Experimental Investigation for Small Horizontal Portable Wind Turbine of Different Blades Profiles under Laboratory Conditions

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ABSTRACT
Experimental investigation for small horizontal portable wind turbine (SHPWT) of NACA-44, BP-44, and NACA-63, BP-63 profiles under laboratory conditions at different wind velocity range of (3.7-5.8 m/s) achieved in present work. Experimental data tabulated for 2, 3, 4, and 6- bladed rotor of both profiles within range of blade pitch angles $\left(\beta = 10^{\circ}, 20^{\circ}, 30^{\circ}, 40^{\circ}, and\ 50^{\circ}\right)$. A mathematical model formulated and computer Code for MATLAB software developed. The least-squares regression is used to fit experimental data. As the majority of previous works have been presented for large scale wind turbines, the aims were to present the performance of (SHPWT) and also to make a comparisons between both profiles to conclude which is the best performance. The overall efficiency (η) and electrical output power (P_o) affected by changing blades number and (β). The best (η) for both profiles of 2 and 3-bladed rotor occurred at ,($\beta = 30^{\circ}$) and NACA-44, BP-44 profile was better than NACA-63, BP-63 profile. The best η for both profiles of 4-bladed rotor occurred at ($\beta = 20^{\circ}$), and NACA-63, BP-63 profile was better than NACA-44, BP-44 profile. The best (η) of 6-bladed rotor occurred at ($\beta = 20^{\circ}$) for NACA-44, BP-44 profile and at ($\beta = 10^{\circ}$) for NACA-63, BP-63 profile, clearly NACA-44, BP-44 profile was better than NACA-63, BP-63 profile. Finally, the maximum value of mean overall efficiency was ($\eta = 31.1813$ %) concluded for NACA-44, BP-44 profile of 6-bladed rotor at ($\beta = 20^{\circ}$).

Keywords
Portable wind turbines, Mini wind turbine, Performance of Wind turbine, Modeling and control of wind turbine, Aerodynamic of wind turbines.

1. INTRODUCTION
The resources of renewable energy are a successful alternative solution compared with the traditional resources. The successive depletion of fossil fuels lead to the atmospheric pollution which causes the global warming. Consequently, the international markets went to use the systems of renewable energy as sustainable resources, inexpensive, clean, and environmental friendly. One of most important of renewable energies systems are the wind energy systems. Off-shore and on-shore wind farms use large scale wind turbines. While the small scale wind turbines use in remote and populated areas for domestic and industrial applications, pumping the water to farmland, charging the batteries, streets and bridges lightening, and other applications. Majority of previous researches focused on large scale wind turbines. Accordingly, the current work presented on the small scale portable wind turbines under laboratory conditions.

Ultimately, theoretical and experimental tests of small wind turbines proposed by many researchers. At low wind speed the behavior of (SWEPT), (SHAWT), and (SWT) investigated [1, 6, 8]. Several important application were mentioned for small wind turbines [1].

In this field, the wind tunnel was used to check the characteristics of small wind turbines. The rotor efficiency (power coefficient), overall efficiency, rated speed, and rated power were obtained [1]. Additionally, the measurements of output power for (SSHAWT) were used to find out the annual energy extraction for remote areas [7].

Obviously, the tests of (SWTG) and (SWT) under laboratory conditions were submitted by some of researchers. Methodology were used to obtain power curve of (SWTG) [2]. According to horizontal and perpendicular angles the characteristics behavior of (SWTG) was different. Also, the Lab View platform were used to test system of (SWT) [3]. The efficiency of the test system showed via the simulation testing results.

It is worth mentioning that Modeling and control of small wind turbines established by others researchers. Nowadays the Setting performance accurately is an important issue for a small wind turbines. Modeling and control of (SWT) by using PSIM software were presented [4]. The simulation circuit of (SWT) was achieved by PSIM software. Modeling of (SWE) based of (PMSG) was offered [5]. Tools were developed for design, analysis, and optimization of (SWT) to optimize performance.

The energy yield and cost of generated electricity comparison of (SWT) Took into consideration for conditions and areas of low wind speed [8]. In this work, the rotor diameter above 3 m had better performance. Also, comparisons among three selected (MWTs) to generate sufficient electricity investigated [9].

2. METHODOLOGY
Ravi Anant Kishore, et al., [1] classified wind turbines According to rotor blades diameter, Micro-scale, small-scale, Mid-scale, and large-scale wind turbines. The range of wind turbines rotor diameters among (10cm $<$ rotor diameter $\leq$ 100cm) is small scale wind turbine. Accordingly, the portable wind turbine of rotor diameter ($D = 36\ cm$) under tests of current work was from small scale wind turbines group. The tests of (SHPWT) for different rotor blade profiles used inside Energy Engineering laboratory at University of Baghdad. The

(SHPWT) is mounted on an aluminum post to extract maximum possible energy. The kinetic energy stored in the wind is convert to mechanical energy by the rotor of wind turbine and then into electrical energy across the generator. The blade airfoils is the biggest factor affecting to optimize the overall efficiency of wind turbines. Consequently, aerodynamics theories for designing wind turbine blades followed by the manufacturer, which were the same adopted for airplanes and helicopters. NACA-44, BP-44 and NACA-63, BP-63 profiles as shown in (Fig. 1) used to make comparison between the behavior of the overall efficiency with tip speed ratio and for the electrical output power with wind velocities.

