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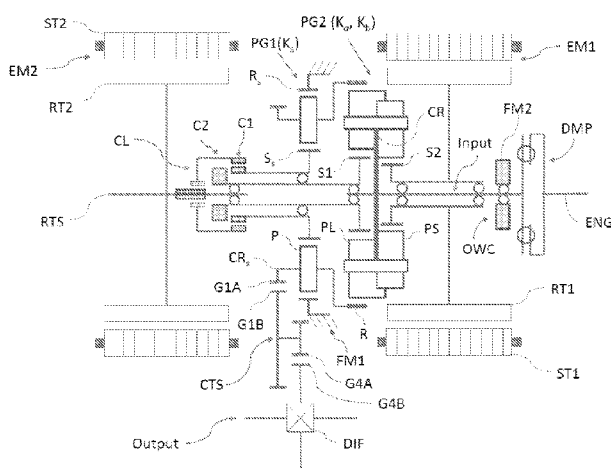
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CONTROL

Figure 7

(57) Abstract: A multi-mode electro-mechanical variable
speed transmission, includes an input shaft (Input), an output
system (Output), at least one planetary gear set having at least
three branches each representing a co-axial rotating member,
two electric machines (EM1, EM2) along with the associated
controllers for the electric machines, and at least a clutch
(CL). The first branch couples to the first electric machine
(EM1) with a constant speed ratio, the second branch couples
to the output system (Output) with a constant speed ratio, the
third branch couples to the input shaft (Input) with a constant
speed ratio, and the second electric machine (EM2) select-
ively couples to two different branches of the planetary gear
set with two different constant speed ratios, respectively. Said
multi-mode electro-mechanical variable speed transmission is
capable of providing multiple operation modes including two
electric drive modes and two power split operation modes.
Different operation modes cover different speed ratio regimes
and are suitable for different power requirements. At the
mode switching point, the corresponding clutch is automatic-
ally synchronized. This avoids shock loads during operation
mode switching. The transmission is capable of providing op-
erations with at least a fixed output to input speed ratio.



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MULTIMODE ELECTROMECHANICAL VARIABLE SPEED TRANSMISSION APPARATUS AND METHOD OF CONTROL

TECHNICAL FIELD

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The invention is related to a multi-mode electro-mechanical variable speed transmission in a powertrain, and to a method of operating the transmission and the powertrain. It is applicable to a wide variety of vehicles and power equipment.

10 TECHNOLOGY BACKGROUND

To reduce fuel consumption and emission, hybrid vehicles combine an electric power plant with a conventional internal combustion engine. The internal combustion engine operates in a certain range of speed and power. Inside this range, there usually exists a
15 smaller regime where the engine archives the best performance. On the other hand, however, driving conditions vary enormously, not only in wheel speed but also in driving torque at the drive wheels. A combination of a given speed and torque defines a power state. Selectively operating the internal combustion engine and matching its power state of with that of the drive wheels are the primary functions for a hybrid
20 transmission.

The development of hybrid technology provides new avenues for achieving improved operation and match of power state of the internal combustion engine with the drive wheels. Among various power-train architectures, a well-known design is the
25 electro-mechanical continuous variable transmission, known as Toyota hybrid system, or THS. THS allows for electric propulsion at low power and slow speed operation and turns on the engine in hybrid operation when vehicle speed and or power demands exceed certain thresholds. In the hybrid operation, THS splits the input power into two paths of different nature. Part of the input power passes through a
30 so-called mechanical power path which is comprised of gears and shafts; the rest of the input power passes through an electric power path which contains electric machines and inverters. The device used to split the power is a simple planetary gear system. THS offers only one power splitting mode and provides a single output to input speed ratio node point *SR*. When the transmission operates at a speed ratio
35 higher than the speed ratio node point, internal power circulation occurs. One of the power paths sees more power than that is transmitted through the transmission, which reduces power transmission efficiency. This, to a large extent, constrains the effective operating speed ratio of the transmission. For high power vehicle applications, the power ratings for the electric machines have to be increased significantly. In the
40 electric drive mode, only one of the electric machines provides motive power. This makes THS not suitable for all electric drive in power demanding applications. Examples of such an application are all electric range (AER) plug-in hybrid configurations where the vehicles operate in pure electric mode till the battery charge is depleted below a predetermined threshold.

SUMMARY OF INVENTION

One of the objectives of current invention is to overcome the aforementioned drawbacks of prior art by providing a novel multi-mode electro-mechanical variable speed transmissions with much improved fuel efficiency and performance characteristics. The transmission can operate under at least two different power splitting modes, offering higher power transmission efficiency by avoiding internal power circulation. The transmission is capable of providing continuously variable output to input speed ratio and independent power regulation with significantly extend the operational speed ratio range. The transmission may also be operated in two pure electric modes with much improved acceleration performance, and two fixed speed ratio modes with maximum transmission efficiency.

To achieve above objectives, the current invention provides following technical solution:

Said multi-mode electro-mechanical variable speed transmission includes a gear system, a stationary member, an input shaft, an output system, at least one clutch, and two electric machines along with their electric drives and controllers. Said gear system further includes two planetary gear sets each having at least three co-axial rotate-able members or components.

For those skilled in the art, a planetary gear set can be described and understood in a lever diagram format. A lever diagram is a schematic representation of the components of a planetary gear set. It defines kinematic and dynamic relationships between these components. It contains a lever or a bar and a number of knots. Each knot corresponds to a co-axial rotate-able component of the planetary gear set. The inter-distances between the knots are determined by gear ratio or ratios of the planetary gear set. The knots from one end of the lever to the other are referred consecutively as the first, the second, third knots and so on. The rotation speed of the co-axial rotate-able components of the planetary gear set are represented by vectors that start from the corresponding knots and are perpendicular to the lever. A multi-knot lever diagram has two degrees of freedom: the speeds of any two knots uniquely determine the speed of the remaining knots. The ends of all rotation speed vectors on a lever diagram lay on a straight line.

A lever with three knots represents a three-shaft planetary gear set, also known as the three-branch gear set having three co-axial rotate-able components. Figure 1 shows a three-knot lever diagram. The three knots from left to right are referred to as the first (KN_{11}), the second (KN_{12}) and the third (KN_{13}) knots, respectively. Each knot corresponds to a branch or a co-axial rotatable component of the planetary gear set. The three branches are referred according to their corresponding knots to as the first, the second and the third branches of the planetary gear set. The inter-distance between the first and second knots is one unit in length, the inter-distance between the second

and third knots is K_a unit in length. K_a is the gear teeth ratio (also known as gear ratio) of ring gear to sun gear for a simple planetary gear set.

5 A lever with four knots represents a four-shaft planetary gear set, also known as the four-branch gear set having four co-axial rotate-able components. Figure 2 shows a four-knot level diagram. The four knots from left to right are referred to as the first (KN₂₁), the second (KN₂₂), the third (KN₂₃) and the fourth (KN₂₄) knots, respectively. Each knot corresponds to a branch or a co-axial rotatable component of the planetary gear set. The four branches are referred according to their corresponding knots to as the first, the second, the third and the fourth branches of the planetary gear set. The inter-distance between the first and third knots is K_b unit in length; the inter-distance between the second and third knots is K_a unit in length and the inter-distance between the third and fourth knots is one unit in length, where K_a and K_b are characteristic gear teeth ratios of the four-branch planetary gear set.

