards its rotation [13].

As Mertens remarks on alternative to produce wind energy close to points of uses [14]. Bhutta et al. suggest VAWT can be economical viable for remote zones away from grid transmission lines [4]. Allen et al. remark that micro-generation is a solution to transmission and distribution losses [1]. And Mithraratne suggests that distributed micro-generation systems can provide generation at the point of uses and lower major investments for grid transmissions [10]. Westerholm recommends power storage and distribution systems to provide wind power on demand for economic benefit, particularly in the absence of wind [9]. Even that, Khan et al. illustrate the use of motor-driven to keep rooftop ventilator rotating in the absence of wind [16].

Therefore, for the design of the turbine rotor, as to enable and prolong the turbine to turning as much hours for all year long. Nayar et al. point out that an ability to extract more power, is an ability to respond to wind perturbations [17]. Fernandes et al. site that it is downtime of wind turbines' gearbox failures that present a problem, this causes excessive repair and adds up operational costs [19]. Since, main causes of power loss in the gearbox indicate rotational friction loss in the gearing and bearing mechanisms [19]. To minimize that friction loss is to simplify the design of the direct-drive rotor. This may be improved by low friction and torque properties from magnetic bearing [2].

With various research and development being focused on, these must be coupled along with current wind generation situation in country. First, the country's average wind speed is under 4 m/s, whereas current installed HAWT capacity operates at beyond 8 m/s [8]. Secondly, wind intermittent resource in country causes HAWT to be unable to reach its designated performance and barely generate electricity for some hours in a year [8].

III. DESIGN AND TESTING PROCEDURE

Full-Scale Prototype Development: Engineering design and technical specifications

The rooftop turbine ventilator (RTV) is technically designed to work as a vertical spindle (as rotating curved-vanes body) by using '*SolidWorks*' software to visualize of mechanical assembly. Thus, the full-scale RTV prototype consists of 8 components as illustrated.

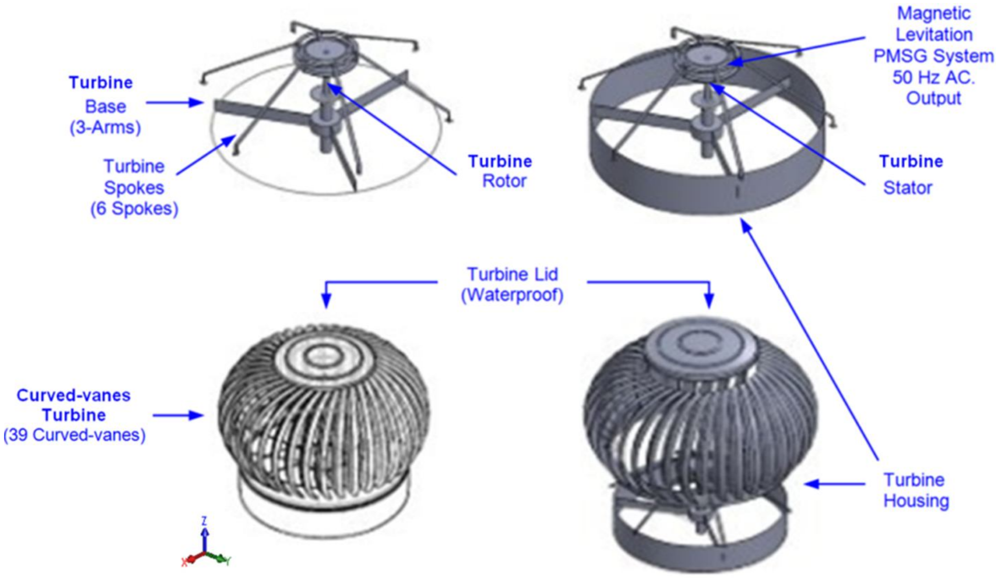


Fig. 2 Engineering design of RTV prototype; 8 components (3-axis dimension)

Fig. 2 illustrates mechanical assembly through the integration of permanent magnet synchronous generator (PMSG) in magnetic levitation system type, as to generating three-phase alternative current (50 Hz AC). This has to be circuiting connected to a charging controller and power storage [3], [9], [17], [20], [21] of a two 12 V_{DC} battery bank system.