2.1 Experimental Work

The equipment used in experimental tests were Fan, (SHPWT), Anemometer, Spark sensor, and Tachometer as shown in (Fig. 2). The upwind velocity (V_1) exerted by the fan toward the (SHPWT), for spinning the rotor blades and generating the electricity. Different distances were fixed between the fan and (SHPWT) mentioned in table (1), to exert a different range of upwind velocity. The upwind velocity (V_1) measured by using a digital anemometer. The (SHPWT) without load, connected to the spark sensor to measure the output voltage (V) and current (I). The digital tachometer, used to measure the rotational speed (N) of the rotor blades.

2.2 Measurements

The upwind velocity ($\mathbf{V_1}$), rotation speed (**N**), voltage (**V**), and current (**I**) measured for every blades number (2, 3, 4, and 6) at different range of blade pitch angles ($\beta = 10^\circ, 20^\circ, 30^\circ, 40^\circ, \text{and } 50^\circ$). The blades can be adjusted for pitch by the hub mechanism. The measured data for the above parameters were so many for both profiles. Consequently, table (1) is sample for the measured data in order to show the tabulated parameters.

3. MATHEMATICAL FORMULATION

The kinetic energy of a moving air can be expressed as:

$$\mathrm{K.E} = \langle (1/2)\mathrm{m}V_1{}^2 \rangle \ldots (1)$$

The air mass flow rate with the air density (ρ) passes through a certain cross-sectional area (A) at velocity (V_1), is

$$m^\circ = \langle \rho\ \mathrm{A}\ V_1 \rangle \ldots (2)$$

The power available in the wind represents the rate of kinetic energy and that leads to following Eq.

$$\mathrm{P_w} = \langle (1/2)\ \rho\ \mathrm{A}\ V_1{}^3 \rangle \ldots (3)$$

The angular velocities (ω) of the rotor blades can be estimate from the rotor rotational speed (N) and can be written as:

$$\omega = (2\pi\ \mathrm{N}/60) \ldots (4)$$

The tip rotor blade velocities (v) , at the blade tip (R) are estimate from the angular velocity multiplied by the rotor blade outer radius and can be written as:

$$\mathrm{v} = \langle \mathrm{R}\ \omega \rangle \ldots (5)$$

The tip speed ratio represents the ratio between rotor blade velocities to the upstream wind velocities, which can be written as

$$\mathrm{TSR} = (\mathrm{R}\omega/V_1) = \langle (\mathrm{v}/V_1) \rangle \ \ldots (6)$$

The electrical output power can be estimate from multiplication of output voltage and current which can be written as:

$$\mathrm{P_o} = \langle V \times I \rangle \ldots (7)$$

The overall efficiency of the (SHWT) is:

$$\eta = \langle \mathrm{P_o}/\mathrm{P_w} \rangle \ \ldots (8)$$

4. RESULTS AND DISCUSSION

The experimental performance of (SHPWT) for NACA-44, BP-44 and NACA-63, BP-63 profiles has been investigated and simulated for different blades numbers (2, 3, 4, and 6) at different range of blade pitch angles ($\beta = 10^\circ, 20^\circ, 30^\circ, 40^\circ, and\ 50^\circ$). Computer Code for MATLAB software has been developed to simulate the results of mathematical model. The least-squares regression of curve fitting was used; which is the most common technique of finding the best fit to experimental data. In general, the wind energy is the one of renewable energies which are stochastic in nature. So, the behavior of (SHPWT) was unstable Mostly. A comparisons between NACA-44, BP-44 and NACA-63, BP-63 profiles achieved in order to conclude which is better performance. The changing influence of blades number and blade pitch angles studied. Figures (3) and (5) illustrates the overall efficiency (η) behavior of NACA-44, BP-44 and NACA-63, BP-63 profiles, at ($\beta = 10^\circ, 20^\circ, 30^\circ, 40^\circ, and\ 50^\circ$) with tip speed ratio (TSR) for 2, 3, 4, and 6-bladed rotor respectively. For 2- bladed rotor the (η) of NACA-63, BP-63 profile was better than of NACA-44, BP-44 profile for the range of ($\beta = 10^\circ, and\ 20^\circ$). While, the ($\eta$) of NACA-44, BP-44 profile was better than of NACA-63, BP-63 profile for the range of ($\beta = 30^\circ, 40^\circ\ and\ 50^\circ$). For 3-bladed rotor the (η) of NACA-63, BP-63 profile was better than of NACA-44, BP-44 profile for ($\beta = 10^\circ$). While, the (η) of NACA-44, BP-44 profile was better than of NACA-63, BP-63 profile for the range of ($\beta = 20^\circ, 30^\circ, 40^\circ\ and\ 50^\circ$). For 4-bladed rotor the (η) of NACA-44, BP-44 profile was better than of NACA-63, BP-63 profile for the range of ($\beta = 10^\circ, and\ 50^\circ$). While, the ($\eta$) of NACA-63, BP-63 profile was better than of NACA-44, BP-44 profile for the range of ($\beta = 20^\circ, 30^\circ, and\ 40^\circ$). For 6-bladed rotor the (η) of NACA-44, BP-44 profile was better than of NACA-63, BP-63 profile for ($\beta = 10^\circ, 20^\circ, 30^\circ, 40^\circ and\ 50^\circ$). Indeed, without entering the turbulent region, and without separation of boundary layers when the boundary layers of free stream attach at the upper and lower surfaces of rotor blades, the best performance occurred. For 2-bladed and 3-bladed rotor, the optimum (η) occurred at ($\beta = 30^\circ$) for both profiles, for 4-bladed rotor the optimum (η) occurred at ($\beta = 20^\circ$) for both profiles, and for 6-bladed rotor the optimum (η) occurred at ($\beta = 20^\circ$) for NACA-44, BP-44 profile, and at ($\beta = 10^\circ$) for NACA-63, BP-63 profile for the same reasons mentioned above. Obviously from the above results, the (η) of NACA-44, BP-44, and NACA-63, BP-63 profiles for 2, 3, 4, and 6-bladed rotor begun to increase until to optimum (β), after this optimum value the flow entered the turbulent flow region. Consequently, the values of (η) decreased.