15 Said gear system is configured with a first three-knot lever and a second four-knot lever. The first knot of the first lever couples to the stationary member and the second knot of the first lever couples to the second knot of the second lever. Said gear system is connected to the input shaft, the output system, and to the first and second electric machines in the following configuration (refer to figure 3): the third knot of the first lever selectively connects and disconnects the second electric machine through the at least one clutch; the first knot of the second lever connects to the first electric machine; the second knots of the first and second levers connect to output system; the third knot of the second lever connects to the input shaft and the fourth knot of the second lever selectively connects to and disconnects from the second electric machine.

Alternatively, said gear system is configured with a first three-knot lever and a second three-knot lever. The first knot of the first lever couples to the stationary member and the second knot of the first lever couples to the second knot of the second lever. Said gear system is connected to the input shaft, the output system, and to the first and second electric machines in the following configuration: the third knot of the first lever selectively connects to and disconnects from the second electric machine through the at least one clutch; the first knot of the second lever connects to the first electric machine; the second knots of the first and second levers connect to output system; the third knot of the second lever connects to the input shaft and selectively connects to and disconnects from the second electric machine.

Said multi-mode electro-mechanical variable speed transmission may further include a counter shaft. The rotatable connection between the gear system and output system is established through said counter shaft.

Said multi-mode electro-mechanical variable speed transmission may further include a one-way clutch that engages in one direction and disengages in the opposite direction to allow one connected member to transfer torque to another connected

member in one-direction only. In general, clutch and one-way clutch are referred to as torque transfer devices. Through coordinated operation of said torque transfer devices and control of electric machines, the transmission can be operated in multiple operating modes, including a first electric drive mode where one of the electric machines provide motive power, a second electric drive mode where two electric machines work together to provide improved motive power, a first hybrid drive mode where the engine is on and transmission is operated with continuously variable speed ratio with low output-to-input speed ratios, a second hybrid drive mode where the engine is on and the transmission is operated with continuously variable speed ratio with high output to input speed ratios, and at least a fixed speed ratio drive mode where the output-to-input speed ratio of the transmission is a constant. Fixed speed ratio operation may be desirable for special applications.

Said multi-mode electro-mechanical variable speed transmission can be operated under pure electric drive modes with engine being turned off to meet all electric drive range requirements. When operating under electric only modes, said at least one clutch selectively connects the second electric machine to the third knot of the first lever and disconnects the second electric machine from the fourth knot of the second lever. The second electric machine provides drive torque and motive power to output system to propel the vehicle. The first electric machine provides torque to balance resistant torque from the engine and to keep engine at zero speed or a predetermined speed. When equipped with the optional one-way clutch at the third knot of the second lever or at the input shaft, the transmission can utilize both the first and second electric machines to provide drive torque and motive power to the output system to propel the vehicle for improved acceleration and enhanced power performance. The one-way clutch prevents the engine from rotating in reverse direction and provides a reaction torque to balance the drive torque of the first electric machine. This allows for the first electric machine to provide drive torque and motive power in tandem with the second electric machine to propel the vehicle. This operation mode may be required for plug-in hybrid vehicles with demanding all electric drive range specifications.

During operation, said multi-mode electro-mechanical variable speed transmission is capable of switching between various operating modes. When switching between the two hybrid operation modes, the second electric machine selectively couples to the first or the second levers via the clutch to realize two different power split configurations. The switching is synchronized, that is to say at the moment of switching the third knot of the first lever has essentially the same rotation speed as that of the fourth knot of the second lever. Both match the speed of the second electric machine. To ensure speed synchronization between the third knot of the first lever and the four knot of the second knot, the gear ratio of the first lever K_s and the gear ratios of the second lever K_a and K_b must satisfy a predetermined proportional relationship. This relationship is set forth

$$K_s = \frac{K_a + 1}{K_b - K_a} \quad (1)$$

At the switching point between the different power split modes, the torque of the second electric machine is essentially zero. No torque impact exerts on the clutch.
 5 This leads to a smooth, continuous and non-interruptive operation in terms of speed, torque and power for components associated with the input shaft, the output system, and the first and second electric machines.

The current invention also provides a method for design, producing and operating said multi-mode electro-mechanical variable speed transmission. Said method includes following steps:

(1) Produce a first planetary gear set; said planetary gear system includes at least three co-axial rotate-able components each corresponding to a knot on a three- knot lever diagram; the inter-distance between the first and the second knots is one unit in length and inter-distance between the second and the third knots is K_s unit in length. Produce
 15 a second planetary gear set; the second planetary gear system includes at least four co-axial rotate-able components each corresponding to a knot on a four-knot lever diagram; the inter-distance between the first and third knots is denoted by K_b , the inter-distance between the second and third knots is K_a , the inter-distance between the third and the fourth knots is one unit. The two planetary gear sets are designed such
 20 that the following relationship is closely met

$$K_s = \frac{K_a + 1}{K_b - K_a}.$$

(2) Produce a first and a second electric machine; the maximum continuous power ratings of the electric machines are set to be no less than P_{EM} .

25 (3) Design and produce an input shaft capable of transmitting a maximum power no less than P_{in} .

(4) Design and produce an output system; said output system further include at least one drive shaft.

(5) Design and produce at least one torque transfer device having at least one
 30 engagement position.

(6) Connect the first co-axial rotate-able component of the first planetary gear set to a stationary member of the transmission; connect the second co-axial rotate-able component of the first planetary gear set to the second co-axial rotate-able component of the second planetary gear set.

35 (7) Connect the first electric machine to the first co-axial rotate-able component of the second planetary gear set; connect output system to the second co-axial rotate-able component of the second planetary gear set; connect the input shaft to the third co-axial rotate-able component of the second planetary gear set, and connect the second electric machine selectively to the third co-axial rotate component of the first

planetary gear set or to the fourth co-axial rotate-able component of the second planetary gear set.

(8) Operate said transmission in at least two hybrid drive modes; switch between said operating modes through said at least one torque transfer device by selectively
5 connecting the second electric machine to the first planetary gear set and disconnecting it from the second planetary gear set or connecting the second electric machine to the second planetary gear set and disconnecting it from the first planetary gear set; at the switching point, the component to of the respect planetary gear set be connected by the torque transfer device to the second electric machine is
10 automatically synchronized in speed with the second electric machine; at switching point, the speed ratio between the second branch and the third branch of the second planetary gear system is denoted by SR_b .

(9) Select the characteristic parameter K_s of the first planetary gear set and characteristic parameters K_a and K_b of the second planetary gear system such that the
15 following relationship holds true,

$$\frac{(K_a + 1)(1 - SR_b)}{K_a \cdot SR_b} = K_s \quad (2)$$

$$\frac{K_b(K_a + 1)}{K_b - K_a} \leq \left(\frac{1 + \frac{P_{em}}{P_{in}}}{1 - \frac{P_{em}}{P_{in}}} \right)^2 \quad (3)$$

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Above mentioned technical solution has following benefits: it offers a novel multi-mode electro-mechanical variable speed transmission with reduced power demands on electric machines. Said transmission has simple and compact mechanical structure and low manufacturing cost. It is capable of providing continuous variable
25 speed operation from reverse to stop and to forward, without requiring the conventional launching device. Said transmission significantly improves the overall efficiency of the vehicle.