The design aims to extract maximum energy at low-speed wind (wind intermittent resource) by keeping the turbine turning, by which can hold more moment of inertia from its spinning body. Thus, the turbine spokes are re-designed to retain with unique bending feature so as to hold more the moment of inertia from vertical spinning, in which can be able to turn and continue to rotate for last longer period. This may provide rated power for ranges of wind speed. On top of that, rotor and stator spinning cylinder-disk mechanism is stationed on top of the turbine base. Moreover, the rotor's length is shortened and the turbine base is transformed to withstand structural load and material stress aim to last for a suggested 25 years [11].

By means of the cost-effective turbine, the eight components are assembled and thus weights of materials are reduced aim to lighten the entire body and also to minimize the unit cost. By which, the total weight constraint is minimized at 6.6 kg and similarly to total unit cost (Table I). Accordingly, the RTV was assembled using aluminum, zinc and corrosion-resistant steel. The prototype configurations and technical specifications (based on 24 inch diameter: 39 curved-vanes) are summarized in Table I.

TABLE I
Prototype Configurations and Technical Specifications of RTV Summary

Configurations	Specifications	Configurations	Specifications
Full-Scale Prototype	Rooftop Turbine Ventilator (RTV)	**Turbine Body**	Aluminum 39 airfoil curved-vanes
Type	VAWT / Air-Flow out Ventilator	Turbine Spoke	6 spokes (steel)
Generator Output	50 Hz AC.	Turbine Lid	Zinc
Generator Type	PMSG (3-phase)	Net Weight	2,500 g.
Diameter of Turbine	24 inch (610 mm.)	**Turbine Base**	Zinc
Height	480 mm. (w/o rooftop stand)	Internal Frame	Corrosion-resistant steel
Materials	Aluminum / Zinc / Steel	Base Arm	3 arms (steel)

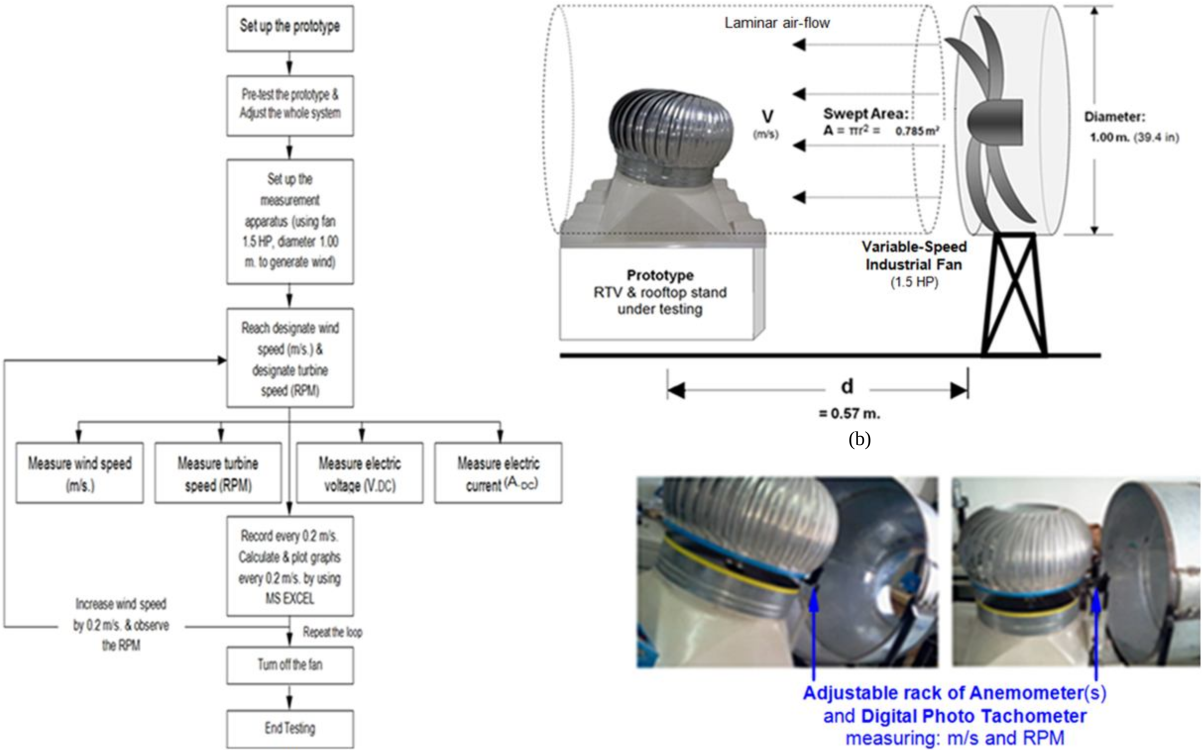
Turbine Spoke	6 spokes	Net Weight	4,100 g.
Special Feature(s)	Magnetic Levitation System	**Turbine Rotor**	Corrosion-resistant steel
Operating Life	25 years	Length	135 mm.
Maintenance	Maintenance-free	Outer Race Diameter	15 mm.
Start-up Wind Speed (also cut-in wind speed)	0.4 m/s.	**Turbine Stator**	Corrosion-resistant steel
Cut-out Wind Speed (also rated output speed)	14.0 m/s.	Width (thickness)	40 mm.
Operational Range	0.4-14.0 m/s.	Outer Race Diameter	170 mm.
Minimal Charged Speed	7.8 m/s.	**Total Weight**	6,600 g.
Minimal Charged Turbine Speed	95.8 RPM	**Turbine Cost (unit cost)**	5,000 THB (155 USD) exclude battery bank system
Rated Voltage (charged)	12 V_{DC}	**Variable-Speed Industrial Fan**	3-phase 380 V_{AC} (in Laboratory)
Battery Bank	12 Volts 100 A. (2 units parallel connection)	Output	1.5 HP ; 11 A.
Output Controller	Charging Controller (for solar PV) & Inverter 220 V_{AC}	Frequency	0.1-400 Hz 50/60 Hz

