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Efficient Generation of Wind Power from Fast-Moving Heavy Vehicles during Deceleration

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***Abstract*—This work focuses on generating wind power by incorporating the kinetic energy of the head wind, during deceleration of heavy vehicle like a train by placing multiple wind turbines on the rooftop of individual coaches. Turbine working on principle action of drag force like the simple Savonius rotor is operated during deceleration of the vehicle. Drag mitigation during zero and constant acceleration motion is achieved by covering the effective turbine cross section with symmetrical airfoil flaps which also guide the wind at the turbine blades during deceleration with the help of mechanisms explained in this study. Theoretical efficiency analysis is performed for specific trains of Indian Railways considering the surplus weight of the mechanism, increased drag and power required to operate the flap mechanism. Feasibility and payback calculations by taking into account the efficiency and estimated construction and maintenance cost of the mechanism, are performed. Investigations regarding the effect of parametric variations in operating velocity, the number of stops, number of coaches and number of trips per day reveal that increasing the values all these parameters help in mitigating the energy production cost. This system will prove more efficient for trains with high operating velocity and high number of stoppages like the metro trains.**

Keywords—Wind power, roof mounted turbine, decelerating trains, areofoil flaps, feasibility.

I. INTRODUCTION

The detrimental effects of conventional energy sources on the environment are well documented through history, which impose a dire need for the development of non-conventional energy harnessing philosophies. Despite the scintillating advances in non-conventional energy technology, mankind still relies solely on conventional sources in order to satisfy the tremendous demand for energy needed in sectors some of them are namely industry, agriculture, and household usage. In actuality, this demand can easily be quenched by harnessing renewable potentials available naturally from the environment like wind energy and solar radiation. Many countries have become entirely reliant on non-conventional sources, with wind power as a non-trivial contributor.

According to an article in The Aspen Times [1] cities like Aspen, Greensburg and Burlington in the United States have met their total demand for energy from renewables with a large proportion of the total power coming from wind energy. By implying proper techniques wind power can prove to be a highly potent and easily accessible source of power. The most common method of power extraction from wind is the conversion of the kinetic energy carried by the wind to mechanical energy by action of drag or lift on wind turbine blades. This mechanical energy can either be converted to electrical power or can be used directly to drive other rotating machinery. There are many limits on the efficiency of the conversion technologies resulting in a large amount of power loss. Therefore, recently many new technologies are being developed incorporating mechatronics and piezoelectric devices for more efficient conversion. Chang et al. [2] fabricated such a device using Zinc Oxide piezoelectric transducer with efficient output characteristics. Efforts should be made for the generation and utilization of renewable energy from any and all sources possible. There is an increasing focus in on utilizing the high-speed wind generated as a result of displacement of air particles and the relative motion between air and vehicles, for power generation. Chaitanya et al. [3] incorporated the usage of a capacitor and change in electrical capacitance during power generation cycles to increase the amount of power obtained. Edward and Bateson [4] proposed installation of turbine generator units on roads or near train tracks to obtain power. Tseng et al. [5] proposed the use of a rotary mechanical unit on rooftops of vehicles like trains or airplanes for harnessing the wind energy and an electrical generator unit for power generation. A new type of turbine design coupled with the electrical generation system was proposed by Dwivedi et al. [6] for the specific purpose of power generation for railways. Neeraj et al [7] proposed the mounting of vertical axis wind turbines on roof of trains.

By operating the wind turbine during zero or constant acceleration motion of the vehicle, the power produced will be at the cost of increased drag on the train. This drag will have to be compensated by an increase in the energy required to drive the train requiring more fuel. Therefore, the efficiency of generating power while the train is in acceleration or constant speed motion will be very low, if not negative. Therefore, in this work, a stellar focus is on the power generation during deceleration and the airfoil flaps mechanism employed to achieve the required. The concept is proposed for heavy vehicles due to negligible surplus load to the engine by an addition of the new equipment as compared to intrinsic weight.

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II. DESIGN

A. Operating Mechanism type-1: for air channelling and drag reduction

In order to minimize the added drag on the vehicle due to the installation of the power extracting mechanism, the effective cross section as projected from the front of the vehicle is covered with a symmetrical airfoil shaped flaps split into a combination of upper and lower flaps as shown in Fig. 1, Fig. 2 and Fig 3. During acceleration or constant speed motion of the vehicle, the flaps are closed to effectively form a symmetrical airfoil with a minimum coefficient of drag c_d as shown in Fig. 2 (a). This arrangement will redirect the air over the flaps and effectively over the turbine blades. Due to the symmetrical nature of the airfoil and low value of c_d, minimal surplus drag will act on the vehicle effectively. During deceleration of the vehicle, the flaps will open directing the wind towards the turbine blade as shown in Fig. 2 (b). The flaps are proposed with such a profile that the air impacting on the turbine blades goes through a gradually reducing cross-section thereby increasing the kinetic energy at the cost of pressure energy, similar to nozzle action.