BRIEF DESCRIPTION OF ACCOMPANYING DRAWING

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In the accompany drawings which form part of the specification:

Figure 1 is a three-knot lever diagram that represents a three-branch planetary gear set, describing the rotational speed relationship among the three co-axial rotating
35 components of the gear set;

Figure 2 is a four-knot lever diagram that represents a four-branch planetary gear set, describing the rotational speed relationship among the four co-axial rotating components of the gear set;

Figure 3 is a schematic lever diagram of a preferred embodiment (embodiment 1) of multi-mode electro-mechanical variable speed transmission of the current invention;

Figure 4 is a schematic lever diagram of the preferred embodiment (embodiment 1) of multi-mode electro-mechanical variable speed transmission of the current invention;

5 Figure 5 is a schematic lever diagram of a variant of the preferred embodiment (embodiment 1) of multi-mode electro-mechanical variable speed transmission of the current invention with an optional torque transfer device at the third knot of the second lever;

Figure 6 is a schematic diagram of another variant of the preferred embodiment (embodiment 1) of multi-mode electro-mechanical variable speed transmission of the current invention;

Figure 7 is a component schematic diagram of the referred embodiment (embodiment 1) of multi-mode electro-mechanical variable speed transmission of the current invention;

15 Figure 8 is a component schematic diagram of a torque transfer device, showing the first engagement position;

Figure 9 is a component schematic diagram of a torque transfer device, showing the second engagement position;

Figure 10 is a component schematic diagram of a torque transfer device, showing the third engagement position;

Figure 11 is a component schematic diagram of a torque transfer device, showing the fourth engagement position;

Figure 12 is a schematic lever diagram of another preferred embodiment (embodiment 2) of multi-mode electro-mechanical variable speed transmission of the current invention;

Figure 13 is a schematic lever diagram of another preferred embodiment (embodiment 2) of multi-mode electro-mechanical variable speed transmission of the current invention.

DESCRIPTION OF PREFERRED EMBODIMENT

The current invention can have various embodiments, variants and configurations that incarnate the spirit of current invention. Embodiments and configurations disclosed thereafter in text and in illustrations are used for the purpose of explanation only and shall not be interpreted as limitation to the scope of current invention. The following detailed description illustrates the invention by way of example and not by way of limitation.

40 Figure 1 shows a three-knot lever diagram, representing a three-branch planetary gear set. The three-branch planetary gear set has three co-axial rotatable components, the ring gear, the planet carrier and the sun gear. They are represented respectively by the three knots of the three-knot lever. From left to right (or from right to left), these three knots are referred to as the first knot, the second knot and the third knot, respectively.

The inter-distance between the first and second knots in the lever diagram is one unit in length; the inter-distance of the second knot and the third knot is K_s unit in length wherein K_s is the gear teeth ratio of the ring gear to the sun gear. The gear ratio K_s is the characteristic parameter that fully defines the three-knot lever.

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Figure 2 shows a four-knot lever diagram, representing a four-branch planetary gear set. The four-branch gear set has four co-axial rotatable components each represented by a knot on the four-knot level diagram. For left to right (or from tight to left), these four knots are referred to as the first knot, the second knot, the third knot and the fourth knot, respectively. The inter-distance between the first and third knots is K_b unit in length; the inter-distance between the second and third knots is K_a unit in length and the inter-distance between the third and fourth knots is one unit in length wherein K_a and K_b are characteristic gear teeth ratios of the four-branch planetary gear set. K_a and K_b are characteristic parameters that fully define the four-knot lever. That is to say, the performance characteristics of the four-branch planetary gear set are uniquely defined by the characteristic parameters K_a and K_b . The relationships between the parameters K_a , K_b and the teeth numbers of the associated gears of the corresponding planetary gear set are determined by the actual structure of the planetary gear set.

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It should be understood that a lever diagram is a schematic representation of a planetary gear set wherein the co-axial rotatable components of planetary gear set are each represented by a knot on the lever diagram. The lever diagram can be used to graphically describe rotation speeds among the co-axial rotatable components. Those having ordinary skill in the art will recognize that when referring a knot on a lever diagram, it is equivalent to referring the corresponding co-axial rotatable component of the planetary gear set which the lever diagram is representing and vice versa. Those having ordinary skill in the art will understand that the terms such as “couple”, “connect” and “engage” are used to represent fixed mechanical connections or rotatable meshing engagements (though a pair of gears for example) between two or more mechanical components to transmit torque and mechanic power. These terms are also used to represent electric connections between two or more electric components to transmit electric power. Mechanical coupling or connections between the various members or components are illustrated solid lines.

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Figure 3 and figure 4 show a preferred embodiment, the embodiment 1 of current invention. The embodiment is illustrated in the lever diagram format. The multi-mode electro-mechanical variable speed transmission is comprised of a gear system including a first planetary gear set (PG1) represented by a first lever and a second planetary gear set (PG2) represented by a second lever, an input shaft (Input), an output system (Output), at least one clutch (CL), a first stationary member (FM1), and a first and a second electric machines (EM1, EM2) along with their associated drives and controllers (not shown). Said first planetary gear set is a three-branch planetary gear, having a first co-axial rotatable component, a second co-axial rotatable

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component and a third co-axial rotatable component each represented by a first knot (KN₁₁), a second knot (KN₁₂) and a third knot (KN₁₃) of the first lever, respectively. Said second planetary gear set is a four-branch planetary gear set, having a first, a second, a third and a fourth co-axial rotatable components that are represented by a first, a second, a third and a fourth knots (KN₂₁, KN₂₂, KN₂₃, KN₂₄) of the second lever, respectively. The first knot (KN₁₁) of the first lever (PG1) connects to the stationary member (FM1). The second knot (KN₁₂) of the first lever (PG1) connects to the second knot (KN₂₂) of the second lever (PG2) such that the second knot (KN₁₂) of the first lever (PG1) rotates at the same rational speed as the second knot (KN₂₂) of the second lever (PG2).

The first electric machine (EM1) includes a first rotor and a first stator. Referring to figure 3, the rotor of the first electric machine (EM1) directly couples to the first knot (KN₂₁) of the second planetary gear set (PG2). The output shaft (Output) couples to the second knot (KN₁₂) of the first planetary set (PG1) and to the second knot (KN₂₂) of the second planetary gear set (PG2). The input shaft (Input) couples to the third knot (KN₂₃) of the second planetary gear set (PG2).