Procedure of Testing:

The testing procedure is an experimental procedure based on power output profile, so as to find starting-up speed, cut-in speed, rated output speed, and cut-out speed. The testing rig was then arranged for measuring variable wind speeds. The RTV was mounted on top of a rooftop stand (Fig. 3b), whereas it was positioned directly in front of an air outlet (diameter: 1.00 m., area: 0.785 m^2) with a variable-speed industrial fan (Table I). An adjustable rack of anemometer(s) and digital photo tachometer were positioned in front of the air outlet (Fig. 3c) to measure the wind speed in m/s and revolution per minutes (RPM). Also, two digital multi-meters were connected to the testing rig. Then, wind speed iterations were run and measured each time, in which was incremented by 0.2 m/s. Noting that for finding initial starting-up speed, by gradually started wind speed from 0 m/s for several trials until the RTV starting to actuate and the average of wind speeds was recorded.

Four readings parameters were measured (Fig. 3a) using; anemometer(s), digital photo tachometer, and two digital multi-meters. The first two parameters were carefully taken at the very front of the RTV position and the latter were taken at a spot output location of AC-DC converter (Fig. 4). The adjustable rack of anemometer(s) was attached very close in front of the air outlet. This aims to minimize error from wind decreasing velocity. The tachometer was placed close to its reflective tape attached on the rim of the turbine body so as to compute the RPM. Then, parameters obtained each iteration from 0 until 14.0 m/s (0 - 71 iterations) were calculated and partly illustrated in Table II.

This must be noted that, the testing rig was prepped and tested inside the laboratory with no site monitoring in the outdoor. Then, a preliminary error analysis was made neglecting of turbulence flow or air lifting-flow [21] under rooftop stand. And assume laminar air-flow velocity and slightest amount of wind directional change in the laboratory. Also, assuming average atmospheric ambient air density of 1.22 kg/m^3 [22], and ambient temperature was recorded at 32°C. Errors presented in this apparatus may only be related to distance (d = 0.57 m.) between the air outlet and the RTV position. This expected error was being taken care of by running several trials of wind speed before obtaining the average readings each time.



