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Speed converter controlled river turbines

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Abstract—**Mechanical controls are mostly two-variable system (input and output) with a clutch in between. The author has invented a new three variable mechanical rotary motion control system. The core building block of the system is a "transgear". A transgear has three variables (input, control, and output) same as a transistor. A transgear is a mechanical three-variable gear assembly that just rely on the gear meshes and does not rely on cams or friction. Since transgears have three variables, they can control torque (τ) and angular velocity (ω) separately and independently. The first product application of the core element was to a speed converter and the author named it "Hummingbird". Speed converter Hummingbird is designed with two transgears and has three variables. Two transgear-controlled Hummingbird is a mechanical three-variable rotary motion control. Operationally, when the three variables are assigned with three functions, i.e., a variable input (first independent variable), a control input (second independent variable), and an output (dependent variable), the first transgear identifies the speed differences (delta (Δ) speed) between the variable input and the control input, and the second transgear eliminates the identified speed differences (Δ speed): therefore, the output of the speed converter Hummingbird becomes constant when the control input is constant. A properly designed Hummingbird is balanced with torque and speed, and the generated electrical power is greater than the control power used (electrical advantage). Hummingbird-controlled river turbine controls are scalable and can generate constant frequency baseload electricity with grid (grid-tied) or without grid (distributed generation). Speed converter Hummingbird can be used to harness Marine Hydrokinetic energy of rivers, tidal, wave, ocean current, and also wind energy.**

Keywords—**Baseload Electricity, Distributed Generation, Electrical Advantage, Energy Converter, Hummingbird, Insulated Gate Bipolar Transistors (IGBT), Levelized Cost of Energy (LCOE), Marine Hydrokinetic (MHK) Energy, Mechanical Transistor, Power Converter, Power Converter System (PCS), Rated Speed, Rotary Frequency Converter, Speed Converter, Transgear, Variable Frequency Converter (VFC)**

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I. INTRODUCTION

MARINE Hydrokinetic (MHK) energy is produced by the movement of large bodies of water such as rivers, lakes, tides, and oceans. The produced energy comes in different forms: uni-directional free-flowing rivers and ocean current, bi-directional tidal energy, and turbulent wave energy. MHK energy is renewable, abundant, free, and dependable. With more than 50% of the American population living within 50 miles of the coast, a cost-effective MHK technology could provide a substantial amount of electricity for the nation [1, 2].

Most big rivers flow continuously; if this hydrokinetic energy can be harnessed, the generated electricity can provide baseload electricity to large populations in the vicinity of those resources requiring relatively short distribution infrastructure. River-based turbine/generator infrastructure can be constructed at a lower cost by mooring to nearby shores and shallow riverbeds versus ocean-based systems. Further, construction materials may last longer in fresh-water river environments where there is less corrosive salt versus ocean water. These two factors significantly reduce the construction and operation and maintenance (O&M) costs of river turbines when compared to that of ocean turbine costs.

Currently, the renewable energy industry relies primarily on electronic solid-state Power Converter Systems (PCS) to convert and regulate the 'raw' electrical output of its generators to usable alternating current (AC) power as specified frequencies. In the wind energy industry, wind speed is variable and is not constantly active. The inconsistent nature of a wind resource leads to the necessity of an electrical system which can take in a wide electrical input range, to match the wide wind speed range, and convert to a specified AC electrical output. Operationally, wind turbines generate variable frequency AC power using conventional variable speed generators. A PCS must then convert the variable AC power to grid-compatible frequency at a regulated AC voltage. The process requires first converting the variable AC to direct current (DC), then back to AC in a specified condition per grid regulations. PCS operating in this manner also can be called Variable Frequency Converters (VFC). Using VFC, wind power systems can effectively operate over wider resource conditions harvesting more energy and increasing capacity factor. However, during this conversion process, all generated power is being processed by the converters' Insulated Gate Bipolar Transistors (IGBT). This process has two major vulnerabilities: the power rating is limited by heat dissipation capacity, and, excessive heat over prolonged periods can lead to device failures and increased O&M costs. The PCS also consumes some parasitic energy in the process, though typically only on the order of several percent or so.

The available or useable power of wind and water energy can be calculated by

$$P = \frac{1}{2}\rho A v^3 \quad (1)$$

where ρ is the fluid density, A is the rotor sweep area, and v is the input speed. When harnessing river energy, the water density is high, approximately 800 times denser than air, and, similar to wind energy, the variation of flow is wide. For example, the discharge rate of the Ohio River, according to Wikipedia, varies from the average 8,000 m^3/s to the maximum 52,000 m^3/s. For the sake of comparison, assume the river banks are vertical (not sloped) and the variation of the discharge rate is the same as the speed variation, the maximum speed is 52,000/8,000=6.5 times faster than the average speed and the maximum power is $(6.5)^3$=274 times more powerful than the power harnessed at the average speed. Due to the high density and wide speed variation, the hydrokinetic power of the Ohio River is impractical to be harnessed with a power converter since the wide speed variation requires an extremely large power converter at the maximum speed, however, is harnessing much smaller amount of power at the average speed most of the time. This results in increased product costs and the generation of low amounts of electricity. Power converters can, however, be used to harness relatively lower energy amounts from resources c such as tidal and wave since potential energy there is less.