Figures (4) and (6) illustrates the electrical output power (P_o) behavior of NACA-44, BP-44 and NACA-63, BP-63 profiles, at ($\beta = 10^\circ, 20^\circ, 30^\circ, 40^\circ, 50^\circ$) with wind velocities for 2 bladed, 3-bladed, 4-bladed, and 6-bladed rotor respectively. For 2- bladed rotor the (P_o) of NACA-63, BP-63 profile was better than of NACA-44, BP-44 profile for ($\beta = 10^\circ, and\ 20^\circ$). While, the ($P_o$) of NACA-44, BP-44 profile was better than of NACA-63, BP-63 profile for ($\beta = 30^{\circ}, 40^{\circ}$ and 50°). For 3-bladed rotor the (P_o) of NACA-63, BP-63 profile was better than of NACA-44, BP-44 profile for ($\beta = 10^{\circ}$). While, the (P_o) of NACA-44, BP-44 profile was better than of NACA-63, BP-63 profile for ($\beta = 20^{\circ}, 30^{\circ}, 40^{\circ}$ and 50°). For 4-bladed rotor the (P_o) of NACA-44, BP-44 profile was better than of NACA-63, BP-63 profile for the range of ($\beta = 10^{\circ}, 20^{\circ}, and\ 50^{\circ}$). While, the ($P_o$) of NACA-63, BP-63 profile was better than of NACA-44, BP-44 profile for ($\beta = 30^{\circ}, and\ 40^{\circ}$). For 6-bladed rotor the (P_o) of NACA-44, BP-44 profile was better than of NACA-63, BP-63 profile for ($\beta = 10^{\circ}, 20^{\circ}, 30^{\circ}, 40^{\circ} and\ 50^{\circ}$). Figure (7) illustrates a comparison between the (η) of NACA-44, BP-44 and NACA-63, BP-63 profiles with (TSR) at optimum (β) for every case of 2, 3, 4, and 6-bladed rotor respectively. Obviously, from figure (7) and table (2) NACA-44, BP-44 profile was better than NACA-63, BP-63 profile for 2, 3 and 6-bladed rotor. By contrast, for 4-bladed rotor NACA-63, BP-63 profile was better than NACA-44, BP-44 profile.

5. CONCLUSIONS

In this paper, the overall efficiency (η) and electrical output power (P_o) of (SHPWT) has been investigated. The (η) and (P_o) was affected by changing the blades number and blade pitch angles, and it's changed randomly for NACA-44, BP-44 and NACA-63, BP-63 profiles. The results of the present study lead to the following conclusions:

a) The best overall efficiency for both profiles of 2 and 3-bladed rotor occurred at blade pitch angle ($\beta = 30^{\circ}$). Obviously, the NACA-44, BP-44 profile was better than NACA-63, BP-63 profile.

b) The best overall efficiency for both profiles of 4-bladed rotor occurred at blade pitch angle ($\beta = 20^{\circ}$). It is worth mentioning that the NACA-63, BP-63 profile was better than NACA-44, BP-44 profile.

c) The best overall efficiency of 6-bladed rotor occurred at blade pitch angle ($\beta = 20^{\circ}$) for NACA-44, BP-44 profile. While the best overall efficiency occurred at blade pitch angle ($\beta = 10^{\circ}$) for NACA-63, BP-63 profile. Noticeably, the NACA-44, BP-44 profile was better than NACA-63, BP-63 profile.

d) Generally, the performance of NACA-44, BP-44 profile was better than NACA-63, BP-63 profile for 2, 3, and 6-blades numbers. By contrast, the performance of NACA-63, BP-63 profile was better than NACA-44, BP-44 profile for 4- blades numbers.

e) It is worth mentioning that the overall efficiency and electrical output power of (SHPWT) were depended upon the blades number and blade pitch angles.

f) For current work, the maximum mean overall efficiency ($\eta = 31.1813$ %) for NACA-44, BP-44 profile occurred for 6- bladed rotor at ($\beta = 20^{\circ}$). While the maximum mean overall efficiency ($\eta = 30.3578$ %) for NACA-63, BP-63 profile occurred for 6- bladed rotor at ($\beta = 10^{\circ}$).