(a) (b) (c)

Fig. 3 Testing procedure schematics (a) Testing process flow (b) Testing apparatus (c) Actual testing rig

In addition to that, the wind micro-generation system was constructed primarily to contribute to this case study as the RTV (and rooftop stand) are mounted on top of this system (Fig. 4). This system is accountable only an electrical discharging part, in which the system consists of AC-DC converter, a charging controller (for solar PV), battery bank of two 12 Volt 100 A, DC-AC inverter 220V_{AC} and pieces of equipment through a seven household light panel (total load: 165 Watts).

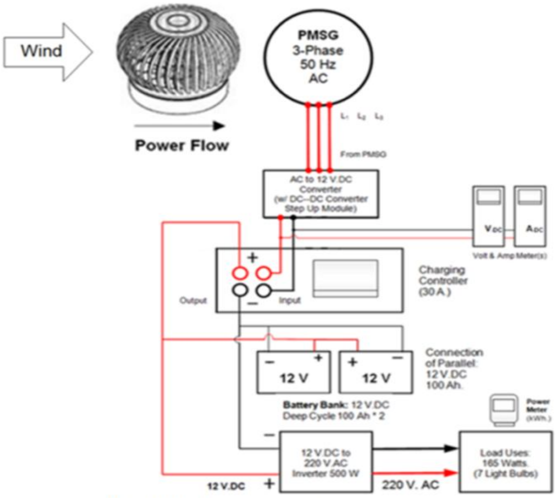


Fig. 4 Wind micro-generation system

IV. TEST RESULTS

In principle, the power flow is converted from wind kinetic energy into the PMSG (3-phase, 50 Hz) as of alternative current (AC) and then be converted down into 12 volts direct current (12 V_{DC}) as to be fed into the charging controller. Then, the DC current was obtained from this point as to calculate actual power output by power equation (1).

RTV Power Output: P_{DC} at output of AC-DC converter position

$$\mathbf{P_{DC}} = \mathbf{V_{DC}} \cdot \mathbf{I_{DC}} \text{ (Watts)} \quad ; V_{DC} = \text{Direct Current Voltage } (V_{DC}) \tag{1}$$

$$I_{DC} = \text{Direct Current Ampere } (A_{DC})$$

TABLE II

Power Output Profile and Financial Modes

Wind Speed	Turbine Speed	Volt	Ampere	Power Output	Power Output	ROI	Payback Period	Cost per kWh
m/s	RPM	V.DC	A.DC	Watts	kW	ROI	Yrs	THB/kWh
0.0	0.0	0.00	0.000	0.0000	0.0000	0.00	-	-
0.2	0.0	0.00	0.000	0.0000	0.0000	0.00	-	-
0.4	7.1	0.13	0.010	0.0013	0.0000	0.00	-	-
0.6	11.7	0.13	0.030	0.0039	0.0000	0.00	-	-
0.8	18.0	0.13	0.040	0.0052	0.0000	0.00	-	-
1.0	23.8	0.13	0.040	0.0052	0.0000	0.00	-	-
2.0	32.8	0.23	0.040	0.0092	0.0000	0.00	-	-
3.0	41.8	0.47	0.040	0.0188	0.0000	0.00	-	-
4.0	51.4	0.71	0.050	0.0355	0.0000	0.01	-	-
5.0	56.4	1.06	0.070	0.0742	0.0001	0.01	-	-
6.0	69.6	1.32	0.150	0.1980	0.0002	0.03	-	-
7.0	86.1	2.49	0.230	0.5727	0.0006	0.10	253.21	39.87
7.2	91.9	4.30	0.240	1.0320	0.0010	0.18	140.51	22.12
7.4	94.1	4.60	0.250	1.1500	0.0012	0.20	126.10	19.85
7.6	95.0	7.63	0.260	1.9838	0.0020	0.34	73.10	11.51
7.8	95.8	12.07	0.280	3.3796	0.0034	0.58	42.91	6.76
8.0	97.1	12.60	0.300	3.7800	0.0038	0.65	38.36	6.04
9.0	110.9	25.50	0.370	9.4350	0.0094	1.63	15.37	2.42
10.0	116.4	34.70	0.480	16.6560	0.0167	2.87	8.71	1.37
10.2	118.1	34.90	0.490	17.1010	0.0171	2.95	8.48	1.34
10.4	118.7	35.10	0.500	17.5500	0.0176	3.03	8.26	1.30
10.6	118.9	35.30	0.510	18.0030	0.0180	3.10	8.05	1.27
10.8	119.1	35.30	0.530	18.7090	0.0187	3.23	7.75	1.22
11.0	120.7	35.30	0.540	19.0620	0.0191	3.29	7.61	1.20
12.0	148.5	35.30	0.620	21.8860	0.0219	3.77	6.63	1.04
13.0	155.1	35.30	0.870	30.7110	0.0307	5.29	4.72	0.74
14.0	160.6	35.30	1.020	36.0060	0.0360	6.21	4.03	0.63

