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GyroTorque™ Continuously Variable Transmission for Use in Electricity-Generating Systems Utilising Wind and/or Wave Energy

1. ABSTRACT

Based on the rectification of gyroscopic reaction torque, the GyroTorque™ continuously variable transmission (GTCVT) is an innovative, kinetic-type, continuously variable transmission that is the functional equivalent of a hypothetical ideal torque converter. There is no direct mechanical coupling, nor speed relationship, between the input and the output of GTCVT. The input energy is equal to the output energy over a cycle and, consequently, the input torque is proportional to the output speed and the output torque is proportional to the input speed. This unique functionality enables significant benefits when GTCVT is incorporated in power-transmitting drive trains. The potential application of GTCVT in wind-powered and wave-powered electricity generators is discussed.

Key words: *gyro vector, gyroscopic reaction, continuously variable transmission, torque rectification*.

2. INTRODUCTION

A connecting drive train incorporating a variable transmission is required to transfer power from a variable energy source to a variable driven load in systems such as electricity generators, stationary machinery and propelled vehicles.

An ideal variable transmission may be described as highly reliable and capable of maintaining constant or desired input revolutions per minute (rpm) values for output rpm values varying over the full speed range, or vice versa, while matching the input power to the desired output power and quality, or vice versa, with minimum feedback control, power losses and costs.

Many kinds of variable transmission systems exist, based on various technologies and exhibiting differing functionalities. However, despite major investments made in recent years, particularly in the automotive industry, none of these initiatives have succeeded in developing a system that emulates the ideal system described above.

The unique functionality of the GyroTorque™ continuously variable transmission (GTCVT) arises from the novel technique used to rectify and apply gyroscopic reaction torque using simple engineering elements and methods. Consequently, GTCVT enables the design of a transmission system that closely emulates the ideal. Indeed, GTCVT can be considered as being the functional equivalent of a hypothetically ideal torque converter, but without the need for hydraulic fluid. GTCVT exhibits the functionality of a highly efficient infinitely variable transmission over the full speed range. For commercial purposes, GTCVT is trademarked under the name GyroTorque™.

3. PRINCIPLES OF THE GTCVT

3.1 Gyroscopic inertial reaction

GTCVT's unique functionality results from the innovative exploitation of gyroscopic inertial reaction. The inertial reaction of a mass results from resistance to a change in its state of motion. Depending on the cause of change, inertial reactions are classified as being linear, centrifugal, Coriolis or gyroscopic.

Gyroscopic inertial reaction results from the out-of-plane motion of a spinning rotor and is not generated by an applied torque. In other words, gyroscopic reaction is the result of motions and not the result of applied forces. Further, gyroscopic reaction enables spatial movements without changing the energy levels of the dynamic system and hence behaves as a “quasi-mechanical” element.

As there is no need for a gyroscopic rotor to exchange energy with its surroundings to generate torque, gyroscopic reaction has long been recognised as the ideal means to enable a variable power transmission.

3.2 Operating principle of GTCVT for power transmission

The basic principle of the use of the gyroscopic reaction for power transmission in GTCVT is illustrated in figures 1 and 2.

In figure 1, *J* is the polar moment of inertia of the rotor shown. *a* is the spinning velocity vector of the rotor about the rotor axis *Y*. The rotor axis is being rotated (precessed) with velocity vector *b* about *Z*-axis. The resultant gyroscopic reaction is *J (a x b)* in the direction *X*. No effort is required to maintain the spin of the rotor at a velocity “*a”* or maintain the rotation of the rotor axis about the *Z*-axis at a velocity “*b”* as long as the bearings of the rotor shaft are frictionless. Also, the energy of the rotor remains constant because there is no inertial reaction taking place about *Y*-axis, which is same as the rotor axis.

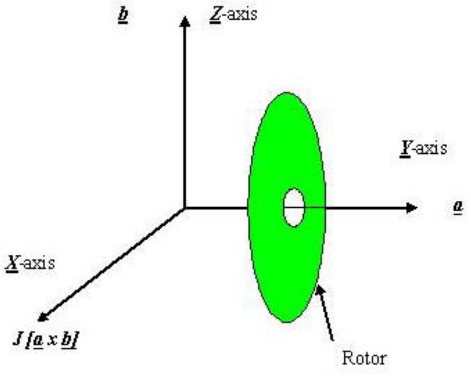


Figure 1: Gyroscopic reaction principle

If the torque generated about the *X*-axis is allowed to do work then reaction will be simultaneously generated against the rotation *b* thus drawing the energy from Z-axis as illustrated in figure 2.

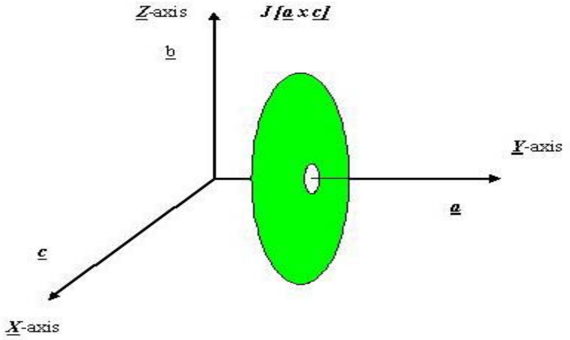


Figure 2: Power transmission by gyroscopic reaction

c is the rotational speed of the rotor axis about *X*-axis at which the reaction torque *J (a x b)* is doing work and *J (a x c)* is the reaction torque against rotation *b*.