The second electric machine (EM2) includes a second rotor and a second stator. The rotor of the second electric machine (EM2) couples selectively through said clutch (CL) to the third knot (KN₁₃) of the first planetary gear set (PG1) or to the fourth knot (KN₂₄) of the second planetary gear set (PG2), or to both the third knot (KN₁₃) of the first planetary gear set and the fourth knot (KN₂₄) of the second planetary gear set. Thus the second electric machine (EM2) selectively couples directly to the fourth knot (KN₂₄) of the second planetary gear set (PG2) with a first constant speed ratio, or indirectly through the first planetary gear set (PG1) to the second knot (KN₂₂) of the second planetary gear set (PG2) with a second constant speed ratio.

The first and second electric machines (EM1, EM2), along with their respective drives, are electrically connected to transmit power to and from each other. Said multi-mode electro-mechanical variable speed transmission may further include an energy storage device such as a battery pack (BT, not shown in illustrations) to store and recapture energy. The energy storage device is connected to the first and second electric machines to receive power from or deliver power to one or both of the electric machines.

When the second electric machine (EM2) couples to the first planetary gear set (PG1), said at least one clutch (CL) connects the second electric machine EM2 to the third knot (KN₁₃) of the first planetary gear set and disconnect the second electric machine (EM2) from the fourth knot (KN₂₄) of the second planetary gear set (PG2) as shown in figure 3. The transmission is operated under the first power split mode. The input power from the engine is split into two power paths to transmit to the output system. One is the pure mechanical power path that goes from the input shaft (Input), through the second knots (KN₁₂, KN₂₂) of the first and second planetary gear sets (PG1, PG2),

to the output system (Output). The other is the electro-mechanical power path that goes from input shaft (Input), through the second planetary gear set (PG2), the first electric machine (EM1), the second electric machine (EM2), the at least one clutch (CL) and the first planetary gear set (PG1), to the output system (Output).

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When the second electric machine (EM2) couples to the second planetary gear set (PG2), said at least one clutch (CL) disconnects the second electric machine (EM2) from the third knot (KN_{13}) of the first planetary gear set (PG1) and connects it to the fourth knot (KN_{24}) of the second planetary gear set (PG2) as shown in figure 4. The transmission is operated under the second power split mode. Similarly, the input power from the engine is split into two power paths to transmit to the output system (Output). The pure mechanical power path goes from the input shaft (Input) through the second planetary gear set (PG2) to the output system (Output); the electro-mechanical power path goes from the input shaft (Input), through the second planetary gear set (PG2), the first electric machine (ME1), the second electric machine (EM2), and the at least one clutch (CL) back to the second planetary gear set (PG2), and finally to the output system (Output).

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To facilitate the description, the ratio of the output system (Output) speed to the input shaft (Input) speed is defined as the output-to-input speed ratio of the transmission and is simply referred to thereafter as the speed ratio denoted by SR .

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The first embodiment (embodiment 1) is capable of providing a natural speed ratio node $SR0$ where the speed of the output shaft system is zero and two regular speed ratio nodes $SR1$ and $SR2$. At the regular speed ratio nodes, at least one of the electric machines achieves zero rotational speed. The natural speed ratio node $SR0$ divides the entire speed ratio regime into a forward speed ratio regime and a reverse speed ratio regime. Above the natural speed ratio node is the forward regime; below the natural speed ratio node is the reverse regime. The first regular speed ratio node $SR1$, also simply referred to as the first speed ratio node, further divides the forward regime into a low-speed ratio regime and a high-speed ratio regime. Below the first speed ratio node $SR1$ is the low speed ratio regime and above the first speed ratio node $SR1$ is the high speed ratio regime.

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At the first speed ratio node point $SR1$, the torque of the second electric machine (EM2) is zero if there is no net power exchange between the transmission and the energy storage device. Thus, it would be advantageous to choose $SR1$ as the switching point between different power split modes to avoid or minimize possible shock load in torque for the transmission. In the low speed ratio regime below $SR1$, the transmission adopts the so-called output power split configuration. In the high speed ratio regime above $SR1$, the transmission adopts the so-call compound power split configuration. In the reverse regime, the hybrid system operates under pure electric drive mode. Thus, the power in each power path, whether the mechanical power path or the electro-mechanical power path, is always less than the power transmitted through the

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transmission from the input shaft to the output system. No internal power circulation exists in any speed ratio regime for the multi-mode electro-mechanical variable speed transmission. The speed ratio range of the transmission is thus effectively extended. To ensure speed synchronization of the clutch (CL) at the mode switching point $SR1$, the one of the following relationships between the gear ratios has to be satisfied as closely as possible,

$$K_s = \frac{K_a + 1}{K_b - K_a} \quad (4a)$$

$$K_s = K_b \quad (4b)$$

Taking into consideration of possible internal power losses of the electric machines and the associated drives, and the consideration constraint imposed by gear teeth numbers, the actual switching point SR_b in speed ratio may be at the vicinity of $SR1$. The output power split operating mode is adopted at the low speed ratio regime below $SR1$, the compound power split operating mode is adopted at the mid to high speed ratio regime above $SR1$. In reverse regime pure electric drive mode could be adopted to effectively avoid internal power circulation. To ensure clutch rotational speed synchronization at switching speed ratio SR_b , the gear ratios have to satisfy following relationship:

$$SR_b = \frac{K_a + 1}{K_a(K_s + 1) + 1} \quad (5)$$

Figure 5 shows a variant of the preferred embodiment (embodiment 1A) wherein the multi-mode electro-mechanical variable speed transmission further includes a second stationary member (FM2) and a second torque transfer device. The second torque transfer device in a simple form is a one-way clutch (OWC). The one-way clutch (OWC) selectively connects the second stationary member (FM2) to the third knot (KN₂₃) of the second planetary gear set (PG2). The one-way clutch prevent the input shaft (Input) from rotating in the reverse direction and provide reaction torque to balance the drive torque of the first electric machine (EM1) when it acts as motor during one of the pure electric drive mode.

Figure 6 shows another variant of the preferred embodiment (embodiment 1B) wherein the multi-mode electro-mechanical variable speed transmission further includes a third stationary member (FM3) and a third torque transfer device. The third torque transfer device is a brake (BR). The brake selectively connects or disconnects the fourth knot (KN₂₄) of the second planetary gear set (PG2) to or from the third stationary member (FM3).

Figure 7 shows the same variant as figure 5 in component format wherein the knots of the lever diagrams are each represented in an actual component of the corresponding planetary gear sets. The multi-mode electro-mechanical variable speed transmission is comprised of a first planetary gear set (PG1) including three co-axial rotatable components, a second planetary gear set (PG2) including four-coaxial rotatable components, an input shaft (Input), an output system (Output), a first torque transfer device or a clutch (CL), a second torque transfer device, a first stationary member (FM1), a first electric machine (EM1) and a second electric machine (EM2). The transmission may also include a torsional damper (DMP) to connect the input shaft (Input) to the engine output shaft (ENG) and a counter shaft system (CTS) to connect the first and second planetary gear sets to the output system (Output).