From Table II, Fig. 5 illustrates graphing in derived relationship between wind speed (m/s) versus RPM versus V_{DC} and versus A_{DC}.

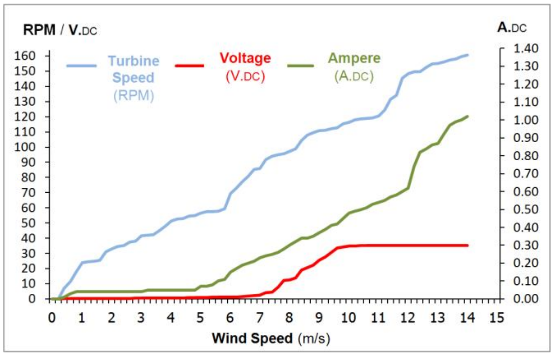


Fig. 5 Wind speed (m/s) vs. Turbine speed (RPM) vs. Voltage (V_{DC}) vs. Ampere (A_{DC})

From Fig. 5, it can be observed that the voltage and ampere had increased gradually proportional to the wind speed and the RPM, the RTV started to actuate at 0.4 m/s at turbine speed of 7.1 RPM, which also started generating of 0.13 V_{DC} and 0.01 A_{DC}. This was recorded as starting speed and cut-in speed at the same point. Then, wind speed was incremented by 0.2 m/s, the power output had increased noticeably until 7.8 m/s. By which, the RTV reached the turning of 95.8 RPM, the voltage then jumped rapidly to a stabilized level of 12.07 V_{DC} and 0.28 A_{DC}. This was recorded as minimal charged speed through the activated charging voltage of 12 V_{DC} of the battery bank.

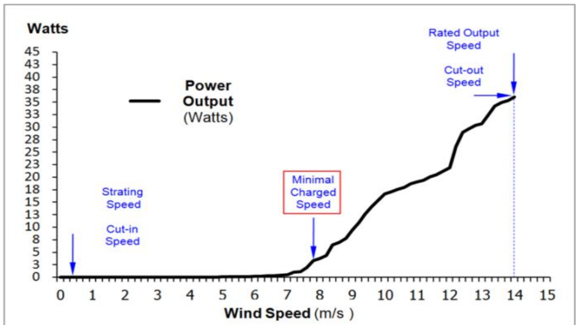


Fig. 6 Wind speed (m/s) vs. Power output (Watts)

Fig. 6 illustrates power output profile between wind speed versus power output in watts by Eq. (1). Thus, when the wind speed was approached 10.6 m/s, the voltage climbed gradually to reach ceiling voltage of 35.3 V_{DC} with 118.9 RPM, while generated 0.51 A_{DC} and produced power output of approximately 18 watts. Then from 10.6 m/s onward, the voltage made no further increase and kept ceiling at 35.3 V_{DC} for the rest of the iterations even when the wind speed was increased to 14.0 m/s. This was the point where the testing iteration ended, and the RTV reached the optimal turning at 160.6 RPM while generating 1.02 A_{DC}, produced maximum power output of approximately 36 watts. This can be recorded as rated output speed and cut-out speed at the same point. Economically, the stabilized level found during the test that the charging controller was continually activated by the incoming current (12.07 $V_{DC.}$) from the RTV at 7.8 m/s at turbine spinning at 95.8 RPM. This level had maintained smooth-out charging period, as the charging controller was functioning well to maximize power extraction.

V. FINANCIAL ANALYSIS

For financial modes of the RTV, by calculating total return and total cost (Return on Investment: ROI), payback period, and cost per kilowatt-hour (kWh) via using derived equations from wind turbine mainstream software's equations [7] as following.