Thus, figures 1 and 2 illustrate how the energy is transferred from the input to the output while the input and the output are physically independent but receive torque reactions according to the input and the output motions.

It will be demonstrated later that the torque reactions become cyclical when energy is transmitted via gyroscopic reaction and this must be rectified to enable net transmission of power. This is readily accomplished by having two one-way clutches on the output, one being opposed to the other so that one of the clutches transmits torque to the output and the other transmits torque to the transmission housing.

This is the fundamental solution to exploiting gyroscopic reaction to enable power transmission. Another solution is to arrange torque rectification by a reversing gear train to transmit the torque from the second one-way clutch to the output, instead of to the transmission housing.

To allow for the spatial motions of the rotor axis, GTCVT involves the use of a unique arrangement of gimbals.

3.3 Fundamental GTCVT mechanical configuration

The most fundamental and useful configuration for a single GTCVT unit, depicted in figures 3 and 3a, allows us to better understand the key functional components of a GTCVT unit. In the case shown, the input motion is reciprocating, which is typically preferred.

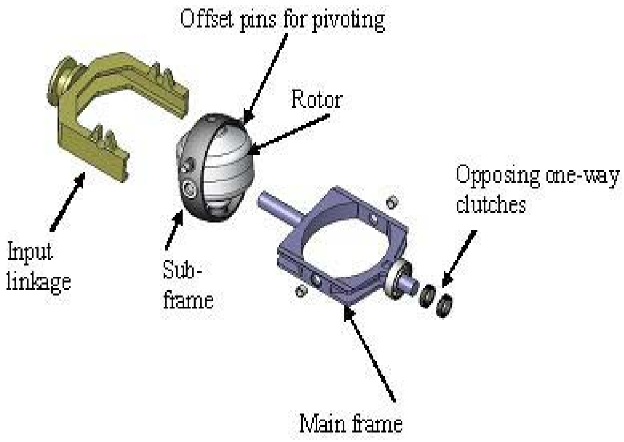


Figure 3: Fundamental CTCVT configuration – exploded view

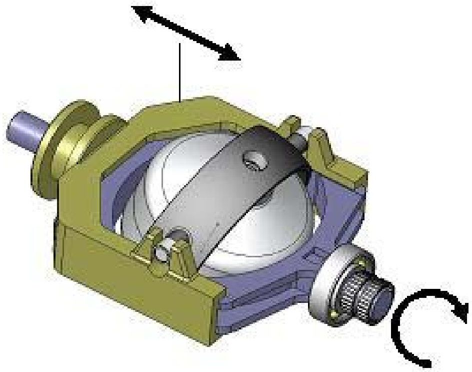


Figure 3a: Fundamental GTCVT configuration – assembly view

It consists of a gyroscopic rotor that is held in an inner ring (sub-frame), the latter being free to pivot in an outer ring (main frame). The main frame is free to rotate in the transmission housing. The sub-frame is connected to the input mechanism by linkages (in the case shown via off-set pins), which pivot the sub-frame in the main frame. The main frame, sub-frame and linkages rotate together under the influence of output gyroscopic reaction torque. The main frame is connected to the output (rotating shaft) and the transmission housing via opposed one-way clutches.

The rotor may be driven by any means. Power is only required to overcome bearing friction and accelerate the rotor.

The rotor, when precessed cyclically by the input linkage, generates opposing gyroscopic torque components that are alternately transferred to the output shaft and the transmission housing via opposing one-way shafts.

3.4 Functionality of fundamental GTCVT unit

The “vector diagram” shown in figure 4 graphically illustrates how the direction of the “gyro vector” changes as the sub-frame is caused to oscillate by the movement of the input linkage.

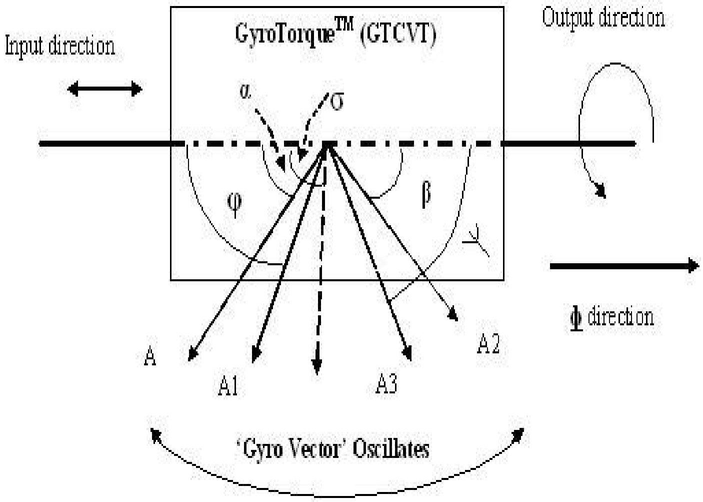


Figure 4: Gyro vector oscillation diagram

The gyro vector $\underline{V}$ is defined by the following equation:

$\underline{V}$ = [rotor spin speed (vector $\underline{a}$)] [rotor inertia about the spin axis (polar moment of inertia, J)]

A, A1, A2 and A3 are positions of interest of the gyro vector as the sub-frame is oscillated by the input linkages.

Change in gyro vector in the $\underline{\boldsymbol{\phi}}$ direction as it moves from A to A2 = $[V\cos(\alpha) + V\cos(\beta)]$.

$[V\cos(\alpha) + V\cos(\beta)]$ = Change in angular momentum of the assembly in $\underline{\boldsymbol{\phi}}$ direction plus time integral of external torque in $\underline{\boldsymbol{\phi}}$ direction.