For controlling the actuation of the flaps, rack and pinion are employed. The bottom flap is rigidly connected to a shaft which is also rigidly coupled to the pinion as shown in Fig. 1. A motor with high starting torque will be connected to the shaft of the lower flap imparting angular motion to the shaft. This angular motion will be translated into linear motion of the rack. The shaft connected to upper flap is coupled rigidly to a crank. The slider coupled with this crank is rigidly connected to the rack. Thus, the vertical motion of rack is translated into angular motion of the shaft of the upper flap through the slider crank.

B. Operating Mechanism type-2: for air channelling and drag reduction

The mechanism explained above involves many complications like requirement of high degree of accuracy and precision during gear manufacturing and irrefutable kinematic

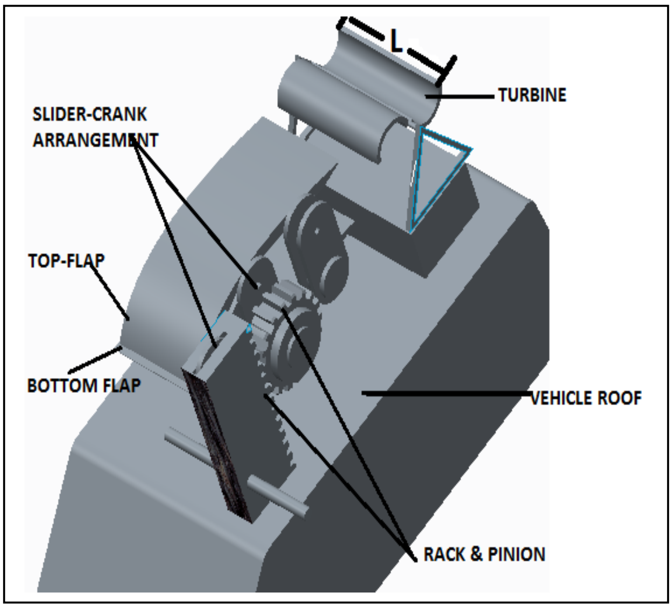

Fig. 1. Flap mechanism Type-1 and turbine placement

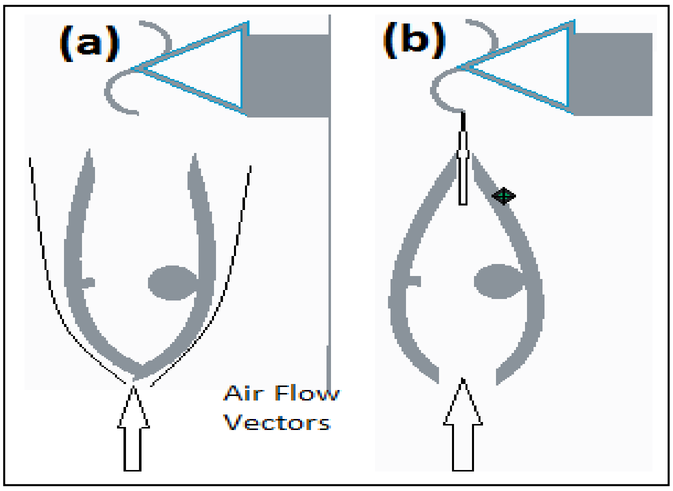

Fig. 2. Direction of air flow for mechanism type-1 (a) over the airfoil during zero or constant acceleration of the vehicle (b) through the converging airfoil during vehicle deceleration

calculations for transferring motion from one shaft to the other. This can be achieved in versatile manufacturing shops. For simple manufacturing in a laboratory and for testing purposes, type-2 is proposed as shown in Fig. 3. In this case, instead of giving motion to entire flaps, a small section is detached from the front of the flaps and it is attached by means of mechanical linkage to a shaft mounted on a truss support. At the back end of the link, extra weight for balance is mounted.

During acceleration or constant speed motion, the detached section is horizontal as shown in Fig. 3. This will direct air over the flaps similar to Fig. 2 (a). During deceleration, the shaft connected to the detached section is rotated counter-clockwise for some degrees which will move the section downwards in order to allow air to pass through the converging flaps to impact on the turbine blades similar to Fig. 2 (b).