Return on Investment (ROI): for turbine's ROI

$$\frac{\text{Total Return}}{\text{Total Cost}}\ (\text{ROI}) = \frac{365\ \text{Days} * 24\ \text{Hrs.} * \text{Operational Life (yrs.)} * \text{P output} * \text{T ref}}{\text{Turbine Cost} + (\text{Annual Recurrent Cost} * \text{Operational Life (yrs.)})} \tag{2}$$

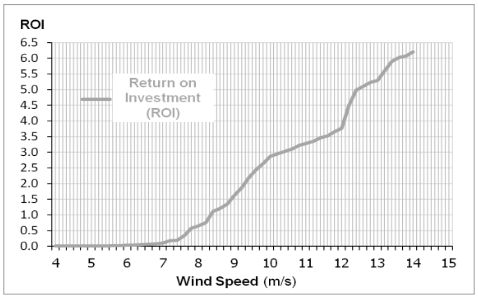


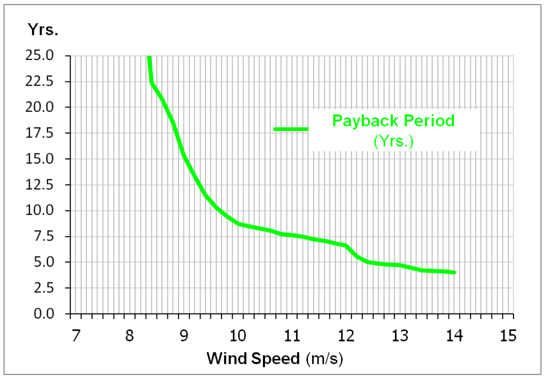
Fig. 7 Turbine's Return on Investment

Operational Life = 25 years
P_{output} = Power output (kW)
Utility Tariff (T_{ref}) = Reference electricity price [15], 3.9361THB/kWh for urban electricity users (small general service)
Turbine Cost = 5,000 THB (155 USD)
Annual recurrent cost = Maintenance-free

By Eq. (2) [7], Fig. 7 illustrates the ROI versus wind speed from 4.0 m/s, as the ROI initiated value was started at 0.01. At the minimal charged speed of 7.8 m/s, the ROI had increased to 0.58. And, at the wind speed of 10.6 m/s the ROI had improved to 3.10. And also when the RTV reached the rated output speed and cut-out speed at the same point at 14.0 m/s, the ROI remarked at 6.21 at its best for this testing.

Payback Period: for turbine's payback period

$$\text{Payback Period (Yrs.)} = \frac{\text{Turbine Cost}}{365\text{ Days} * 24\text{ Hrs.} * \text{P output} * \text{T ref} * \left[1 - \frac{\text{Annual Recurrent Cost}}{365\text{ Days} * 24\text{ Hrs.} * \text{P output} * \text{T ref}}\right]} \qquad (3)$$



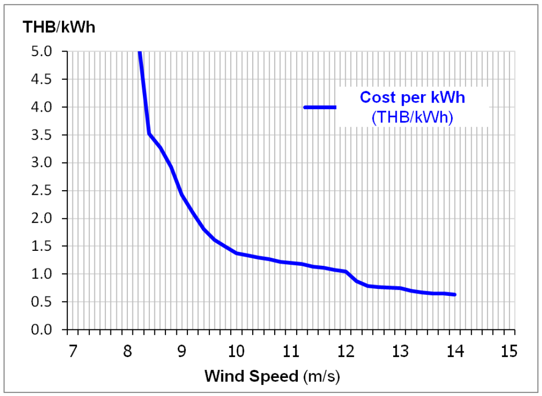
P_{output} = Power output (kW)
Utility Tariff (T_{ref}) = Reference electricity price [15], 3.9361 THB/kWh for urban electricity users (small general service)
Turbine Cost = 5,000 THB (155 USD)
Annual Recurrent Cost = Maintenance-free

Fig. 8 Turbine's payback period

By Eq. (3) [7], Fig. 8 illustrates the payback period from wind speed of 7.0 m/s, as the payback period was started to be very much improve from 7.0 m/s onward and this corresponded to the ROI value of 0.10. Thus, at wind speed of 7.8 m/s the payback period came out at 42.91 years. And at the speed of 10.6 m/s, the payback period came down to 8.05 years. This implies that between 7.8-10.6 m/s, the payback period had improved for 34.86 years. And at the rated output speed and the cut-out speed of 14.0 m/s, the payback period came down to 4.03 years or roughly being able to pay back in a 4 year period. For faster payback, it must be noticed that in case of high speed wind above 7.8 m/s the payback period was absorbed much faster than the rest.