An MHK turbine consists of three modules: harnessing, controlling, and generating. Our research indicates that most current MHK developers are developing harnessing modules and implementing PCS units that were developed for the wind industry [3], for integration with electrical distribution systems. Therefore, the power ratings of the PCS-based MHK turbines are limited by manufacturing capabilities to effectively scale IGBTs. A recently released DOE report [4] states that the potential of these small-scale MHK turbines that are developed or under-development does not guarantee a low-cost solution that can be deployed in commercial scale applications. PCS are expensive and limited in power range [5]. Increasing the power ratings and lowering the LCOE of MHK turbines with scalable speed converters may address these concerns.

By replacing PCS with mechanical speed converters, *river turbines can harness more electricity at a lower cost per unit.* Advantages of speed-controlled river turbines are summarized below.

1) Dams or penstocks: No dams or penstocks are necessary. Low levelized cost of energy (LCOE) and low environmental impact from infrastructure.
2) Baseload electricity: Continuously flowing river energy can generate baseload electricity with a higher capacity factor versus other renewable energy sources.
3) Electrification for grid-less remote regions: Speed-controlled river turbines leverage traditional variable speed generators capable of isochronous and droop-mode operation with or without the presence of a utility grid. Allows for cost avoidance of building utility transmission lines to reach remote areas and lowers the barriers-to-entry of smaller, more remote equipment manufacturers.
4) Scalability: Technology used in the proposed speed converters is easier and more cost-effective to scale versus currently implemented electronic power converters.

II. CONVERTERS

The grid power is constant but all renewable energy to be harnessed is variable so the energy must be converted to constant. There are various types of converters.

A commonly used converter is a thermal energy converter. Produced steam energy is produced by the burning of fossil/nuclear fuel burning it into constant energy. All baseload electricity, except hydro, is generated by this method. Unfortunately, fossil fuel deposits are limited, and research indicates that peak production is behind us [6]. There is no doubt that the supply will run out, it is just a matter of time.

Hydroelectric power plants with dams dominate the current market of water-based energy generation, but the best available sites are either already taken or require unfeasible infrastructure due to site conditions. This industry segment is either not growing or growing only in certain countries.

Harnessing intermittent wind and solar energy with power converters and developing storage systems is helpful, but is unlikely to satisfy worldwide power demand on their own.

Meanwhile, MHK resources are abundant and naturally adjacent to population centres, but harnessing water energy with PCS may not be the final solution. The industry needs more efficient and robust methods for harnessing this energy.

Water energy is classified in two categories: hydro potential energy or hydroelectric, and hydrokinetic

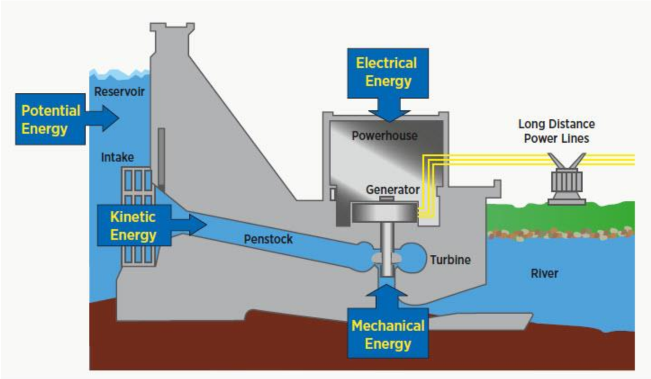

Fig. 1. Layout of a Hydroelectric Power Plant. Hydroelectric power plants are designed with three variables: (1) input is upstream river, (2) control is dam, spillways, sluice gates, wicket gates, and turbine blade pitch, and (3) output is constant speed. Form of energy changes many times: kinetic energy from upstream changes to potential energy by a dam. With various controls the potential energy converts to constant kinetic energy, to mechanical energy, then to electrical energy.

energy (MHK energy). MHK energy is further divided into bi-directional tidal energy, erratic wave energy, and uni-directional river and ocean current energy. The focus of this paper is to uni-directional river energy.

A. *Energy Converters*

The term "energy converter" was created by the author to clarify the differences between the thermal energy controlling system and the frequency controlling or a newly developed speed controlling system.

Energy converters convert variable energy to constant prior to producing constant speed. The concept of producing a certain constant speed prior to generating a certain constant frequency is common to all baseload generating turbines including hydroelectric power plants and fuel-burning turbines. Three of the most commonly used fuels are coal, natural gas, and nuclear rods.

As shown in Fig. 1, Hydroelectric power plants, for example, have three variables: (1) water resource coming from up-stream, (2) the controlling variable: dams, spillways, crest gates, sluice gates, penstocks, wicket gates, and turbine (runner blades) pitch, and, (3) the dependent variable: constant speed output. The controlling variable or energy converter converts the variable hydrokinetic energy to constant so that the turbines can rotate at a constant speed. Once constant speed is produced, a constant speed generator can generate grid-quality constant frequency electricity. As stated above, the concept of converting a certain constant speed to a certain constant frequency is in all baseload generating turbines.