Input linkage is isolated from torque by thrust bearings and hence experiences only linear forces; external torque is from the output and the housing only.

Output and the housing are communicated by the gyroscopic torque reaction in the $\underline{\boldsymbol{\phi}}$ direction via opposing one-way clutches only. This means only one, ie either the output or the housing, can experience the gyroscopic torque at any given instance.

The output direction is determined by the sense of the one-way clutch coupled to the output shaft.
In general the output cannot rotate in the other direction.

There is no direct physical communication between the input and the output as in other transmissions.

The output speed can be many times the input frequency, an ideal feature for regenerative braking and flywheel storage.

During each cycle the gyro vector $\underline{V}$ moves, say from A to A2 and back to A.

As $\underline{V}$ moves from A to A1 the assembly is accelerated to output speed.

As $\underline{V}$ moves from A1 to A2 the output experiences the corresponding torque.

As $\underline{V}$ moves from A2 to A3 the assembly is decelerated to the housing speed, normally zero.

As $\underline{V}$ moves from A3 to A the housing experiences the corresponding torque while input is moving free.

When output speed is zero, the output torque is a pure sinusoidal.

When the output speed is non-zero a corresponding part of the half sinusoid (A to A1) is lost for transmitting power. However, as explained below there is an optimum output speed at which the power transmitted is maximum.

3.4.1 Derivation of output and input power

3.4.1.2 Output power

$[V\cos(\alpha) + V\cos(\beta)] = [J@A2)(N(o)] + \int T\,dt$

Where $J@A2$ is the inertia of the assembly about the transmission axis at position A2, $N(o)$ is the output speed, T is the instantaneous gyro torque on the output and t is time. For simplicity let us assume that the inertia of the assembly remains constant J and the output speed $N(o)$ remains constant N.

Energy transmitted to the output = $N\,(\int T\,dt)$

Therefore energy transmitted E over a cycle
= $N\,(V\cos(\alpha) + V\cos(\beta)) - (J)(N)^2$.

Power = E / p where p is the cycle period.

3.4.1.2 Input power

The exchange of energy between the input, the system and the output over a cycle consists of:

1) kinetic energy to accelerate the system to output speed as the gyro vector moves from position A to A1 *(K.E 1)*
2) mechanical output via the system one-way clutch as the gyro vector moves from A1 to A2 *(W)*
3) kinetic energy from the system back to the input as the gyro vector moves from A2 to A3 causing the system to slow down to zero speed *(K.E 2)*

Therefore input energy over a cycle = $(K.E\ 1) + W - (K.E\ 2)$

$K.E\ 1 = \int [V\sin(\sigma)]\, N\, d\sigma$, σ going from σ to φ = $(0.5)(J)(N)^2$

$K.E\ 2 = \int [V\sin(\sigma)]\, N\, d\sigma$, σ going from $(180 - \beta)$ to $(180 - \psi) = (0.5)(J)(N)^2$

In order to derive (W) let us consider the gyro vector in a general position (angle σ). Due to the rotation N of the gyro vector component $V \sin(\sigma)$ a resisting torque, $N V \sin(\sigma)$ is created against the oscillation of the gyro vector, ie against the input. It is this torque which is responsible for the exchange of energy between the input and the system / output.

$W = \int [V\sin(\sigma)]\, N\, d\sigma$, σ *going from* φ *to* $(180 - \beta)$

Therefore $W = V N (\cos(\beta) + \cos(\varphi))$

But $V\cos(\varphi) = V\cos(\alpha) - J N$

Therefore $W = N [V\cos(\alpha) + V\cos(\beta)] - (J)(N)^2$ which is the same as the output energy E over a cycle.

3.5 Transmission variables

The transmission variables determine the torque characteristics achievable for each GTCVT design. The variables are:

- the gyro vector, the product of the moment of inertia of the rotor about its axis of spin and that of the spin speed
- the input stroke and speed
- the system inertia values

If the required load torque does not balance the generated output torque, the output speed will change accordingly. The output torque (and proportionately the output speed) is then adjusted by altering one or more of the transmission variables, such as spin speed.

The gyroscopic torque component generated by the output rotation generates corresponding reaction to the input. Consequently, the input torque is proportional to the output speed and the output torque is proportional to the input speed.

3.6 Peripheral mechanisms

The GTCVT mechanism transmits power from a drive source to a driven component.

It is important to understand there is no direct mechanical coupling and speed relationship between the input and the output RPM. The important parameters to consider when setting the output requirements for a particular application of GTCVT are the maximum power the input motor can develop, and its “power–RPM” curve.

The design of the peripheral output mechanism depends on the specific requirements for each GTCVT application. While the output speed is infinitely variable, it is best to optimise the GTCVT output torque and incorporate a fixed speed gearing between the GTCVT and the output. Further, outputs from individual GTCVT units coupled in parallel may be combined by suitable gearing.

3.7 Reversing direction and power flow

Whereas the mechanical output direction, together with the associated power flow, are intrinsically irreversible in a GTCVT system, external reversing can readily be accomplished:

- An external mechanical reversing option, incorporating decoupling features, may be fitted at the output. It is important to note that, unlike other transmissions, a GTCVT can be decoupled without the use of a conventional clutch.
- Reversal of power flow can be caused by either of the following methods: incorporation of a bypass overrunning clutch between the input and the output; or reversing the main frame rotation and partial braking.