Table 1. Measured parameters of 2 bladed (SHPWT) for NACA-44 profile BP-44 at blade pitch angle ($\boldsymbol{\beta = 30^{\circ}}$)

Measured Parameters	Test No.									
	1	2	3	4	5	6	7	8	9	10
Distance (m)	1.0	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2	0.1
V_1 (m/s)	3.7	3.9	4.0	4.3	4.5	5.0	5.2	5.4	5.6	5.8
N (rpm)	40	60	80	80	140	160	190	230	280	398
V (volt)	0.5	1.0	1.5	1.5	2.6	2.6	3.6	4.1	5.2	5.7
I (A)	0.004	0.005	0.013	0.012	0.030	0.025	0.041	0.046	0.058	0.069

Table 2. Average of overall efficiency for NACA-44, BP-44, and NACA-64, BP-63 profiles at different blades number and blades pitch angles

Blades No.	NACA profile	Average of overall efficiency ($\boldsymbol{\eta}$) at different blade Pitch angle ($\boldsymbol{\beta}$)				
		$\boldsymbol{\beta = 10^{\circ}}$	$\boldsymbol{\beta = 20^{\circ}}$	$\boldsymbol{\beta = 30^{\circ}}$	$\boldsymbol{\beta = 40^{\circ}}$	$\boldsymbol{\beta = 50^{\circ}}$
2 B	NACA-44	0.1629 %	1.2695 %	4.8699 %	3.7837 %	3.8729 %
	NACA-63	0.5093 %	1.9591 %	3.8892 %	3.1753 %	3.3519 %
3 B	NACA-44	0.4071 %	10.3688 %	11.8106 %	8.1074 %	6.1878 %
	NACA-63	1.2993 %	7.6252 %	7.7759 %	5.5172 %	4.2605 %

4 B	NACA-44	3.7678 %	19.5786 %	11.7226 %	7.6338 %	5.9908 %
	NACA-63	0.9138 %	20.6318 %	14.6938 %	8.9134 %	4.8449 %
6 B	NACA-44	30.3578 %	31.1813 %	16.3847 %	6.7119 %	6.6300 %
	NACA-63	25.2368 %	17.2105 %	10.4515 %	6.5406 %	3.4057 %

Table 3. Average of electrical output power for NACA-44, BP-44, and NACA-64, BP-63 profiles at different blades number and blades pitch angles

Blades No.	**NACA profile**	**Average of output power (P_o) at different blade Pitch angle (β)**				
		$\beta = 10^{\circ}$	$\beta = 20^{\circ}$	$\beta = 30^{\circ}$	$\beta = 40^{\circ}$	$\beta = 50^{\circ}$
2 B	NACA-44	0.0182	0.1219	0.3685	0.2921	0.2722
	NACA-63	0.0477	0.1516	0.3145	0.2315	0.2717
3 B	NACA-44	0.0378	0.8222	0.8914	0.5547	0.4047
	NACA-63	0.1252	0.6720	0.5281	0.4213	0.2990
4 B	NACA-44	0.2918	1.4888	0.8973	0.5643	0.4231
	NACA-63	0.0756	1.4710	1.0427	0.6261	0.3236
6 B	NACA-44	2.4484	2.1696	1.1385	0.4885	0.4754
	NACA-63	2.2165	1.3503	0.7576	0.4856	0.2600