B. *Power Converters*

Power converters convert variable frequency to constant. Since the power converter technology is well known, the technology itself will not be discussed in this paper.

The majority of water power harnessed today is done so by hydroelectric power plants, more specifically, dams, however, there has been little growth in recent years. For harnessing MHK energy, a common trend is developing tidal and ocean wave energy turbines. Currently MHK turbine developers are designing various harnessing modules but are using power converters as controls.

There are many MHK turbine developers. For the purpose of examining the various methods of control comparison, we have identified three developers who are using distinctively different control technology.

Verdant Power (USA) is selectively harnessing tidal energy when the flow speed is "steady". They turn the generator on and off. ORPC (USA) and Tocardo (Netherlands) are harnessing variable power, then converting the power to constant using power converters. The power ratings of their turbines, according to published information on their websites are Verdant Power 21kW (at a steady speed), ORPC 35kW at 2.25 m/s, and Tocardo 240kW at a specified speed range. The power rating of Tocardo is much higher due to its unique feature of raising the turbines from water when the flow speed is beyond the designed speed range. Their design consists of five 240kW-rated T2 bi-directional turbines making a semi-submersive, floating 1.2 MW tidal power platform. The higher power rating comes with a big and expensive lifting mechanism.

III. SPEED CONVERTERS

C. *Gap in Available Technology*

The author believes that there are two reasons why MHK turbine developers are developing tidal and wave energy turbines: (1) developers are using PCS that are limited in power rating and (2) PCS can harness low power of tidal and wave energy. These turbines are generating limited amounts of electricity, only kilowatts to date, for example, Verdant Power 21kW, ORPC 35kW, and Tocardo 240kW (due to the defined speed range), resulting in a non-competitive LCOE.

The author also believes that the most favourable MHK energy is uni-directional hydrokinetic river energy and that the best method of harnessing the energy is converting the harnessed variable speed to constant.

He has developed a mechanical, three-variable speed converter that converts variable speed directly to constant, eliminating the need for energy conversion or frequency conversion.

D. *Building Block: Transgear*

The core building block of speed converters is *transgear*. A transgear is an assembly of gears that has three variables. Any type of gear can be used to construct a transgear including spur gears, helical gears, internal gears, bevel gears, or worm and pinion gears. There are many types of transgears but only one type will be discussed in this paper: a perspective view of a basic symmetrical spur gear transgear is shown in Fig. 2.

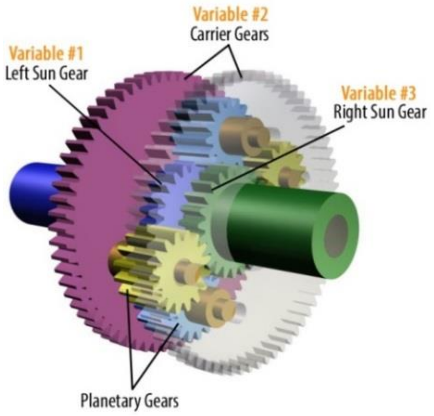

Fig. 2. A perspective view of a basic symmetrical spur gear transgear with three variables. A transgear has three variables: namely left sun gear, right sun gear, and carrier gears. Two sets of planetary gears are shown here, but more sets can be added. Normally three sets of planetary gears are used to balance the system and to transfer more torque. When the carrier gears are not rotating (fixed), only one set can be used.

A transgear consists of a left sun gear, a right sun gear, and carrier gear(s). The left sun gear is meshed to the right sun gear through planetary gears as shown in Fig. 3. Having three variables, transgears can be used as variable rotary motion controls, similar to how transistors are used in electronic circuits. Because transgears are assembled with gears, they are scalable in power handling with conventional manufacturing processes. The number of planetary gear sets can be one or more depending upon application.

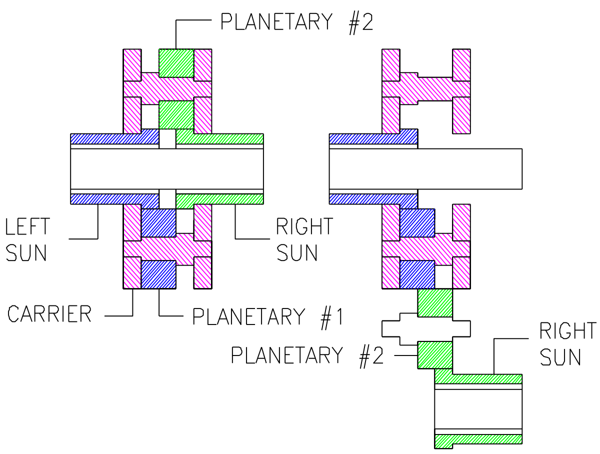

Fig. 3. Cut-view schematics of a basic spur gear transgear with three variables. These schematics are shown with a set of planetary gears in order to explain how the gears are meshed. The assigned functions to this transgear are color coded: input (blue) to left sun gear, output (green) to right sun gear, and control (magenta) to carrier gears.