4 GTCVT FEATURES AND PERCEIVED FUNCTIONAL ADVANTAGES

The unique and defining feature of GTCVT is that, at zero output speed, any required output torque can be generated without the "slippage losses" that occur in other types of variable speed transmissions. For a given set of transmission variables there will be a one-to-one relationship between the output speed and the output power. The output power will peak at a certain output speed and, even without any feedback control on the transmission variables, there is an inherent continuous variability. However, by varying the transmission variables, say the rotor speed, at any given instance, the operating point can be shifted as desired and the output torque and RPM can be set with specific parameters to meet product performance and operational requirements.

There are two other valuable features:

- The transmission does not require any clutch arrangement between the transmission and the input for engagement and disengagement, and provides complete power overload protection since overloading at the output automatically results in reduction of the output speed and hence the torque on the input.
- As the input rotation direction has no bearing on output rotation, reversal of the output must be achieved mechanically by the final transmission set.

GTCVT has fundamental advantages compared to all other continuously variable transmissions:

- GTCVT has a unique ability to match the input power to the output power without any feedback control, while allowing desired speed variations at the input or the output; with feedback control desired power transmission is achieved at high efficiency over the full speed range.
- GTCVT enables fully effective parallel coupling without any feedback controls.
- GTCVT has a unique ability to provide high speed ratios (eg 40:1) at low input speed (eg 100 RPM) without the use of speed multipliers such as gears.
- The operating characteristics can be altered at will by controlling the variables such as the speed of the gyroscopic rotor.
- Other useful features of the GTCVT are easy decoupling methods and scaling advantage for high power transmission.

Consequently, by replacing the following transmission types, GTCVT could enable a wide range of scaleable power drive options for many product applications:

- variable speed electrical drives employing power electronics
- variable speed belt and traction continuously variable transmissions
- multi-speed manual and automatic transmissions

5 GTCVT CONCEPT VALIDATION

The claims made in the patents covering GTCVT have been validated through extensive computer modeling and simulation, together with testing of experimental models and engineering prototypes. Experimental prototypes were evaluated using the customised test bench shown in figure 5. Specific engineering prototypes for low power transport applications have been field-tested in quad bikes and ride-on lawnmowers. The latter prototypes were evaluated in various configurations, with and without differential gearing.

Figure 5: GTCVT experimental test bench

6 GTCVT PATENTS

Patents covering GTCVT have been issued in Australia, China, New Zealand and the United States of America. The European Patent Office has issued a Certificate of Grant. Patent applications have been filed in 20 additional countries, four of which are currently in the examination process.

7 APPLYING GTCVT IN WIND TURBINES

7.1 Problems of large scale interconnection of wind power to the grid

Physically, a national grid is a very large distributed network of interconnected power generating sources and consuming loads, whose dynamic electrical behavior must be monitored and managed in real time. Any consideration of the feasibility and economics of providing consumers with electricity generated from renewable power sources such as wind must take into account the electrical characteristics and behavior of the grid. Unless the electrical output from a wind-powered electricity generator meets rigorous quality and reliability standards, it will not be accepted by the grid. Consequently, the large-scale interconnection of wind turbines to the grid requires these compatibility issues be satisfactorily addressed

7.2 Variable wind power profile

Wind-generated electricity is intermittent, variable, less controllable and less predictable than conventional forms of electricity generation. In addition, modern wind turbines with variable-speed drives do not provide an inertia which is synchronously connected to the electricity system. With a high penetration of such generation systems, the following potential problems arise:

- The fluctuations in output from wind turbines increase the total variability in net electricity demand, which must be met largely by conventional generation. Because of the spatial averaging of fluctuations in output power from dispersed wind farms, the important power fluctuations occur on timescales of minutes or longer.
- The fluctuations in output power from a single wind farm, when connected to a distribution system, results in voltage fluctuations. Because of the spatial averaging of fluctuations in output power from multiple turbines within a wind farm, the important voltage fluctuations generally occur on timescales of 10 seconds or longer.
- The inertia of the grid will be reduced, as less of the conventional synchronous generating capacity will be operating at any one time. This has two effects: the sudden loss of generating capacity will result in a larger frequency deviation; and in normal operation, the system frequency will be more volatile. Reactive power from induction machines, as often used in wind turbines, contributes to lagging power factor. The reactive power increases the current flowing in the electricity system, which results in higher electricity losses and can cause difficulties with voltage control.
- Stability during faults – several types of wind turbines have difficulty remaining in operation during major network disturbances. Many system operators require that wind generation is able to “ride-through” specified disturbances.

Many utilities around the world are studying these issues in anticipation of growth in the wind power generating sectors. Some of the solution strategies implemented or being considered are:

- use of spinning inertia (stored energy in wind turbine rotor and blades) with variable-speed transmissions, for short-term power fluctuations (at the expense of the turbine efficiency)
- increased need for fast-response conventional generators, or operation of conventional generators part-loaded, at less than optimum efficiency

7.3 Applying GTCVT in wind turbines

The potential application of GTCVT in wind energy generators was first outlined by its inventor, M. Jegatheeson, in a presentation titled *Gyroscopic Variable Transmission* at the Global Wind Power Conference and Exhibition in April 2002.

Subsequently, the potential use of GTCVT to replace the gearbox in a 1 MW wind turbine system was independently evaluated by Garrad Hassan and Partners Limited (Garrad Hassan) and documented in their report *Evaluation of a GVT System for Wind Turbines* (2004).