(a)  **(b)** 

Fig 1: Blade profiles (a) NACA-44, BP-44 profile, (b) NACA-63, BP-63 profile

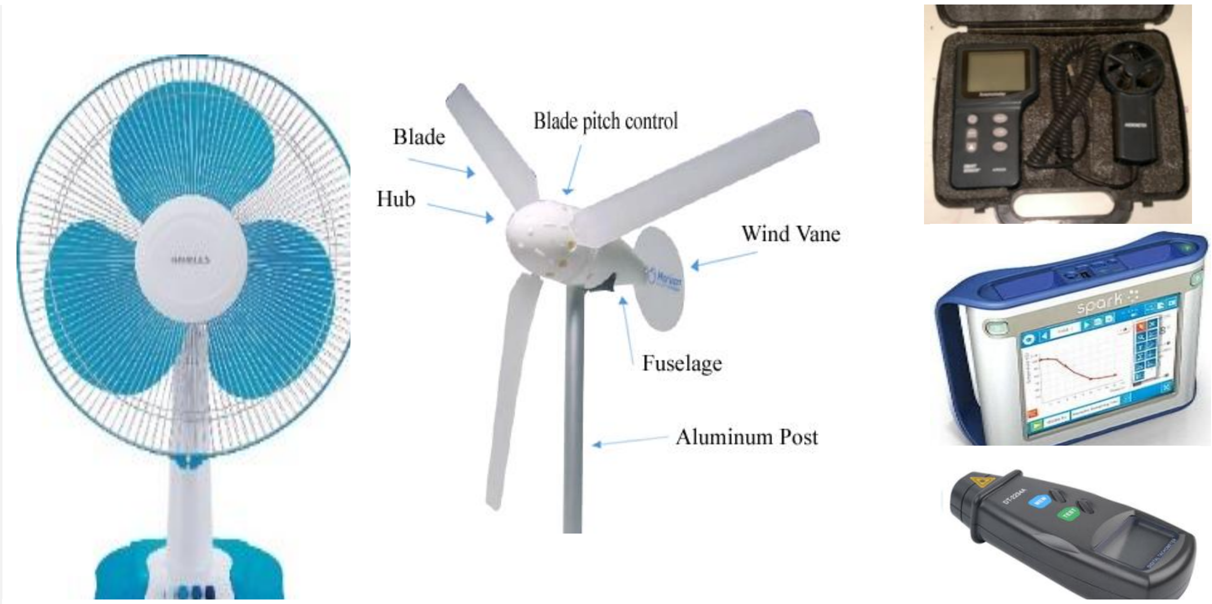

Fig 2: Instruments used in the current work

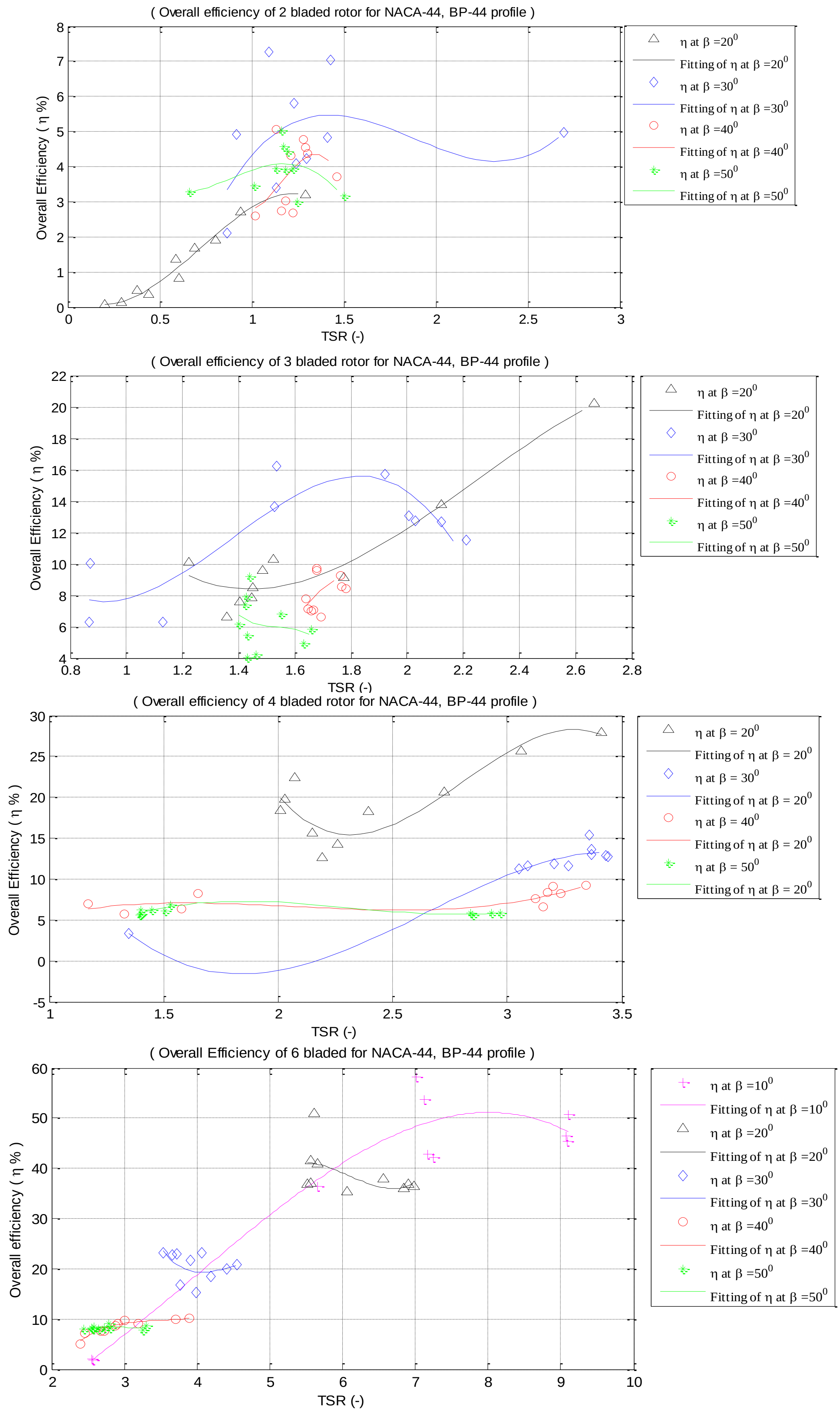

Fig 3: Behavior of overall efficiency for NACA-44, BP-44 profile at different pitch angle for 2, 3, 4, and 6-bladed rotor