C. Wind Turbine

Savonius turbines with blade cross section as shown in Fig. 4. are proposed in this work. Simple savonius turbines operate on the philosophy of drag force of the wind on turbine blades

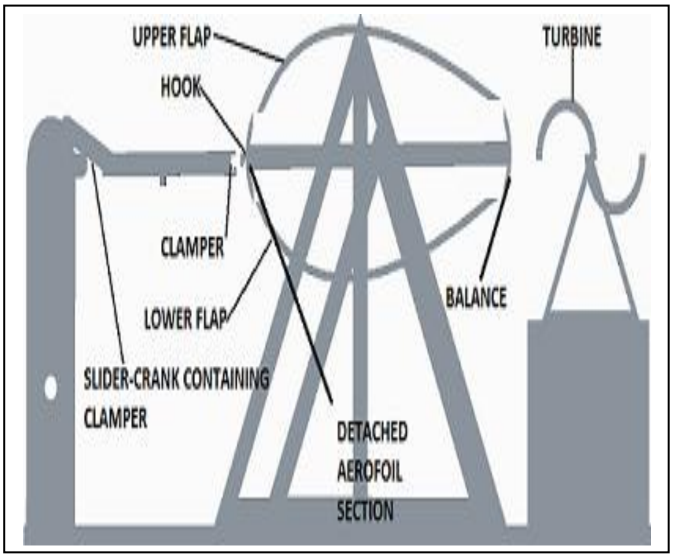

Fig. 3. Flap mechanism Type-2

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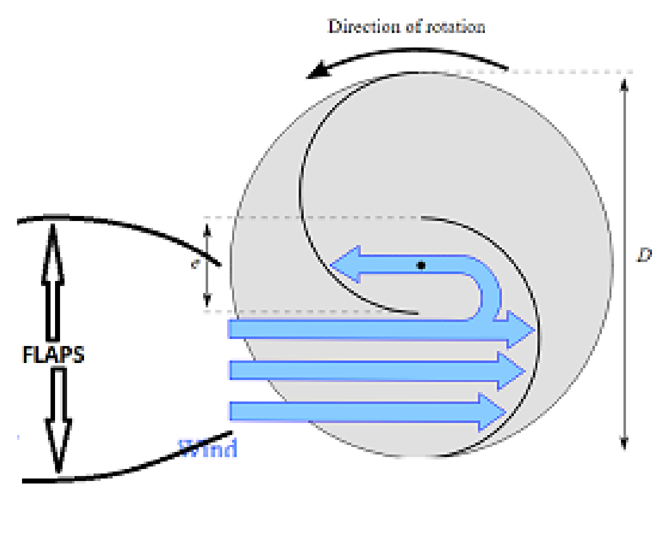

Fig. 4. Air flow directed by the flaps on the turbine cross section

placed orthogonal to the direction of air flow, converted to torque. A size constraint gets imposed on the turbine placed on the rooftop of trains as well as heavy road vehicles. According to a report on standard dimensions of Indian railways [8], an average minimum of 2.5meter clearance is required either between train roof and overhead power lines for electrical coaches or between roof and tunnel surface for diesel powered cases. Heavy road vehicles also have to pass many a time under low clearance bridges. The dimensions of the turbine should be on the basis of appropriate safe height between the turbine and the overhead structures. Therefore, the dimensions of the turbine considered for power calculations is such that the vertical height of the turbine or the total diameter D as shown in Fig. 4. is 0.5metre. and length L perpendicular to the direction of wind flow is 2metre which can fit adequately on the roof of intended vehicles. Therefore, the effective cross-sectional area of turbine encountering the wind orthogonally and ultimately responsible for power production is 1 square meter. The drag action on the turbines will be at irregular intervals due to stochastic braking of the vehicle, during which the turbines will be operated. Therefore, the turbines must have a high moment if inertia in order to maintain a constant rotating angular speed required for the electrical power generation unit.

III. MATHEMATICAL MODEL FOR POWER GENERATION, EFFICIENCY AND FEASIBILITY

A. Generated power

For a vehicle with a stopping distance of s after the application of brakes, total distance travelled during the journey D_t, total journey time T_t, number of scheduled stops in the entire journey N, the constant acceleration a given by kinematic equations of motion as

$$a = \frac{(v^2 - u^2)}{2s} \tag{1}$$

Where u is the magnitude of velocity before braking which is also the average velocity of the train during entire journey

$$u = \frac{D}{T} \tag{2}$$

v is the magnitude of final velocity, here equals to zero after application of brakes. In order to calculate the available energy from the turbines which are to be operated during deceleration only, the average time t during which the turbines are operated must be calculated as follows

$$t = \frac{(v-u)}{a} \tag{3}$$

The power (P) carried by wind of density ρ moving with an average velocity of v_{avg} and cross sectional area A can be given by

$$P = \frac{1}{2}\rho A v_{avg}^3 \tag{4}$$

The v_{avg} will be same as the average speed during deceleration of the vehicle.

$$v_{avg} = \frac{(v+u)}{2} \tag{5}$$

According to Betz correlation the maximum efficiency of a wind turbine cannot exceed 59 % [9]. In practice the value of efficiency is around 20 % to 40 %. By considering the bearing, gearbox, and other losses the efficiency comes to 10 to 30 %. The efficiency η is taken as 25% throughout the calculations.