The dynamic analyses described in the Garrad Hassan (2004) report were performed by Professor W. Leithead of The Strathclyde University, Glasgow, Scotland using Simulink, an add-on of the Matlab analysis package. The model embodies a Lagrangian system of equations of motion of a six unit GTCVT system. The Garrad Hassan (2004) report shows a graphical depiction of a single GTCVT unit together with a graphical depiction of the system of six GTCVT units in parallel that was simulated. Also shown are some representative results from the evaluation of this simulation of the 1 MW GTCVT wind turbine model.

The structure of the top level of this GVT simulation is shown in figure 6 together with a key to the abbreviated nomenclature shown in figure 6a.

The potential advantages of GTCVT for wind power generation, as acknowledged by Garrad Hassan (2004), are:

- excellent power quality and complete insensitivity to wind turbulence
- elimination of highly loaded gear transmission and power electronics with potentially significant cost savings
- allows use of conventional synchronous generator
- potential scaling advantage for larger systems enhanced by parallel operation
- turbine rotor speed variability over the full speed range to maximize efficiency
- larger speed ratio at low input speed

In concluding their evaluation, Garrad Hassan (2004) recommended a further design study to complete the evaluation.

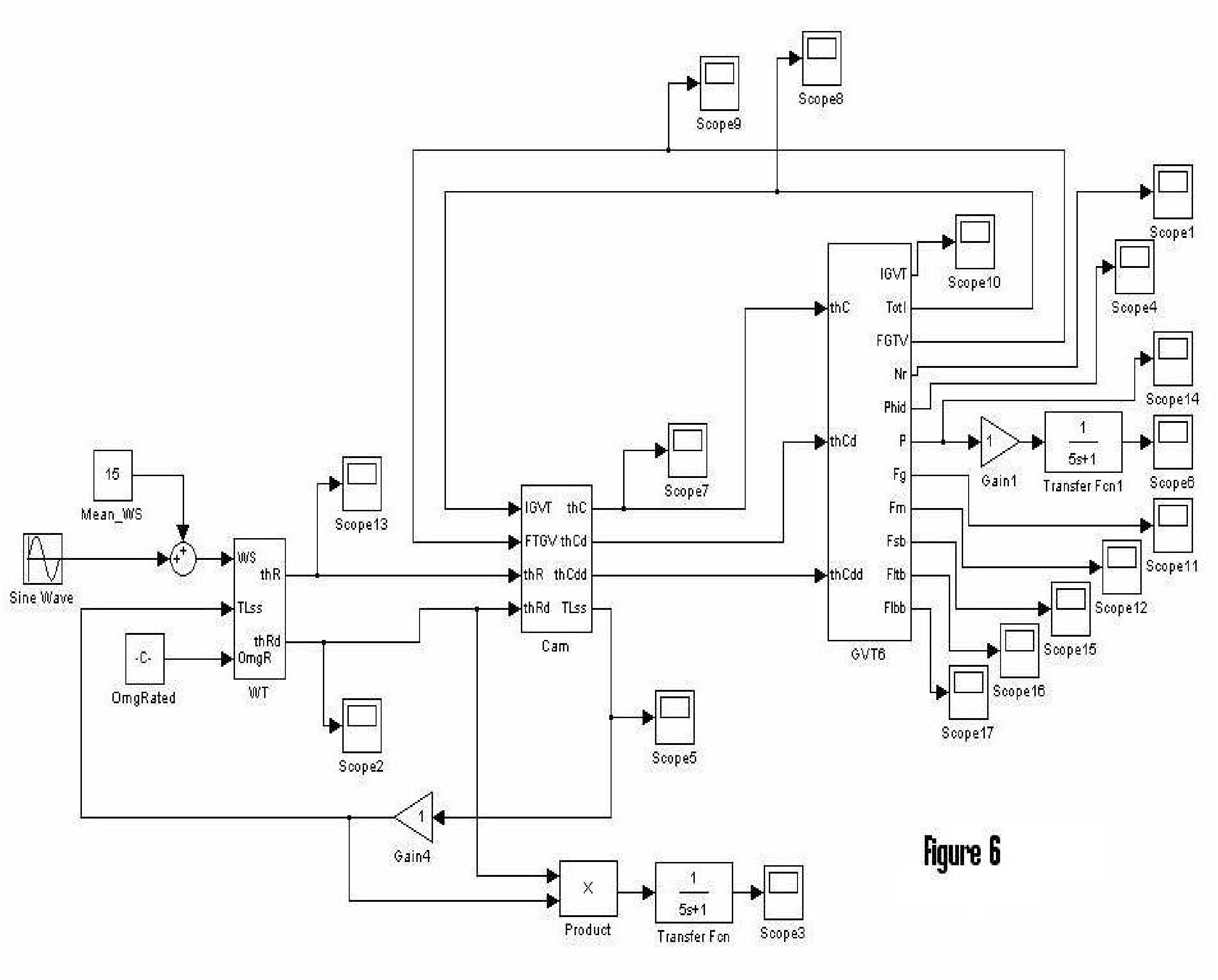
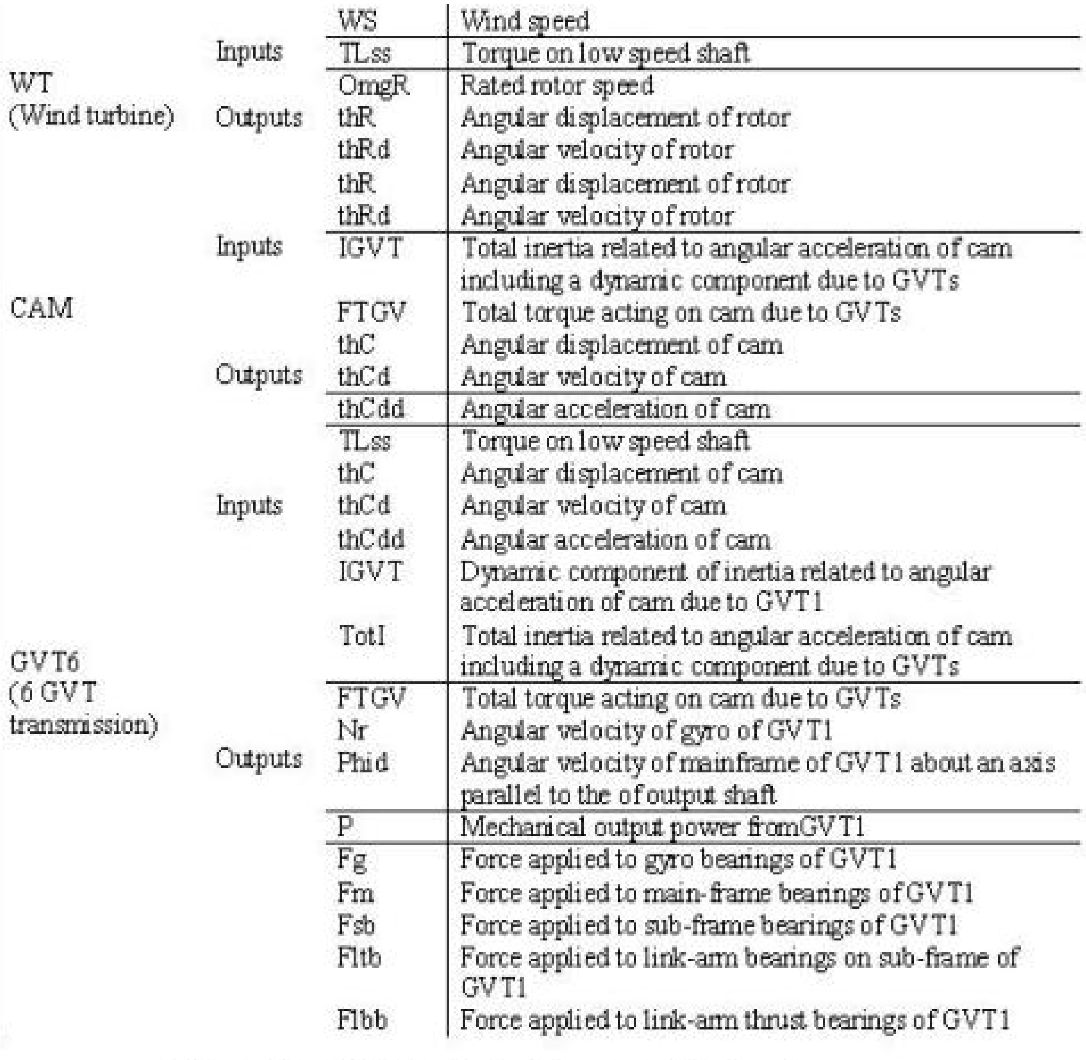