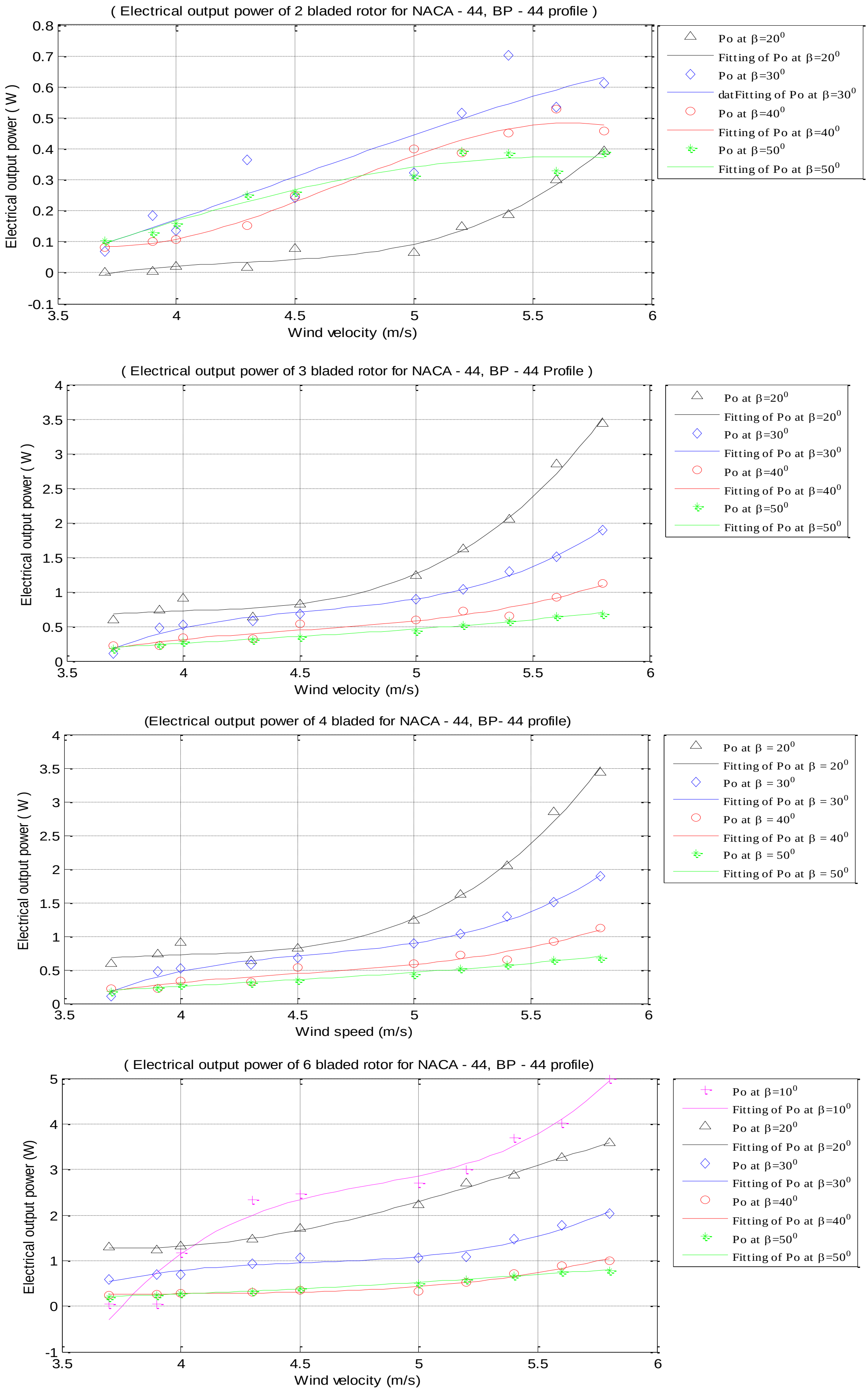

Fig 4: Behavior of electrical output power for NACA-44, BP-44 profile at different pitch angle for 2, 3, 4, and 6-bladed rotor