Cost Per Kilowatt-Hour: for turbine's cost per kWh

$$\text{Cost per kWh} \left(\frac{\text{THB}}{\text{kWh}}\right) = \frac{\text{Turbine Cost} + (\text{Annual Recurrent Cost} * \text{Operational Life (yrs.)})}{365\text{ Days} * 24\text{ Hrs.} * \text{Operational Life (yrs.)} * \text{P output}} \qquad (4)$$



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Operational Life = 25 years
P_{output} = Power output (kW)
Turbine Cost = 5,000 THB (155 USD)
Annual Recurrent Cost = Maintenance-free

Fig. 9 Turbine's cost per kilowatt-hour (kWh)

By Eq. (4) [7], Fig. 9 illustrates the cost per kWh from wind speed of 7.0 m/s, at 39.87 THB/kWh. At this point, the RTV produced a rather small amount of power output. However, at the wind speed of 7.8 m/s, the cost per kWh had much improved to 6.76 THB/kWh. This implies that between 7.0-7.8 m/s, the cost per kWh came down for 33.11 THB/kWh. And at wind speed of 10.6 m/s, the cost per kWh had well improved to 1.27 THB/kWh. And at rated output speed and cut-out speed of 14.0 m/s, the cost per kWh came down to the lowest at 0.63 THB/kWh or roughly costing 0.02 USD/kWh (2 cents per kWh) for this testing.

VI. CONCLUSION

This case study re-designed, constructed and tested the RTV prototype based on wind turbine power output profile. The RTV mechanical characteristic shows a low self-starting speed of 0.4 m/s, as equal to the cut-in speed at the same point. The rated output speed and cut-out speed were recorded at the same point as well at 14.0 m/s, in which the RTV optimized the turning at 160.6 RPM and produced maximum power output of 36 watts. This concludes that the RTV may still be insufficient in term of the power output at the low-speed wind ranging from 0.4-4.0 m/s. However, from 4.0-8.0 m/s range, the RTV can trigger stabilized charging level at 7.8 m/s easily while producing approximately 3.38 watts at turbine turning 95.8 RPM. And from 8.0-14.0 m/s, the RTV reached out its full performance with the financial modes of ROI remarked at 6.21, payback period at 4.03 years, and cost per kWh at 0.63 THB/kWh or 0.02 USD/kWh (2 cents/kWh).

As for technological viability, the first mechanical ability found is that the RTV can lower the self-starting speed to accept and make use out of low-speed wind ambient from 0.4 m/s onward. This implies that the RTV can extracting lower amount of kinetic energy from wind intermittent resource in the country. Secondly, the electrical generation ability, is that the RTV can start generating amount of electricity at the self-starting speed of 0.4 m/s as well, even though at a very small power output. These mechanical and electrical generation abilities can advantageously be researched further for improving the power output at the low-speed wind range. As for economic viability, first, the single unit of RTV may be insufficient in spot-produced power output of 36 watts. However, this can be recommended for such advanced household lighting application uses. Therefore, as to drive down the economical cost per kWh, this can be recommended further by increasing quantitative units of the RTV, by which this can add up the total amount of power outputs from many array units combined upon rooftop of factories. And secondly, the RTV's instance feature by which capable of be retrofitted properly back onto existing rooftops, since it inherits simple feature of rooftop ventilator type.

Thus far, this can be concluded that even though the RTV has not yet been proven for the economic viability, especially for the very long payback period at the low-speed wind range, but mechanically capable of capturing the un-captured amount of kinetic energy by the others. This redefines a technologically innovative type of rooftop turbine ventilator for such complete the whole picture of point of generating and point of using altogether as of the wind micro-generation system, while stepping forward to work outside remote wind zones.

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