The first planetary gear set (PG1) includes a sun gear (S_s), a ring gear (R_s), a set of planet gears (P) supported on a planet carrier (CR_s). The planet gears (P) are arranged around and in external mesh with the sun gear (S_s). The planet gears (P) are in internal mesh with the ring gear (R_s). The sun gear (S_s), the planet carrier (CR_s) and the ring gear (R_s) are the three co-axial rotatable components of the first planetary gear set (PG1). These three co-axial rotatable components are represented respectively as the first knot (KN_{11}), the second knot (KN_{12}) and the third knot (KN_{13}) on a three-knot lever diagram. The first planetary gear set (PG1) is characterized the gear teeth ratio K_s of ring gear (R_s) to the sun gear (S_s) which is expressed as the inter-distance between the second and third knots on the three-knot lever diagram.

$$K_s = \frac{Z_{S_s}}{Z_{R_s}} \quad (6)$$

where Z_{S_s} and Z_{R_s} are the number of teeth for sun gear (S_s) and ring gear (R_s) of the first planetary gear set (PG1), respectively.

The second planetary gear set (PG2) is a Ravigneaux planetary gear-train. It includes a first sun gear (S1), a second sun gear (S2), a ring gear (R), a first set of planet gears (PS), a second set of planet gears (PL), and a planet carrier (CR) that hosts and supports the first and second sets of planet gears (PS, PL). The planet gears in the first set are short planet gears and the planet gears in the second set are long planet gears. Each of said long planet gears (PL) is in internal meshing engagement with the ring gear (R) and in external meshing engagement with the first sun gear (S1); each of said short planet gears (PS) is in external meshing engagement with a corresponding long planet gear (PL) and with the second sun gear (S2). The second sun gear (S2), the ring gear (R), the planet carrier (CR) and the first sun gear (S1) are the four co-axial rotatable components of the second planetary gear set (PG2) and as represented as the first knot (KN_{21}), the second knot (KN_{22}), the third knot (KN_{23}) and

the fourth knot (KN₂₄) on a four-knot lever diagram. The second planetary gear set is characterized by two gear teeth ratios K_a and K_b .

$$K_a = \frac{Z_{S1}}{Z_R}; \quad K_b = \frac{Z_{S1}}{Z_{S2}} \quad (7)$$

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where Z_{S1} , Z_{S2} and Z_R are the tooth numbers of the first sun gear (S1), the second sun gear (S2) and the gear (R) of the second planetary gear set (PG2), respectively. On the four-knot lever diagram, K_a and K_b are denoted as the inter-distance between the second and third knots and the inter-distance between the first and third knots, respectively.

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The first planetary gear set and the second planetary gear set are co-axially arranged and adjacent to each other in the axial direction. The ring gear (R_s) of the first planetary gear set (PG1) is connected to the first stationary member (FM1). This this regard, the first planetary gear functions merely as a stepping up gear with a constant gear ratio. The planet carrier (CR_s) of the first planetary gear set is fixed with the ring gear (R) of the second planetary gear set (PG2) such that they have a same rotational speed.

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The output system includes at least one drive shaft and an optional differential (DIF). The first torque transfer device (CL) has at least two engagement states. It could be an integrated unit of a first and a second clutches (C1, C2) each having an engagement and a disengagement states. The first electric machine EM1 includes a first rotor (RT1) and a first stator (ST1). The second electric machine (EM2) includes a second rotor (RT2) and a second stator (ST2). The second torque transfer device includes a second stationary member (FM2) and a one-way clutch (OWC). The counter shaft system (CTS) includes a first pair of meshing gears (G1A, G1B) and a second pair of meshing gears (G4A, G4B).

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Said multi-mode electro-mechanical variable speed transmission is configured to provide multiple modes of operations through the unique connections between the gear system (PG1, PG2) and the motive components (Input, Output, EM1 and EM2). Referring to figure 7, the rotor (RT1) of the first electric machine (EM1) is connected to the second sun gear (S2) of the second planetary gear set (PG2). The output system (Output) is connected through the two pairs of meshing gears (G4B, G4A and G1B, G1A) of the counter shaft system (CTS) to the planet carrier (CR_s) of the first planetary gear set (PG1) and the ring gear (R) of the second planetary gear set (PG2) wherein the differential (DIF) connects to the driven gear (G4B) of the second pair of meshing gears of the counter shaft system (CTS) and drive gear (G1A) of the first pair of meshing gears of the counter shaft system (CTS) connects to the planet carrier (CR_s) of the first planetary gear set (PG1) and the ring gear (R) of the second planetary gear set (PG2). The engine (ENG) drives the input shaft (Input) through the torsional

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damper (DMP). The input shaft (Input) in turn connects to the planet carrier (CR) of the second planetary gear set. The input shaft (Input) also couples to the second torque device wherein the one-way clutch (OWC) directionally engages the second stationary member (FM2) to prevent the input shaft from rotating in the opposite direction as the engine. The rotor (RT2) of the second electric machine (EM2) is selectively coupled through the first torque transfer device (CL) either to the sun gear (S_s) of the first planetary gear set (PG1) wherein the first clutch (C1) engages and the second clutch (C2) disengages, or to the first sun gear (S1) of the second planetary gear set (PG2) wherein the first clutch (C1) disengages and the second clutch (C2) engages. Thus the second electric machine (EM2) couples selectively to the first sun gear (S1) of the second planetary gear set (PG2) with a first constant speed ratio (a speed ratio of 1:1) or through the first planetary gear set (PG1) to the ring gear (R) of the second planetary gear set (PG2) with a second speed ratio (a speed ratio of $[K_s+1]:1$).

The first and second torque transfer devices (CL, OWC) are arranged on the same axial line of rotation as the first and second planetary gear sets. That is to say, the first planetary gear set (PG1), the second planetary gear set (PG2), the first torque transfer device (CL) and the second torque transfer device (OWC) are all on the same axial line of rotation. In addition, the first torque transfer device (CL) and the first and second planetary gear sets (PG1, PG2) are co-axially arranged with and sandwiched between the two electric machines (EM1, EM2). This has a great advantage in reducing package size.

The first torque transfer device (CL) may further be integrated with the brake (BR) and the third stationary member (FM3). It may be modified to include four engagement positions as shown in figures 8 to 11. The integrated torque transfer device (CL) is comprised of a first clutch having a first clutch member (C1), a second clutch having a second clutch member (C1), a third clutch having a third clutch member (BR), and a sleeve ring (SL). The first clutch member (C2) is fixed with the sun gear (S_s) of the first planetary gear set (PG1), the second clutch member (C2) the fixed with the first sun gear (S1) of the second planetary gear set, and the third clutch member (BR) is fixed with the third stationary member (FM3). The sleeve ring (SL) is connected to a rotor shaft (RTS) of the second electric machine (EM2) through a pair of mating splines (SP_i , SP_o). The male spline (SP_o) of the mating pair is fixed to the rotor shaft (RTS) and the female spline (SP_i) is fixed to the sleeve ring (SL). The female spline (SP_i) slides back-and-forth over the male spline (SP_o) along the axial direction by an actuator (not shown) under command.