All Transgears have three variables and, to each variable, a function can be assigned. As shown in Figs. 2 and 3, for example, input (blue) is assigned to the left sun gear, control (magenta) to the carrier gears, and output (green) to the right sun gear. When the carrier gears are fixed, the input to the left sun gear will be transmitted to the right sun gear through planetary gears.

The variation of rotational speed of a transgear is tabulated in Table 1. When the input speed is a constant 1 rpm, for example, the output speed can be varied infinitely from +1 to -1, clockwise and counter-clockwise, respectively, when the control speed is controlled as shown.

As shown in Table I, *using the formula developed according to the author's transgear rule*, the output speed through the right sun gear, R, can be calculated as shown in (2) below. For example, when L=1 rpm and C=1/4 rpm,

$$R = 2C - L = 2 \times \frac{1}{4} - (1) = -\frac{1}{2} rpm \qquad (2)$$

The input speed of 1 rpm is decreased to an output speed of 1/2 rpm and the direction is reversed.

TABLE I
VARIATION OF TRANSGEAR INPUT AND OUTPUT SPEEDS

Left Sun Gear (L)	Carrier Gear (C)	Right Sun Gear (R)
L = 2C - R	C = (L + R)/2	R = 2C - L
1	1	1
1	1/2	0
1	1/4	-1/2
1	1/8	-3/4
1	0	-1

Note: The formulas shown are developed according to transgear rule for a basic transgear, i.e., the diameters of the left sun gear and right sun gear are same.

Again as shown in Table 1, any given input speed can be converted to any output by infinitely controlling control speed. When speed can be controlled, torque also can be controlled as shown below:

Power (P) = Torque (τ) · Rotational Speed (ω)
$P = \tau\omega$
$P = \tau_1\omega_1 = \tau_2\omega_2$ --- if Power (P) is constant
$\tau_2 = (\omega_1 / \omega_2)\ \tau_1$
If $\omega_1 > \omega_2$, then $\tau_2 > \tau_1$ --- torque (τ) can be controlled

When a system has three variables and each variable can be varied infinitely, a mechanical advantage can be produced. For example, Pascal's principle was developed based on three variables: force, pressure, and area. When two variables are controlled, a mechanical advantage is created.

Pascal's principle in fluid mechanics states that, in a fluid at rest and in a closed system, a pressure change in one part is transmitted without loss to every portion of the fluid, and to the walls of the container [7].

- Pascal's Principle: Hydraulic System
- Force (F) = Pressure (p) • Area (A)
- If Pressure (p) is constant,
- $p = F_1/A_1 = F_2/A_2$

- $F_2 = (A_2/A_1)\,F_1$
- If $A_2 > A_1$, then $F_2 > F_1$
- ***Mechanical Advantage***

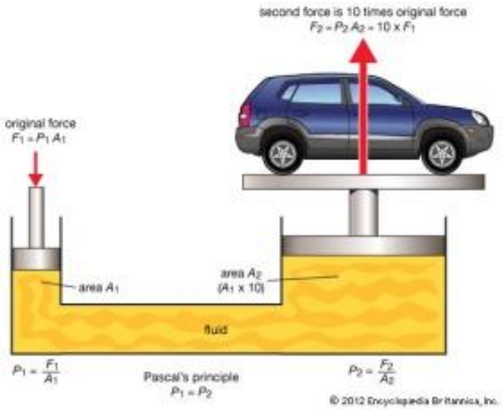

Fig. 4. Pascal's Principle. In a closed hydraulic system, a small control force can create large work force by controlling areas.

Similar to Pascal's Principle, in a balanced, three-variable rotary motion control system, electrical power can be controlled. This is possible by controlling two of the three variables in the system.

- Han's New Principle: Three Variable Rotary Motion Control System.
- Power (P) = Torque (τ) • Rotational Speed (ω)
- $P = \tau \bullet \omega$
- If Torque (τ) is constant,
- $\tau = P_1/\omega_1 = P_2/\omega_2$
- $P_2 = (\omega_2/\omega_1)\,P_1$
- If $\omega_2 > \omega_1$, then $P_2 > P_1$
- ***Electrical Advantage***

E. Speed Converter "Hummingbird"

Speed converter Hummingbird is an assembly of two enmeshed transgears. It should be noted that a transgear has three variables and, when two transgears are connected by a variable from each set, the resulting assembly will have four variables since two variables are used to connect them. Hummingbird is connected by two variables of each transgear and has three variables total. There are many different ways to connect two transgears, but a variation was selected for this paper, as shown in Figs. 5 and 6.

Left Transgear shown in Fig. 5: The variable input ω rpm + Δ rpm (first independent variable) is assigned to the left sun gear (dark blue) and the control input -ω rpm (second independent variable) to the right sun gear (magenta). Here we're defining our *desired* output speed as ω rpm. The output (dependent variable) becomes the carrier gear(s) (green). According to the developed transgear rule:

$$C = \frac{L+R}{2} = \frac{(\omega+\Delta)+(-\omega)}{2} = \frac{1}{2}\Delta\,rpm \qquad (3)$$

The carrier gears will be the output (1/2)Δrpm. This means, the first transgear identifies the variable amount of the input speed, with a scaling factor, or (1/2)Δ rpm.