Therefore, the energy E produced by the turbine per stop per turbine in time t when the vehicle halts from an initial speed of u to v is

$$E = \eta(P * t) \tag{6}$$

B. Additional losses incurred

- Firstly, due to the weight of the setup, surplus energy E_1 per stop per turbine will be required for carrying the entire setup of mass m-approximated to be 20 kilograms for this work, required for the additional power generation. This will be equal to energy required to accelerate and also decelerate the added weight. While accelerating from velocity magnitude v to u as per above mentioned notation the energy required by the engine will be change in kinetic energy of the setup. This will also be same as the energy required during deceleration. Thus,

$$E_1 = 2\left(\frac{1}{2} m u^2\right) \tag{7}$$

- Secondly, a total energy E_2 will be required to overcome the added drag acting on the setup during the entire trip, which will be the energy required to overcome drag when the flaps are closed. During closed flaps, drag will be encountered at angle of attack of zero degrees by symmetrical airfoil flaps having a drag coefficient c_d of at most 0.05 [10]. This drag force will act for a total distance of D_a.

$$D_a = D - (N * s) \tag{8}$$

Where $(N*s)$ is the total braking distance during the entire journey. Thus, E_2 will be

$$E_2 = \left[D_a * \left(\frac{1}{2} c_d \rho A u^2 \right) \right] \quad (9)$$

- Thirdly, a total energy E_3 will be required for actuating the airfoil flaps mechanism per stop per turbine of the vehicle. For the analysis, it is considered that five hundred joules per stop is required for operation of mechanism

C. Net production of energy

For n number of turbines mounted on the entire vehicle, the net energy produced E_{net} per trip of vehicle of total distance within the total time, will be given by

$$E_{net} = \left[n*N*(E - E_1 - E_3) \right] - E_2 \quad (10)$$

D. Cost feasibility and payback period

There is a negligible power loss in electrical generators according to [11]. Therefore, it is assumed that electrical power available from the entire setup is E_{net}. If the vehicle makes n_{tr} number of identical trips in a day, then the number of units U of electrical energy produced in one year will be

$$U = 365 * n_{tr} * \left(\frac{E_{net}}{3600000} \right) \quad (11)$$

The average cost of installation of each system is c_i. According to a study [12], a maximum of 35% of the installation cost of wind turbine system is required for operation and maintenance. Thus, the total cost C of installation of N number of mechanisms will be

$$C = 1.35*(n*c) \quad (12)$$

Here, installation cost of each setup is considered as five thousand I.N.R. for analysis. Considering the total operation life of the entire system is Y years (here ten), and number of units produced in a year, cost per unit is

$$C_u = \left(\frac{C}{Y*U} \right) \quad (13)$$

This extra cost required to generate electricity will have to be compensated from surplus ticket fare from the passengers or by any other governmental means and policies.

IV. RESULTS AND DISCUSSION

The above mentioned mathematical model is incorporated to perform an analysis for two different trains of the western section of Indian railways with the important disparities being in average operating speed and the ratio of the total stopping distance to the distance of total journey. Firstly, a case study is considered for Ahmedabad-Valsad Gujarat Queen, which is a comparatively slower train having less average speed and a higher number of stoppages. The other train considered for analysis is the New Delhi-Bombay Central Rajdhani, as an example of a fast train with high average speed and less number of stoppages. Data regarding operating parameters of the respective trains like total operating distance, total journey time, number of trips in a day, number of scheduled stops and the total number of coaches is collected from the official website of Indian railways [13] and [14]. The number of turbines that can be mounted on each coach is considered as two and the total number of turbines is calculated accordingly.

From table 1., it can be noted that for the Rajdhani express, due to very less number of stoppages as compared to the total distance of travel, the value of energy loss in overcoming drag while the flaps are closed and the turbine is not operated, is very high. This value exceeds the energy produced by the turbine by a large margin, due to which the net energy output of the entire system during the trip becomes negative. Thus in order to give positive output, the total distance during which the train is decelerating should be a higher percentage of the total distance of travel.