Figure 8 shows the first engagement position of the first torque transfer device, wherein the sleeve ring (SL) is engaged only with the first clutch member (C1). In this case, the rotor shaft (RTS) and thus the rotor (RT2) of the second electric machine (EM2) is coupled to the sun gear (S_s) of the first planetary gear set (PG1). The transmission operates in a first power-split mode

Figure 9 shows the second engagement position of the first torque transfer device, wherein the sleeve ring (SL) is engaged with both the first and second clutch members (C1, C2). In this case, the rotor shaft (RTS) and thus the rotor (RT2) of the second electric machine (EM2) is coupled to both the sun gear (S_s) of the first planetary gear set (PG1) and the first sun gear (S1) of the second planetary gear set (PG2). The transmission operates in a first fixed speed ratio mode

Figure 10 shows the third engagement position of the first torque transfer device, wherein the sleeve ring (SL) is engaged only with the second clutch members (C2). In this case, the rotor shaft (RTS) and thus the rotor (RT2) of the second electric machine (EM2) is coupled to the first sun gear (S1) of the second planetary gear set (PG2). The transmission operates in a second power-split mode.

Figure 11 shows the fourth engagement position of the first torque transfer device, wherein the sleeve ring (SL) engages with both the second and third clutch members (C2, BR). In this case, the rotor shaft (RTS) and thus the rotor (RT2) of the second electric machine (EM2) is coupled to both the first sun gear (S_s) of the second planetary gear set (PG2) and the third stationary member (FM3). The transmission operates in a second fixed speed ratio mode.

The four engagement positions of the first torque transfer device are arranged adjacent to each other along the axial direction. When positive engagement clutches such as dog-clutches are used, this leads to very compact configuration.

The operation of the multi-mode electro-mechanic variable speed transmission is described below.

Continuously variable speed operation

1. Low speed ratio regime

Before the vehicle starts to move, transmission is set to operate in low speed ratio regime. The second electric machine (EM2) couples through the at least one clutch (CL) to the first planetary gear set (PG1) to gain a leverage to propel the output system (Output). The first electric machine (EM1) is idling, and rotating in the opposite direction to that of the internal combustion engine (Input). The second electric machine (EM2) for a brief moment is at zero speed. As the vehicle starts, the controller sends commands to drive circuit. The drive circuit, in turn, provides the required electric power to the second electric machine (EM2) to generate drive torque. The drive torque is amplified through the first planetary gear set (PG1) and delivered to the output system (Output). At this moment, except for an insignificant amount of internal power losses, the second electric machine EM2 does not convert yet any electric power into mechanical power. Because the vehicle is still at standstill, there is

no requirement for drive power but drive torque at the drive wheels. The drive torque to start the vehicle comes primarily from the second electric machine (EM2). Concurrently, the internal combustion engine provides zero starting torque for the vehicle, thus there is no power output from the engine. As the torque of electric machine increases, the vehicle takes off from standstill and moves forward. Accordingly, the second electric machine (EM2) starts to rotate, consuming electric power and converting it into the required mechanical drive power. Meanwhile, the engine starts to provide drive torque to the drive wheels as well. The first electric machine (EM1) in turn provides reaction torque to balance the engine torque and the speed of the first electric machine (EM1) gradually reduces to accommodate the increased vehicle speed. In this process, the first electric machine (EM1) acts as a generator converting mechanical power into electric power. The electric power consumed by the second electric machine (EM2) is fully or partially provided by the first electric machine (EM1) through electric drives and controllers (CTRL, not shown). After the vehicle started to move, the drive torque at the drive wheels is shared between the internal combustion engine and the second electric machine (EM2), causing the torque of the second electric machine (EM2) to reduce.

As the speed of vehicle increases, the rotational speed of the second electric machine (EM2) increases and the torque of the second electric machine (EM2) continues to decrease. In contrast, the speed of the first electric machine (EM1) continues to decrease, till reaching zero. At the moment when the first electric machine (EM1) reaches its zero speed point, the transmission arrives at its first regular speed ratio node *SR1*. Assuming there is no net electric power exchange between the transmission and the energy storage device, the second electric machine (EM2) also arrives at its zero torque point. That is to say the zero torque point (speed ratio node corresponding to zero torque) of the second electric machine (EM2) coincides with the zero speed point (speed ratio node corresponding to zero speed) of the first electric machine (EM1).

2. High speed ratio regime

The first speed ratio node *SR1* marks the transition from low speed ratio regime to high speed ratio regime, or vice versa. At the operation mode switching point, the second electric machine (EM2) produces zero torque and the speeds of the second electric machine (EM2), the third knot (KN_{13}) of the first planetary gear set (PG1) and fourth knot (KN_{24}) of the second planetary gear set (PG2) are synchronized. At this moment, the at least one clutch (CL) disconnects the second electric machine (EM2) from the third knot (KN_{13}) of the first planetary set (PG1) and connects the second electric machine (EM2) to the fourth knot (KN_{24}) of the second planetary gear set (PG2). Transmission is now operating under compound power split mode.

As the speed of the vehicle further increases, the speed ratio of the transmission increases and exceeds the first regular speed ratio node *SR1*. The rotational speed of

the first electric machine (EM1) rises from zero and continues to increase in the same direction as the input shaft (Input). The speed of the second electric machine (EM2) starts to reduce. Should there be no net electric power exchange between the transmission and energy storage device, the torque of the second electric machine (EM2) will rise from zero and increase in value at the opposite direction. The second electric machine (EM2) now functions as a generator, providing electric power to the first electric machine (EM1) or/and to the energy storage device. The first electric machine (EM1), acts as a motor, converting electric power into mechanical power.

As the vehicle continues to increase in speed, the speed of the second electric machine (EM2) continues to decrease to zero. The transmission reaches its second speed ratio node $SR2$. At this speed ratio node, the power transmitted through the electro-mechanical power path becomes zero; all power is transmitted from input shaft (Input) to the output system (Output) through the pure mechanical power path.

Between the first speed ratio node $SR1$ and the second speed ratio node $SR2$, the power split ratio PR , defined as the power transmitted through the electro-mechanical power path to the total engine power to be transmitted at the input shaft (Input), possesses a local maximum value. The maximum value is dependent upon the characteristic gear ratios of the four-branch planetary gear set (the second planetary gear set). Assuming the maximum input power of the transmission is P_{in} and the maximum continuous power rating of the electric machine is P_{em} , the power ratio of the maximum continuous power rating of the electric machine to the maximum input power of the transmission is denoted as $PR_{max} = P_{em}/P_{in}$. For an adequate matching between the sizes of electric machines and the construction of the transmission, so that the transmission can be operated continuously and appropriately between the first and second regular speed ratio nodes, the characteristic parameters of the four-branch gear system must satisfy following condition,

$$\frac{K_b(K_a + 1)}{K_b - K_a} \leq \left(\frac{1 + PR_{max}}{1 - PR_{max}} \right)^2 \quad (8)$$

At or in the vicinity of the second speed ratio node $SR2$, the torque of the first electric machine (EM1) reverses its direction. As the speed ratio of the transmission continues to increase, the speed of the first electric machine (EM1) continues to go up; concurrently, the speed of the second electric machine (EM2) rises from zero and increases in the reversed direction. To avoid excessive internal power circulation when the speed ratio of the transmission exceeds far beyond the second speed ratio node $SR2$, a brake (BR) may be employed in the transmission to brake the fourth knot (KN_{24}) of the second planetary gear set (PG2) when it is deemed necessary.