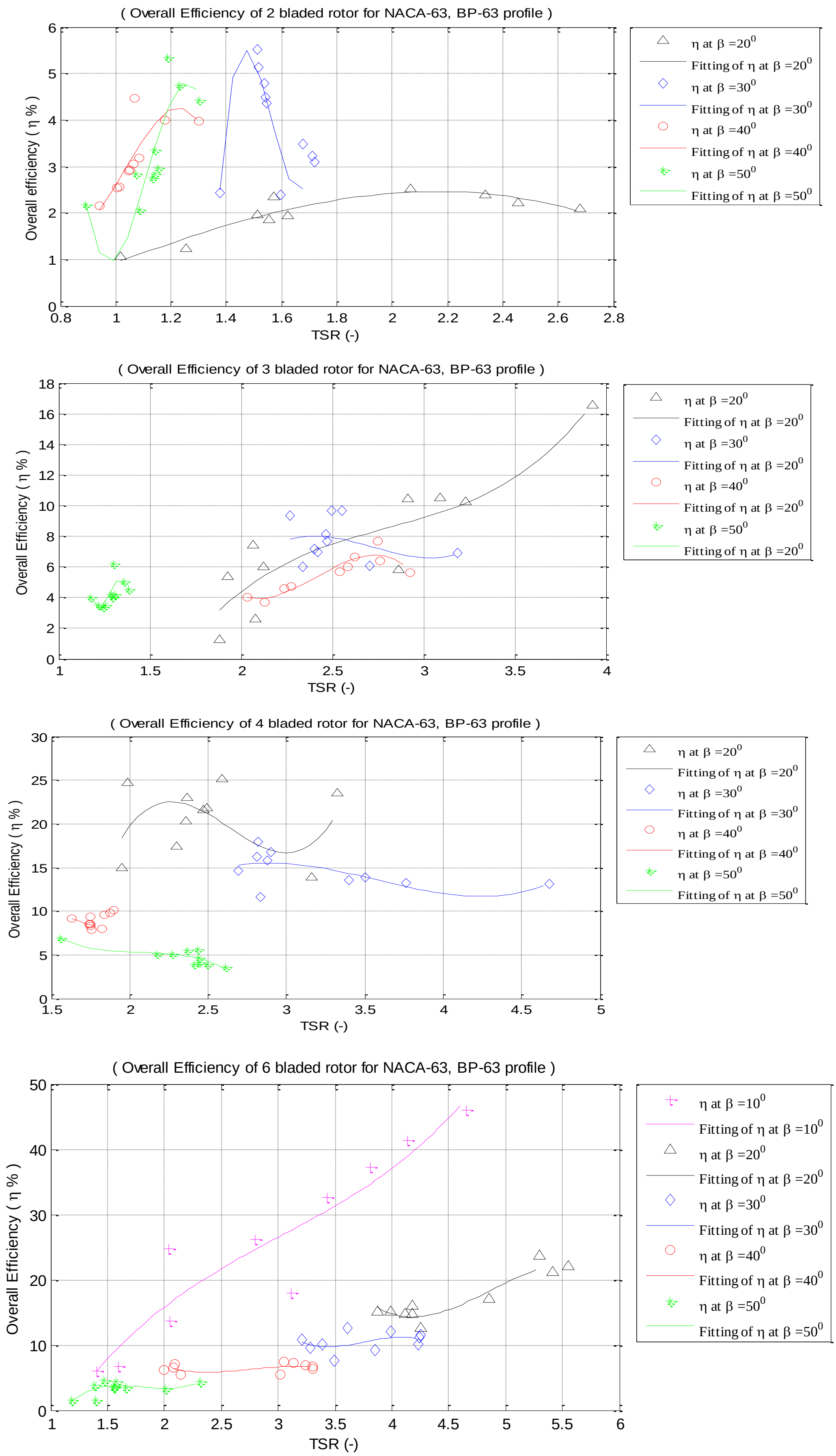

Fig 5: Behavior of overall efficiency for NACA63, BP-63 profile at different pitch angle for 2, 3, 4, and 6-bladed rotor

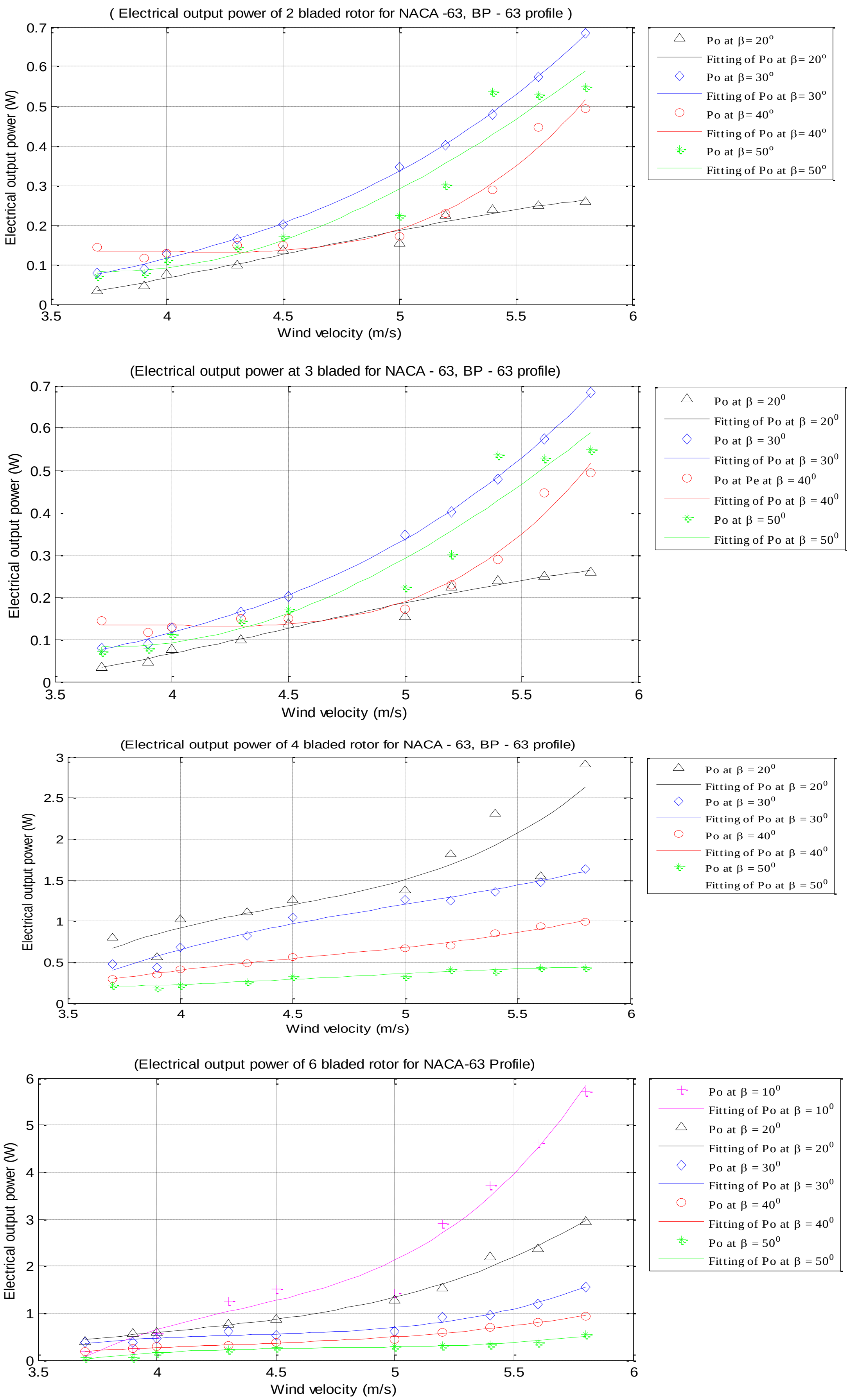

Fig 6: Behavior of electrical output power for NACA-44, BP-44 profile at different pitch angle for 2, 3, 4, and 6-bladed rotor