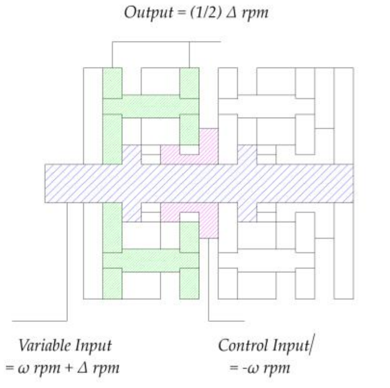

Fig. 5. A cut view of Hummingbird. Focusing on the left transgear, variable input (dark blue) ω rpm+Δ rpm is the left sun gear and control input (magenta) -ω rpm is the right sun gear. Negative sign means the direction is opposite. Output is carrier gears (1/2) Δ rpm.

Right Transgear shown in Fig. 6: The variable input is the same as in the left transgear, ω rpm + Δ rpm (first independent variable), but this time, it is assigned to the left sun gear (dark blue). The output of the left transgear (1/2)Δrpm becomes the control input (second independent variable) to the right transgear through a connecting gear. The control input is assigned to the carrier gear (magenta). The output of the right transgear (or the output of speed converter Hummingbird) is, according to the transgear rule:

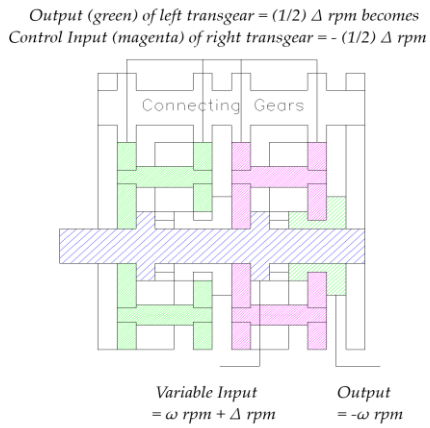

Fig. 6. A cut view of speed converter Hummingbird. Focusing on the right transgear, variable input (dark blue) ω rpm + Δ rpm is the left sun gear and the control input (magenta) is carrier gears (1/2) Δ rpm which is transferred from the left transgear through connecting gear. Output (green) -ω rpm is right sun gear.

$$R = 2C - L = 2\left(\frac{1}{2}\Delta\right) - (\omega + \Delta) = -\omega\ rpm \quad (4)$$

The output is -ω rpm or constant. Hummingbird converted constant speed will rotate a generator to generate constant frequency. The assembly of two transgears converts a variable input to constant without needing an energy converter or a frequency converter.

In summary, Hummingbird is an assembly of two transgears capable of converting variable input speed (first independent variable) to a selectable constant output speed (dependent variable) using a constant *reference* control speed (second independent variable).

F. *Applications of Speed Converter Hummingbird*

Hummingbird is a scalable gear assembly converting variable speed to constant. In this paper, two applications are studied: grid-tied and distributed generation (stand-alone system).

Application #1: Grid-tied River Turbines

When the grid is available, the assembly uses the grid to power the control input as shown in Fig 7.

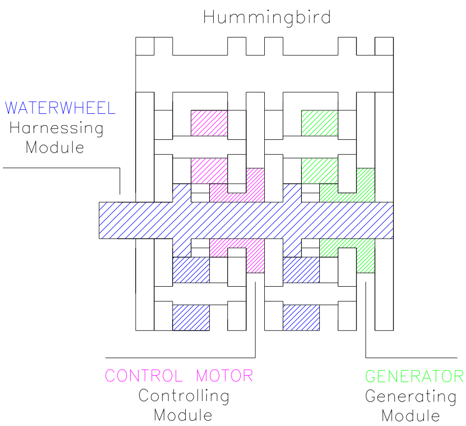

Fig. 7. Schematic of speed converter Hummingbird-controlled River Turbine. The harnessing module can be a waterwheel, the controlling module is a constant speed AC or DC motor powered by grid, and the generating module is a generator.

Application #2: Distributed Generation.

When the grid is not available, the control power is self-generated. One method is using an alternator driven by the input to generate variable DC power and using a DC voltage regulator and battery to supply DC power to a DC control motor as shown in Fig. 8.

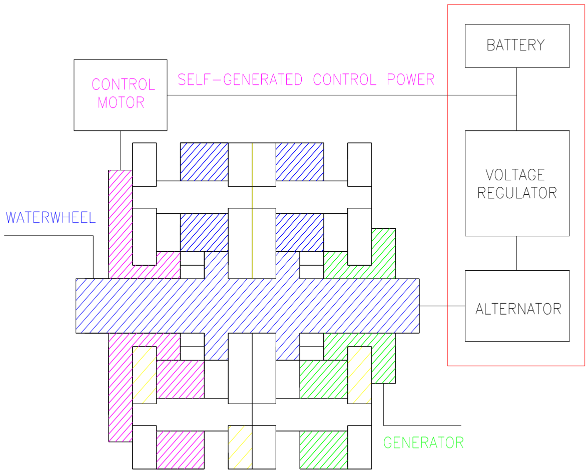

Figure 8: Distributed Generation. When grid is not available, the control power will be generated. The self-generating technology is similar to an automotive system.