Figure 6: GVT simulation structure – top level



WT (Wind turbine)	Inputs	WS	Wind speed
		TLss	Torque on low speed shaft
	Outputs	OmgR	Rated rotor speed
		thR	Angular displacement of rotor
		thRd	Angular velocity of rotor
CAM	Inputs	thR	Angular displacement of rotor
		thRd	Angular velocity of rotor
		IGVT	Total inertia related to angular acceleration of cam including a dynamic component due to GVTs
		FTGV	Total torque acting on cam due to GVTs
	Outputs	thC	Angular displacement of cam
		thCd	Angular velocity of cam
		thCdd	Angular acceleration of cam
GVT6 (6 GVT transmission)	Inputs	TLss	Torque on low speed shaft
		thC	Angular displacement of cam
		thCd	Angular velocity of cam
		thCdd	Angular acceleration of cam
		IGVT	Dynamic component of inertia related to angular acceleration of cam due to GVT1
		TotI	Total inertia related to angular acceleration of cam including a dynamic component due to GVTs
	Outputs	FTGV	Total torque acting on cam due to GVTs
		Nr	Angular velocity of gyro of GVT1
		Phid	Angular velocity of mainframe of GVT1 about an axis parallel to the of output shaft
		P	Mechanical output power fromGVT1
		Fg	Force applied to gyro bearings of GVT1
		Fm	Force applied to main-frame bearings of GVT1
		Fsb	Force applied to sub-frame bearings of GVT1
		Fltb	Force applied to link-arm bearings on sub-frame of GVT1
		Flbb	Force applied to link-arm thrust bearings of GVT1

Figure 6a: Abbreviated nomenclature for GVT simulation structure – top level

7.4 GTCVT enables reduction of fluctuations in power produced by wind turbines

There could be significant benefits in reducing the short-term fluctuations in power produced by wind generators.

GyroTorque^{TM} is the only system capable of simultaneously utilising the inertia of wind turbine rotor to smooth out short-term fluctuations through out the full speed range and, at the same time, permitting variable speed operation to maximise efficiency, cost-effectively.

This can be accomplished without sacrificing efficiency of energy collection, added system costs, and, specifically, power electronics. This is due to the fact that the GTCVT responds to the turbine rotor speed and not to the torque. As a result, the turbine rotor inertia helps to smooth out the short-term fluctuations throughout the full operating range. Typically, this would be accomplished by the system configuration illustrated in figure 7.