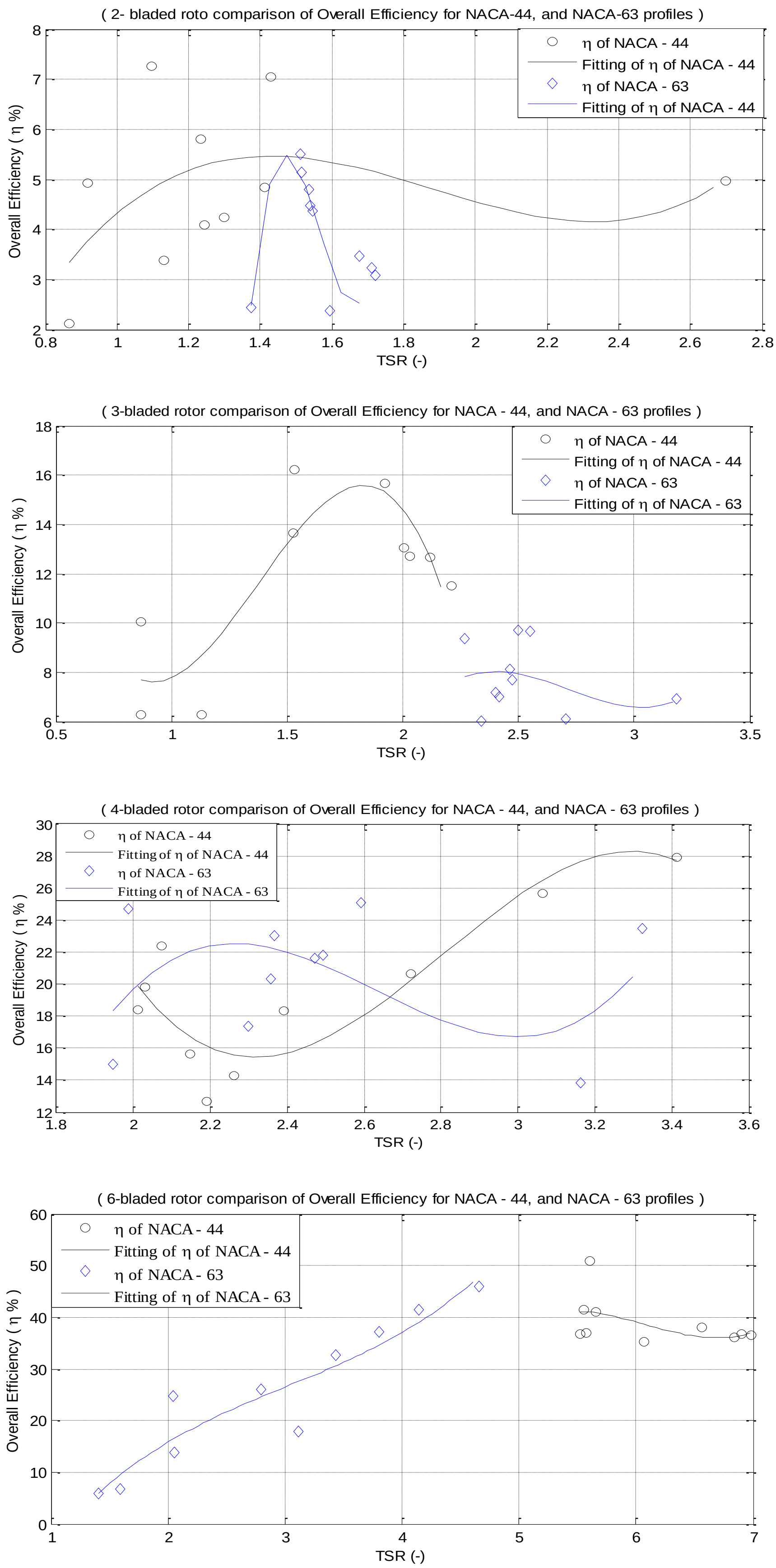

Fig 7: Comparison of NACA-44, and NACA-63 overall efficiency for 2, 3, 4, and 6-bladed rotor

6. NOMENCLATURES

Symbols	Description
$\mathbf{V_1}$	Upwind velocity (m/s)
v	Rotor velocity (m/s)
N	Rotation speed (rpm)
V	Volt) (Voltage
I	Current (Ampere)
R	Radius at blades tip (m)
A	Rotor blade area (m^2)
m	Mass of air (Kg)
$\boldsymbol{m}^{\circ}$	Air mass flow rate (Kg$/s$)
$\mathbf{P_w}$	Power available in the wind (Watt)
$\mathbf{P_o}$	Electrical output power (Watt)
Greek symbols	
$\boldsymbol{\rho}$	Air density (1.24 Kg/m^3)
$\boldsymbol{\omega}$	Angular velocity $(rad/sec.)$
$\boldsymbol{\eta}$	Overall efficiency (%)
$\boldsymbol{\beta}$	Blade pitch angle (°)
Abbreviations	
SHPWT	Small horizontal portable wind turbine
K.E	Kinetic energy
TSR	Tip speed ratio
NACA	National Advisory Committee for Aeronautics
SWEPT	Small wind energy portable turbine
SWT	Small wind turbine
SHAWT	Small horizontal axis wind turbine
SSHAWT	Small scale horizontal axis wind turbine
MWT	Micro wind turbine
SWE	Small wind energy
SWTG	Small wind turbine generator
PSIM	Software
PMSG	Permanent magnet synchronous generator

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