G. *Tests: River Turbines*

In order to validate the speed converters, many samples were built and tested including a river turbine controlled by a speed converter for converting harnessed variable speed input to a constant frequency output. The river turbine consists of a waterwheel (harnessing module), a speed converter (controlling module), and a generator (generating module).

Samples tested are the following and each test will be discussed separately:

I. Sample #3: In-lab test
II. Sample #4B: In-lab test
III. Sample #4C: In-lab and in-river test

Sample #3: In-lab test

Sample #3 was built utilizing variable speed pumps to recirculate water from a large tank to create a variable water flow. The Pelton overshot waterwheel used was constructed with eight straight blades for simplicity. While changing the flow speed from the designed minimum to the maximum, the generated frequency and voltage were measured. The test results were presented at the AWTEC 2018 Conference [8].

Sample #4B In-lab test

Samples #3 and #4B are functionally similar, with the exception that the latter was built with a variable speed motor to replace the big tank of water and pumps, a bigger generator was used, and more controls were added to collect more test data. A picture of Sample #4B is shown in Fig. 9.

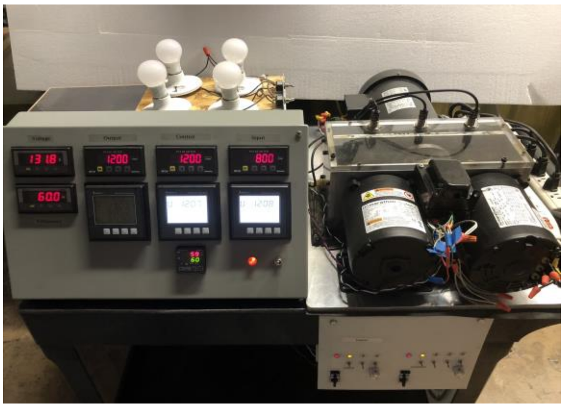

Fig. 9. Test Sample #4B. A variable speed input motor represents the waterwheel and variable load was simulated by multiple light bulbs.

Three tests were performed with Sample #4B. Below, test procedures will be explained first, collected data next in tables, and observation next.

Test #1 Test Procedure:

Input Motor: 1,200~2,400 rpm

Control Motor: 1,200 rpm, constant

Measure Frequency and Voltage

Repeat: Increase the test load and repeat the procedure.

Test Data: Table 2

TABLE 2
TEST #1 EFFECTS OF LOAD VARIATIONS ON CONTROL SHAFT SPEED AND OUTPUT CHARACTERISTICS

Load (W)	Input Speed (rpm)	Control Speed (rpm)	Output Speed (rpm)	Generator Output: Freq (Hz)	Generator Output: Volts (V_{AC})	Generator Output: Amps (A_{AC})
0	1,200	1,200	1,200	60.0	131.8	---
60	1,200	1,196	1,196	59.7	131.2	0.464
120	1,200	1,191	1,191	59.5	128.3	0.935
180	1,200	1,184	1,184	59.2	127.0	1.417

Observation of Test #1: As the load increases, control motor speed, generator speed, frequency, and voltage decrease.

Test #2 Test Procedure:

Initial Test: Same as Test #1 above

Repeat: Increase the test load, adjust the control motor speed to 1,200 rpm, and repeat the procedure.

Test Data: Table 3

Table 3. Test #2: Effects of the load to the Frequency while the control input is constant

Load	Input	Control	Gen	Freq	Voltage	Current
0	1,200-	**1,200**	1,200	60	131.8	---
60	1,200-	**1,200**	1,200	60	131.6	0.461
120	1,200-	**1,200**	1,200	60	129.5	0.926
180	1,200-	**1,200**	1,200	60	128.7	1.398

Observation of Test #2: At a given load, if the control speed is maintained constant at 1,200 rpm, the frequency remains constant at 60 Hz.

Observation of Test #2: At a given load, if the control speed is maintained constant at 1,200 rpm, the frequency remains constant at 60 Hz.

Test #3 Test Procedure:

Analyzing the test result shown in Test #2, it was understood that the frequency can be made constant regardless of the load if (1) the test load is constant, or, (2) the control motor speed is constant. The first method was simple to prove: the total load was made up with two loads, a variable micro-grid load and a compensatory load to make the total load constant, i.e.,

Total Load = Variable Load + Compensatory Load
where Compensatory Load = Total Load – Variable Load

The second method was continuously adjusting the control motor speed to 1,200 rpm by using a variable frequency drive (VFD). Both concepts were tested and validated.

Summary of Sample #4B Test Result:

(1) Hummingbird can convert harnessed variable input speed to constant so that constant frequency electricity can be generated.

(2) By using either one of the two methods, Hummingbird can maintain constant frequency while the load is variable: constant total load or constant control motor speed.

H. Sample #4C CHTTC Tests

The University of Manitoba, Winnipeg, Manitoba, Canada has a river turbine test site located in the Winnipeg River. The Canada Hydrokinetic Turbine Test Centre (CHTTC) is operated by the University's Mechanical Engineering Department. Our river turbine control was tested first at the university lab then at the river test site by the CHTTC staff.