3. Reverse regime.

The regime below the natural speed ratio node $SR0$ is referred to as the reverse regime. In this regime, the output power split configuration is also applicable. The at least one clutch (CL) connects the second electric machine (EM2) to the first planetary gear set (PG1) and disconnects the second electric machine (EM2) from the second planetary gear set (PG2). The power is delivered from the second knots (KN_{12} , KN_{22}) of the first and second planetary gear sets to the output system (Output).

Pure electric drive operation

To restrict the power ratio of the electric power path to the input power, avoiding internal power circulation, a pure electric drive mode may be adopted in the reverse regime. In the pure electric drive mode, the engine is turned off. The second electric machine (EM2) is controlled by the controller (CTRL) to convert electric power from the energy storage (BT) into mechanical power and to provide drive torque to the output system (Output). The drive torque from the second electric machine (EM2) is amplified through the first planetary gear set (PG1) before delivered to the output system (Output).

Pure electric drive operation is also applicable in forward speed ratio regime. In fact, there are a number of electric modes. The first electric drive mode essentially the same as the pure electric drive mode described above for reverse operation. In this electric drive mode, the first torque transfer device (CL) connects the second electric machine (EM2) to the first planetary gear set (PG1) and disconnects the second electric machine (ME2) from the second planetary gear set (PG2). The motive power is provided by the second electric machine (EM2) through the first planetary gear set (PG1). The first planetary gear set (PG1) provides torque leverage by a factor K_s+1 .

The second electric drive mode calls for two electric machines working in tandem to provide enhanced motive power for fast acceleration or for steep hill-climbing. Similar to the first electric drive mode, the first torque transfer device (CL) connects the second electric machine (EM2) to the first planetary gear set (PG1) and disconnect the second electric machine (EM2) from the second planetary gear set (PG2). Part of the motive power is provided by the first electric machine (EM1) through the second planetary gear set (PG2). Referring to figures 5 to 7, the one-way clutch (OWC) prevents the input shaft (Input) from rotating in the opposite direction to the normal rotation direction of the engine. In doing so, it provides a reaction torque to balance the drive torque of the first electric machine (EM1). The second planetary gear set (PG2) provides a torque leverage by a factor of K_b/K_a to the first electric machine (EM1). Part of the motive power is provided by the second electric machine (EM2) through the first planetary gear set (PG1). The first planetary gear set (PG1) provides torque leverage by a factor K_s+1 to the second electric machine (EM2).

Geared neutral and parking

Said multi-mode electro-mechanical variable speed transmission is capable of providing additional practical and useful functions including geared neutral and parking. When said at least one clutch (CL) are disengaged from both the first and second planetary gear sets, and the first electric machine (EM1) is switched off or at the idle state, the transmission is at geared neutral. When both the first and second electric machines (EM1, EM2) are switched off or at the idle state, the transmission is also at geared neutral.

Parking can be achieved by engaging the at least one clutch (CL) to both the first and second planetary gear sets and by engaging the brake (BR). In addition, parking can be achieved by conventional parking pawl (PBR, not shown) installed on the transmission.

Fixed speed ratio operation

The multi-mode electro-mechanical variable speed transmission of the current invention is capable of offering operations with fixed output-to-input speed ratios. The fixed speed ratio operations are provided to suite special application requirements such as towing and acceleration during hill climbing. The conditions for fixed speed ratio operations are listed in the following table.

Fixed speed-ratio mode	SL engagement status		
	C1	C2	BR
1	engage	engage	disengage
2	disengage	engage	engage

The first and second fixed speed ratios are essentially at the first and second regular speed ratio nodes of the transmission. Shifting between adjacent fixed speed-ratio positions is achieved in a smooth and continuous fashion as outlined in previous sections. Thus, there is no power interruption during speed ratio change between the first and second fixed speed ratios. In addition, at each fixed speed ratio position, one or both of the electric machines (EM1, EM2) can act as motors or generators to provide power assisting or regenerative braking functions as in parallel electric hybrid systems. This results in enhanced power and performance of the vehicle system.

The torque transfer devices can be any type of mechanical, hydro-mechanical, or electro-magnetic clutches, brakes or combined packages of clutches and brakes. Since the engagement or disengagement of the torque transfer devices occur under natural synchronization conditions wherein the rotational speeds for all involved components are essentially the same, simple clutches such as positive engagement clutches or dog clutches can be used instead of the more complex and costly friction clutches. This eliminates the hydraulic system normally required by wet friction clutches, and thus effectively reduces internal power losses.

Other operation status

Embodiment 1 and its variants (Embodiment 1A, Embodiment 1B) also provide the function for starting up the engine. Engine start up is accomplished either by one of the two electric machines independently or by both electric machines working collaboratively. For example, when the transmission is at geared neutral, the engine can be started collaboratively by two electric machines. While as when the transmission is under pure electric drive mode, the engine can be started by the first electric machine (EM1).

When energy storage device (BT) is used in conjunction with the multi-mode electro-mechanical variable speed transmission, the transmission is capable of providing not only continuous speed ratio variation, but also energy buffering, offering the so-called hybrid drive operation. Under hybrid drive operation, power between the two electric machines no longer need to be balanced. The electric power generated by one electric machine may be more or less than that electric power consumed by the other electric machine. Under such circumstances, the speed ratio node at which one of the electric machines has zero rotational speed may not coincide with the speed ratio at which the other electric machine has zero torque. The position of speed ratio at which one of the electric machines has zero torque varies with the power imbalance between the two electric machines. However, the position of speed ratio node at which one of the electric machines has zero speed always remains the same regardless the power imbalance between the two electric machines.

When there is net electric power exchange between the electric power path of the transmission and the energy storage device, the electric machines have to fulfill double duties of both speed ratio regulation and power regulation. Thus, the power ratings of the electric machine should not be less than the maximum electric power split ratio times the rated power at the input shaft of the transmission.

Figure 12 shows another embodiment (embodiment 2) in a lever diagram format. Referring to figure 12, the multi-mode electro-mechanical variable speed transmission is comprised of a gear system including a first planetary gear set (PG1) represented by a first lever and a second planetary gear set (PG2) represented by a second lever, an input shaft (Input), an output system (Output), at least one clutch (CL), a first stationary member (FM1), and a first and a second electric machines (EM1, EM2) along with their associated drives and controllers (not shown). Said first planetary gear set is a three-branch planetary gear, having a first co-axial rotatable component, a second co-axial rotatable component and a third co-axial rotatable component each represented by a first knot (KN_{11}), a second knot (KN_{12}) and a third knot (KN_{13}) of the first lever, respectively. The first lever is fully defined by its characteristic parameter K_{S1} . Said second planetary gear set is also a three-branch planetary gear set, having a first, a second, and a third co-axial rotatable components that are represented by a first knot (KN_{21}), a second knot (KN_{22}), and a third knot (KN_{23}) of the second

lever, respectively. The second lever is fully defined by its characteristic parameter K_{S2} . The first knot (KN₁₁) of the first lever (PG1) connects to the stationary member (FM1). The second knot (KN₁₂) of the first lever (PG1) connects to the second knot (KN₂₂) of the second lever (PG2) such that the second knot (KN₁₂) of the first lever (PG1) rotates at the same rational speed as the second knot (KN₂₂) of the second lever (PG2).