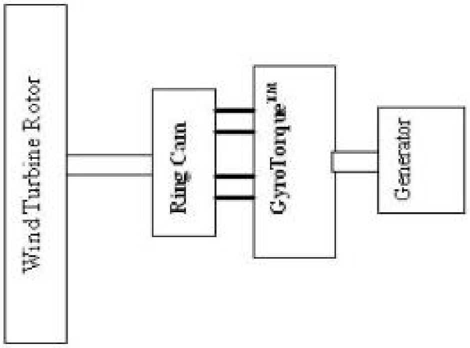


Figure 7: Concept: GTCVT-based wind-powered system

As shown in figure 8, the rotary input from the wind turbine is converted into linear reciprocating motion by the ring cam. The linear reciprocating motions are input to the GTCVT units, which respond to these motions by generating output torque on the generator and simultaneously resistance to the input motions due to the output rotary motions. Multiple GTCVT units in conjunction with the inertia of the generator armature smooth out periodic fluctuations due to the cyclic workings of GTCVT.

Depending on the wind speed, the back torque on the turbine rotor via the cam rods can be varied by adjusting the gyro speed in the GTCVT units and/or by adjusting the linear reciprocating input motion. By adjusting the mechanical torque on the turbine rotor in this way, the rotor speed can be adjusted in order to maintain optimum rotor tip-speed ratio and therefore optimum aerodynamic efficiency of the turbine.

The torque experienced by the generator is the result of input motion and not the result of the input force. In other words, the output torque of the GTCVT is proportional to the input speed and the input force is proportional to the output speed, thus balancing the power flow.

Short-term fluctuations in wind speed cannot affect the output torque without affecting the speed of the turbine rotor. The result is a continuous smoothing of the random fluctuations by the rotor inertia irrespective of whether it is operating above or below the rated speed.

The stored energy in the wind turbine rotors may not be sufficient to deal with power fluctuations on longer timescales. However, two GTCVT features, a large speed ratio and parallel functionality, provide a solution to the unavoidable problem of long-term variability of wind conditions. This is a large-scale solution whereby GTCVT enables flywheel reserves at selected locations while allowing variable speed operation of the wind turbines. Electronic variable speed drives have disadvantages in this application.

The configuration concept depicted in figure 8 illustrates what is required to increase the spinning reserves, at selected locations, without significantly affecting the control of the turbine rotor speed and thus ensuring that maximum efficiency is maintained. The number of stage one GTCVT systems (comprising two or more paralleled GTCVT units) can be fewer since they are only required to charge the flywheel. The stage two GTCVT system (typically six paralleled GTCVT units) can operate at a higher speed as shown or, alternatively, can be reduced by a separate gearing arrangement.

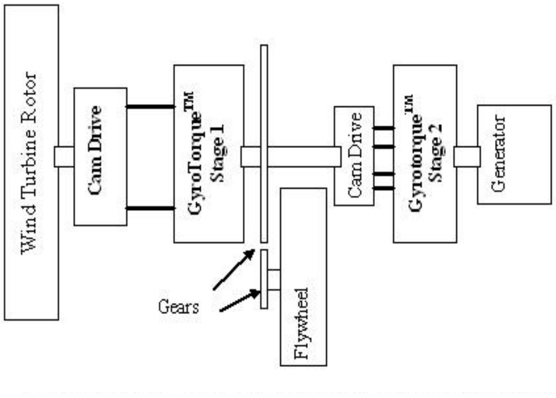


Figure 8: Concept: GVCVT-enabled spinning reserves for long-term stability

Since conventional synchronous generators are used in the GyroTorque™ systems, control of reactive power is straightforward, and it is easier to ride through network disturbances.

8 POTENTIAL APPLICATION OF GTCVT IN WAVE-POWERED ELECTRICITY GENERATORS

"New Zealand is surrounded by ocean, and the waves and tides in our energetic coastal environment are a world-class resource for energy conversion. Internationally, significant research and development efforts are underway devising technologies to extract energy from waves and tides. Such technologies could play a significant part in New Zealand's future energy supply portfolio." (Energy Efficiency and Conservation Authority 2005).

8.1 Challenges facing wave-powered electricity generators

Probably the most important independent assessment of wave energy conversion devices undertaken to date was that reported by the Electric Power Research Institute (EPRI) (2004) in the United States. EPRI (2004) assessed information received from 12 manufacturers of wave energy conversion devices.

Due to the intrinsic nature of ocean waves, a wave energy collector (WEC) must operate in an oscillatory mode under highly variable conditions. Consequently, achieving an efficient and reliable coupling between the WEC and the incoming waves, and then converting the captured energy to electrical output that is acceptable to the grid, is a complex and challenging engineering problem.

One can reasonably conclude from the EPRI (2004) report that the development of commercially viable wave-powered electricity generating systems requires significant advances to be made in the following areas:

- higher collection efficiency ("tune-ability" of the wave/collector interface)
- efficient energy storage and retrieval, especially for the period in between successive waves
- higher energy conversion efficiency through the system

8.2 GTCVT/wind turbine: GTCVT/flywheel/OWC analogy

It can be cogently argued that GTCVT technology could enable significant improvements in the performance of OWC-type wave-powered systems. This is because a GTCVT-based wind turbine is mechanically analogous to an OWC system incorporating a GTCVT-coupled flywheel.