Sample #4C CHTTC In-Lab Test

As was indicated earlier, the test samples #4B and #4C are functionally the same, except the input to #4B was connected through two sun gears, while #4C was connected through carrier gears to facilitate a simpler retrofit of the assembly to the existing test facility at CHTTC. As the generator at the test site was vertically mounted, the gear assembly was also vertically mounted, meaning gears were stacked on top of each other and flat surfaces were rubbing each other, especially the bottom gears were producing more heat due to the weight. It was noted during testing that the vertical design proved unacceptable due to high friction.

The lab test was performed prior to going to the river. The collected data is summarized in Table 4 and the data will be analysed.

TABLE 4
SAMPLE #4C TEST RESULTS PER REPORT

Power Supply	Gearbox	Input Motor	Control Motor	Generator Load	Power Ratio
1.0kW	1.0 kW	0.9kW	0.1kW	0.0kW	
2.3kW	1.0 kW	0.4kW	0.9kW	1.3kW	0.6922
3.2kW	1.0 kW	0.6kW	1.6kW	2.2kW	0.7272
Power		0.6/0.4 =1.5	1.6/0.9 =1.777	2.2/1.3 =1.692	

Note: Black numbers are raw data, red numbers are calculated.

Analysis #1: The gearbox was designed vertically so that the box would fit the existing test facility easily at the test center. The auxiliary consumption of 1.0 kW is due to the vertically mounted gears in the gearbox. Future design will be horizontally mounted to reduce friction losses.

Analysis #2: The basic transgear rule says the input power (river energy) must be equal to or greater than the control power and the output power. The test was therefore performed incorrectly and will be repeated but, fortunately, the collected test data provides insight on the assembly's functionality, regardless.

Analysis #3: The input motor power is decreasing while the control power is increasing. This means the system is demanding more power from the control than from the input. The algorithm should be reversed so that more power is drawn from the input. Further study is planned.

Analysis #4: As the power of the input motor increases, the power of control motor and generator also increase. This was expected.

Analysis #5: The power ratio of a fuel burning system compares the input to output; however, in a renewable system, the renewable energy is free, and the conventional ratio doesn't mean much. In the Hummingbird system, the control power will be compared to the output.

Power Ratio = Control Power / Output Power

The power ratios calculated with measured powers are, for example, 0.6922 (or 69.22%) at 2.3kW input and 0.7272 (or 72.72%) at 3.2kW. The ideal ratio should be low. The result is high. The author's goal is lowering to approximately 10 to 20% level. If the control power is self-generated, the power ratio is not as critical as using grid power but it's preferable to make the control motor as small as possible.

Sample #4C: CHTTC Winnipeg River Test

After the lab test, Sample #4C was taken to the river for the site test. The test started in the fall of 2017 but was discontinued due to the river freezing. The test re-started in the summer of 2018. Some pictures were taken at the test site and are shown in Fig. 10.

The planned full river test was to include the stand-alone system test (distributed generation) and grid-tied system test; however, due to the unstable temperature rise of the gearbox, the test was reduced to a test of general stand-alone functionality without interconnection to the grid. The functional test included measurements of the river flow speed, waterwheel speed, amount of torque produced at the generator, and generator speed.

Test results:

Fig. 10. Testing of the river turbine #4C at the Winnipeg River by CHTTC (Canada Hydrokinetic Turbine Test Centre). The test started in the fall of 2017 but had to stop due to the river freezing. Completed the test during the summer of 2018.

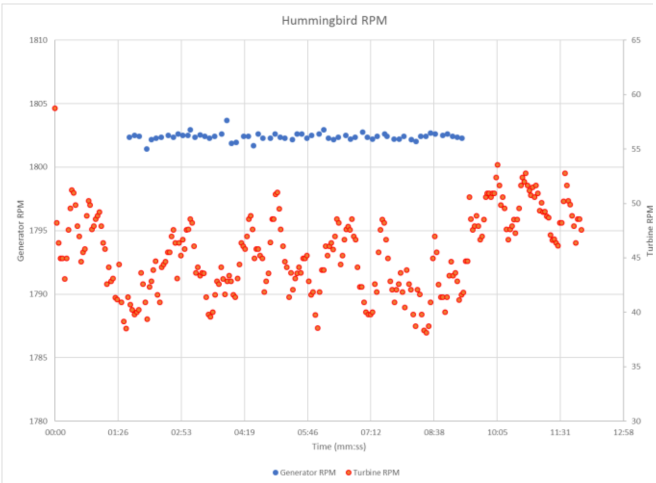

Fig. 11. Test result of Sample #4C tested by CHTTC (Canada Hydrokinetic Turbine Test Centre) in the Winnipeg River. The turbine was mounted vertically on a pontoon boat. The water speed varied 1.6-1.8 m/s. The Hummingbird controlled river turbine converted waterwheel speed of 38-55 to 1,801.4-1,803.6 rpm.

The river speed variation during the test was 1.6-1.8 m/s and waterwheel speed variation was 38-55 rpm. Hummingbird output speed (input speed to generator) ranged from 1,801.4 rpm - 1,803.6 rpm. A graph of these results is shown in Fig. 11.