For the train Gujarat Queen, this stopping distance is much higher considering the overall shorter journey. The net positive energy produced from this system may be used for running the electrical appliances onboard the train or this power can be stored for later usage. The calculated cost per unit production of energy as shown in table 1 for this train can be added as a surplus amount in the passenger fare, which will be a very minimal amount per passenger considering the hundreds or thousands of passengers boarding per trip. Governmental funds can also be granted for this purpose under developing new renewable energy harnessing technologies.

In order to investigate the effect of the individual parameters on the cost per unit, an analysis is performed for hypothetical cases of operation of the Gujarat Queen. Specific parametric variations in the number of stops N, the total number of coaches, operating speed of the train u and the number of trips per day n_{tr} considering all the other parameters constant, impact the production cost as seen in table 2. By doubling the number of stops from the original value of 22, cost becomes almost a third of the original, but the impact of this effect goes on decreasing slowly as the number of stops is further increased to a larger value, and further doubling causes the cost to become half. The number of coaches are doubled from the original value of 22 to get the respective reduction in cost. This reduction also becomes less significant by further increasing the number of coaches from 44 to 88 as seen in table 2. The increase in average operating velocity of the train causes a drastic decrease

TABLE I. VALUES OF VARIOUS QUANTITIES AS CALCULATED

Quantity	Value	
	Queen	*Rajdhani*
Average operating speed u (m/s)	12.74	24.30
Average speed during braking v_{avg} (m/s)	6.37	12.15
Average stopping distance s (m)	1000	1750
Energy produced per turbine per stop E (J)	6208.51	39554.17
Surplus energy required in carrying the added weight of the setup, per setup E_1 (J)	3243.63	5904.29
Energy required to overcome drag E_2 (kJ)	1350.970	24821.94
Net energy produced per trip E_{net} (kJ)	1468.849	-15075.8
Total units of energy produced per year U	297.85	-
Total cost of installation and maintainence theoughout the life of entire setup C (I.N.R.)	297000	283500
Net production cost per unit C_u (I.N.R.)	99.71	-

TABLE II. EFFECT OF PARAMETRIC VARIATIONS ON PRODUCTION COST PER UNIT OF ENERGY

Parameter	Value	Cost per unit (I.N.R)
Number of stops N	26	99.71
	52	33.15
	104	14.19
Number of coaches	22	99.71
	44	68.31
	88	59.01
Average velocity of train u (m/s)	12.74	99.71
	25.48	19.28
	50.96	4.56
Number of trips n_{tr}	2	99.71
	4	49.86
	8	24.93

in the cost. For each case of doubling the velocity, the cost reduces to almost a fifth fraction of the prior value. From equation (11) and (13) it is apparent that cost per unit is inversely related to the first power of the number of trips in a day which can also be noted from table 2. But, this increase in the number of trips per day is only feasible considering that the vehicle remains idle for some part of a day.

V. CONCLUSIONS AND SCOPE FOR FUTURE WORK

The following conclusions can be drawn from the study performed

- In order to achieve positive production of energy, the system should be installed on train or other heavy vehicles having higher ratio of total distance for which the vehicle is decelerating to the total distance of travel, otherwise large energy loss will occur in overcoming the surplus drag acting on the installed system as compared to the energy produced by the mechanism, rendering the system ill-efficient.
- For a specific vehicle generating positive output from the installed system, with the increase in number of coaches, number of stops in one trip, average operating speed of the vehicle and number of trips per day, reduction in the net cost of production of one unit of energy can be achieved.
- Increase in operating velocity will have the most substantial impact on reducing the cost, followed by increasing number of stops, then number of trips per day and least effective is increasing the number of coaches.

Thus fast trains with a higher number of stops will get the most benefit from the installation of such a system. The best vehicular system fitting such a description are the metro trains. This work presents a theoretical analysis of the philosophy. Experimental analysis can also be performed to investigate the practical feasibility of such a system. The extraction of energy from wind can become efficient by incorporating efficient turbines like the helical savonius, darrieus or lift and drag coupled turbines like darrieus-savonius turbines and experimental effects of incorporating these turbines can also be investigated. By collecting standardized data about various trains and vehicles, this method of analysis can be applied to find out trains which give positive efficiency, and green energy can be extracted. Experimental and numerical investigations regarding the efficiency augmentation of the system due to the presence of guiding flaps can be carried out. The current analysis is carried out by considering only scheduled stops, but many times trains and other vehicles are encountered with a large number unscheduled stops, which will increase the quantum of energy produced mitigating the total cost per production of a unit of energy.

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