The validity of this analogy is rooted in the fact that speed fluctuations of a turbine rotor, caused by the fluctuations of the rotor's aerodynamic torque, are minimised by the inertia of the turbine rotor, which acts as a flywheel. As previously discussed, GTCVT responds to the input speed and not to the input torque. Therefore, since the wind turbine rotor is acting as a flywheel, it is directly comparable to the GTCVT-coupled flywheel in the conceptual GTCVT/flywheel/OWC system described below (see 8.3).

Consequently, the relevant conclusions from the Garrad Hassan (2004) report are applicable to the GTCVT/OWC system. The main difference anticipated will be the degree of control required on the GTCVT rotor in the postulated GTCVT/OWC system, as the flywheel speed would be expected to fluctuate by a larger degree.

8.3 OWC-type generating system incorporating GTCVT-coupled flywheels

A highly desirable GTCVT-based system would exploit GTCVT's high speed ratio capability to enable the reciprocating output of a WEC device (eg an OWC) to charge a mechanical flywheel, which would drive a constant speed synchronous generator, or induction generator, via a second GTCVT. No power conditioning electronics would be required in such a system. This is the concept depicted in figure 9.

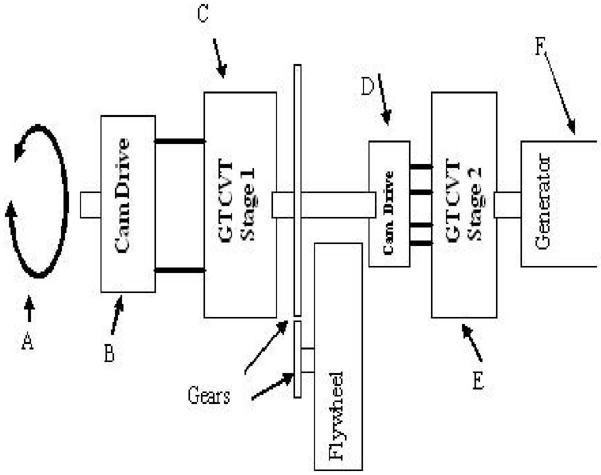


Figure 9: GTCVT/flywheel/OWC generating system

The components of the system concept depicted in figure 10 are as follows:
A – wave energy collector
B – ring cam
C – first stage GTCVT units
D – ring cam
E – second stage GTCVT units
F – synchronous generator

Input to the first stage GTCVT units can be oscillatory as the GTCVT output direction is not affected by the input direction. Thus energy efficient devices such as positive displacement hydraulic motors can be used instead of bidirectional air turbines in the collector system.

The first stage GTCVT units can be at 180 degrees out of phase so that the input experiences sinusoidal loading. This can be beneficial for tuning the collector with the waves.

Using the high speed ratio feature without gears, the first stage GTCVT units will charge up the flywheel.

The second stage multiple GTCVT units will drive a synchronous generator generating high quality power even though the flywheel speed would fluctuate.

The above scheme can increase the overall efficiency and improve the power quality very significantly while eliminating the need for power conditioning using power electronics. These improvements in efficiency and improvement in power quality would bring down the overall cost of the power generated.

8.4 Applicability of GTCVT in wave-powered systems using WEC devices having reciprocating outputs

Since the above description applies to a reciprocating input arrangement, it applies to all other generating systems incorporating similar reciprocating WEC devices, such as “IPS Buoy” and “Pelamis”.

Further, since the GTCVT output can be a constant speed rotation, transfer of energy to an intermediate medium such as high pressure oil or low pressure water can be avoided. The resultant benefits are significantly improved efficiency, and avoidance of capital costs associated with hydraulic systems.

Since the output direction of the GTCVT is independent of the input direction, oscillating input from wave energy collectors can be used conveniently. By providing the flywheel storage short-term and long-term fluctuations can be handled in conjunction with the full range variability of GTCVT units.

An intrinsic characteristic of a single GTCVT is that the resistance to the input does not remain constant; rather it varies with the position of the input stroke. At the beginning of the input stroke it is minimal and then it increases in sinusoidal fashion and at the end of the stroke it is minimal again.

Consequently, if a piston is to operate instead of an air turbine in OWC, a natural improvement in collection efficiency will result, even without prediction of wave phase. Further, this resistance amplitude can be altered easily according to the incoming wave energy. To remove the load on the WEC device at any stage of the input motion, GTCVT can be decoupled almost instantly to improve tuning. In effect, GTCVT provides a new tuning facility.

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10. REFERENCES

Energy Efficiency and Conservation Authority 2005, *Renewable Energy Fact Sheet 5: Marine Energy*, EECA, Wellington.

Garrad Hassan and Partners Limited 2004, *Evaluation of GVT System for Wind Turbines,* Glasgow, Gyro Energy (NZ) Limited, Auckland.

Jamieson P, Jegatheeson M, and Leithead W 2004, *Gyroscopic Variable Transmission for Wind Turbines*, paper presented to Global Wind Power Conference and Exhibition, Chicago, 28–31 March 2004.

Jamieson P, Jegatheeson M and Leithead W, 2004, *Gyroscopic Variable Transmission for Wind Turbines*, paper presented to European Wind Energy Conference, London, 22–25 November 2004.

Jegatheeson M, and Moore H 2005, *GyroTorque™ Continuously Variable Transmission ("GTCVT") for Efficient, Cheaper and Higher Quality Wind Power Generation*, paper presented to American Wind Energy Association 2005, Denver, 15–18 May 2005.

Presvisic, M, Bedard, R and Hagerman, G 2004, Assessment of offshore wave energy conversion devices, *E2I EPRI WP – 004 – US – Rev 1*, 16/6/04, Energy Innovation Institute and EPRI, Palo Alto.