While the waterwheel speed increased 44.7% above its minimum, the Hummingbird output speed varied just 0.122% above its minimum.

Summary of Samples #4B and #4C:

(1) Hummingbird can convert variable speed to constant.

(2) Frequency can be maintained constant while the load is variable (Sample #4B).

(3) A mechanical advantage is possible. Further study is planned.

IV. FURTHER STUDIES: MECHANICAL ADVANTAGE

Technical Challenges

There are three identified technical issues to be validated before harnessing river energy with speed converters:

(1) Conversion of variable input speed to constant.

(2) Constant frequency while load is varying.

(3) Acceptable power efficiency (the control input power is less than the generated output).

The first two issues were validated by the previous tests. A possible solution is the company developed principle that is similar to the Pascal's principle (mechanical advantage). A test sample which may validate the new principle is currently under construction.

Variations of Hummingbird

In-depth study of the Hummingbird design indicates that there are 24 variations constructed with basic spur gear transgears. All of them are physically different, but only six (6) variations are functionally different.

Summarizing briefly what was discussed in Section B: Building Block: Transgear,

1. Transgears can convert any given input speed to any required output speed.
2. When speed can be controlled and the power is constant, torque can be controlled.

   $P = \tau\omega$

   If power is constant,

   $P = \tau_1\omega_1 = \tau_2\omega_2$

   $\tau_2 = (\omega_1 / \omega_2)\ \tau_1$

   For example, if $\omega_1 > \omega_2$, then $\tau_2 > \tau_1$

   Torque can be increased or decreased.

   Constant Power, Torque Adjustment
3. When speed can be controlled and torque is constant, power can be controlled.

   $P = \tau\omega$

   If torque is constant,

   $\tau = P_1/\omega_1 = P_2/\omega_2$

   $P_2 = (\omega_2/\omega_1)\ P_1$

   If $\omega_2 > \omega_1$, then $P_2 > P_1$

   Power can be increased or decreased.

   Constant Torque,

   Power Adjustment by controlling speed ratio

With three variable transgears, speed, torque, and power can be controlled without energy conversions, for example, mechanical to electrical to mechanical.

Power can be controlled if torque and speed can be controlled. Table 5 shows all possible combinations of input speed, control speed, and output speed for a Hummingbird. The input speed is fixed to 450 rpm or greater and the Hummingbird must be balanced for the analysis shown in Table 5 below.

TABLE 5
INPUT SPEED AND OUTPUT SPEED TO HUMMINGBIRD FOR EACH TESTED ASSEMBLY VARIATION

rpm	i	ii	iii	iv	v	vi
Input ω_1	=>450	=>450	=>450	=>450	=>450	=>450
Control ω_2	-450	-450	225	225	900	900
Output ω_3	-450	-225	-450	225	-450	225
Sample	**#4B**		**#4D**		**#4C**	

(1) The input power is greater than the control power and output power. A proposed solution is:

$P_1 = (\omega_1/\omega_2)\ P_2$ and $\omega_1>\omega_2$, then $P_1>P_2$

$P_1 = (\omega_1/\omega_3)\ P_3$ and $\omega_1>\omega_3$, then $P_1>P_3$

(2) The power ratio=control power/output power=a small number (means efficient). A proposed solution is:

$P_3 = (\omega_3/\omega_2)\ P_2$ and $\omega_3>\omega_2$, then $P_3>P_2$

Power Ratio=$P_2/\ P_3<1$

Out of the total six (6) variations of Hummingbird, only Sample #4D, detail iii in Table 5, meets both conditions. A new test sample per Fig. C will be built to validate the concept of the mechanical advantage.

Two configurations, detail i (Sample #4B) and detail v (Sample #4C), were previously tested. Sample #4C testing indicated that more power was coming from the control motor. The test result seems logical understanding that the input speed is 450 rpm and control speed is 900.

A new Sample #4D will be built according to detail iii; input speed is equal to or greater than 450 rpm, control 225 rpm, and output 450 rpm. It is expected that the input power is greater than the control and output, and the power ratio is small giving an efficient assembly.

V. CONCLUSIONS

In this paper, MHK river turbines controlled by speed converter Hummingbird was discussed based on the developed concepts and collected test data. The preliminary test data show that Hummingbirds can convert harnessed variable speed to constant speed to produce constant frequency and constant voltage, and can maintain constant frequency with variable load. The concept of a mechanical three variable rotary motion control system has a potential to replace emission producing baseload turbines and lowering the LCOE.

A major advantage of Hummingbird is to generate electricity without grid (distributed generation) that could electrify grid-less remote regions economically.

Other potential applications are harnessing all types of MHK energy (river, tide, wave, ocean current), harnessing more hydroelectric energy (powered-dams, non-powered dams), and also harnessing wind energy (both horizontal-axis wind and vertical-axis wind turbines).

There are two more major applications where Hummingbird may be used: automotive transmissions (IVTs) for conventional internal combustion engine vehicles and electric vehicles, and, pump or compressor controls for HVAC.

As transistors improved signal processing, transgears can improve power raring of harnessing renewable energy.

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