The first electric machine (EM1) includes a first rotor and a first stator. The rotor of the first electric machine (EM1) directly couples to the first knot (KN₂₁) of the second planetary gear set (PG2). The output shaft (Output) couples to the second knot (KN₁₂) of the first planetary set (PG1) and to the second knot (KN₂₂) of the second planetary gear set (PG2). The input shaft (Input) couples to the third knot (KN₂₃) of the second planetary gear set (PG2).

The second electric machine (EM2) includes a second rotor and a second stator. The rotor of the second electric machine (EM2) couples selectively through said clutch (CL) to the third knot (KN₁₃) of the first planetary gear set (PG1) or to the third knot (KN₂₃) of the second planetary gear set (PG2), or to both the third knot (KN₁₃) of the first planetary gear set and the second planetary gear set. Thus, the second electric machine (EM2) selectively either connects directly to the third knot (KN₂₃) of the second planetary gear set with a first constant speed ratio (1 to 1 ratio), or connects indirectly through the first planetary gear set to the second knot (KN₂₂) of the second planetary gear set with a second constant speed ratio wherein the first and second constant speed ratios are different.

The first and second electric machines (EM1, EM2), along with their respective drives, are electrically connected to an energy storage device such as a battery pack (BT, not shown in illustrations) to receive power from or deliver power to the energy storage device

When the second electric machine (EM2) couples to the first planetary gear set (PG1), said at least one clutch (CL) connects the second electric machine EM2 to the third knot (KN₁₃) of the first planetary gear set (PG1) and disconnect the second electric machine (EM2) from the third knot (KN₂₃) of the second planetary gear set (PG2) as shown in figure 12. The transmission is operated under the first output power split mode. The input power from the engine is split into two power paths to transmit to the output system. One is the pure mechanical power path that goes from the input shaft (Input), through the second knots (KN₁₂, KN₂₂) of the first and second planetary gear sets (PG1, PG2), to the output system (Output). The other is the electro-mechanical power path that goes from input shaft (Input), through the second planetary gear set (PG2), the first electric machine (EM1), the second electric machine (EM2), the clutch (CL) and the first planetary gear set (PG1), to the output system (Output).

When the second electric machine (EM2) couples to the second planetary gear set (PG2), said at least one clutch (CL) disconnects the second electric machine (EM2) from the third knot (KN₁₃) of the first planetary gear set (PG1) and connects it to the third knot (KN₂₃) of the second planetary gear set (PG2) as shown in figure 13. The transmission is operated under the second power split mode. Similarly, the input power from the engine is split into two power paths to transmit to the output system (Output). The pure mechanical power path goes from the input shaft (Input) through the second planetary gear set (PG2) to the output system (Output); the electro-mechanical power path goes from the input shaft (Input), through the second planetary gear set (PG2), the first electric machine (ME1), the second electric machine (EM2), and the at least one clutch (CL) back to the second planetary gear set (PG2), and finally to the output system (Output).

The second embodiment (embodiment 2) is capable of providing a natural speed ratio node *SR0* where the speed of the output shaft system is zero and one regular speed ratio nodes *SR1*. At the regular speed ratio nodes, at least one of the electric machines achieves zero rotational speed. The natural speed ratio node *SR0* divides the entire speed ratio regime into a forward speed ratio regime and a reverse speed ratio regime. Above the natural speed ratio node is the forward regime; below the natural speed ratio node is the reverse regime. The first regular speed ratio node *SR1*, also simply referred to as the first speed ratio node, further divides the forward regime into a low-speed ratio regime and a high-speed ratio regime. Below the first speed ratio node *SR1* is the low speed ratio regime and above the first speed ratio node *SR1* is the high speed ratio regime.

At the first speed ratio node point *SR1*, the torque of the second electric machine (EM2) is zero if there is no net power exchange between the transmission and the energy storage device. Thus, it would be advantageous to choose *SR1* as the switching point between the different power-split modes or configurations to avoid or minimize possible shock load in torque for the transmission. In the low speed ratio regime below *SR1*, the transmission adopts the so-called output power split configuration. In the high speed ratio regime above *SR1*, the transmission adopts the so-call input power split configuration. In the reverse regime, the hybrid system operates under pure electric drive mode. Thus, the power in each power path, whether the mechanical power path or the electro-mechanical power path, is always less than the power transmitted through the transmission from the input shaft to the output system. No internal power circulation exists in any speed ratio regime for the multi-mode electro-mechanical variable speed transmission. The speed ratio range of the transmission is thus effectively extended. To ensure speed synchronization of the clutch (CL) at the mode switching point *SR1*, the following relationship between the gear ratios has to be satisfied as closely as possible,

$$K_{S1} = K_{S2} \quad (9)$$

- 5 Taking into consideration of possible internal power losses of the electric machines and the associated drives, and the consideration of constraints imposed by gear teeth numbers, the actual switching point SR_b in speed ratio may be at the vicinity of $SR1$ deviating from $SR1$. To ensure clutch rotational speed synchronization at switching speed ratio SR_b , the gear ratios have to satisfy following relationship

$$SR_b = \frac{1}{1 + K_{s1}} \quad (10)$$

- 10 A common feature of all the embodiments and variants is that the first electric machine (EM1), the input shaft (Input) and the output system (Output) each couples to a different knot of the second planetary gear set (PG2) with a constant speed ratio. Another common feature of all the embodiments and variants is that one knot of the first planetary gear set (PG1) is coupled to a stationary member (FM1) of the transmission. Yet, another common feature of all the embodiments and variants is that
 15 the second electric machine (EM2) selectively connects to a knot of the second planetary gear set (PG2) with a first constant speed ratio and to another knot of the second planetary gear set (PG2) with a second constant speed ratio. Yet, another common feature of all the embodiments and variants is that the second electric machine (EM2) selectively couples to the first planetary gear set (PG1) and to the
 20 second planetary gear set (PG2).

- As can be appreciated that the transmission of the current invention is capable of operating under multiple modes, including two power-split modes and two fixed
 25 speed ratio modes. These modes of operation can be achieved simply by selectively coupling the second electric machine (EM2) to various component or components and member or members of the transmission.

- The basic steps in design and producing the transmission of the current invention
 30 include constructing a planetary gear set having at least three branches; producing an input shaft, an output system, a first electric machine and a second electric machine; connecting the each of the at least three branches of the planetary gear set to the first electric machine, the output system and the input shaft, respectively; selectively connecting the second electric machine to one branch of the planetary gear set with a
 35 first constant speed ratio and to another branch of the planetary gear set with a second constant speed ratio.

- When four-branch planetary gear set is used to construct transmission of the current invention, restrictions are imposed on the structure and the characteristic parameters
 40 of the four-branch gear system. This is done to ensure that the four-branch gear system so constructed is suitable to produce a multi-mode electro-mechanical variable speed transmission that is capable of satisfying all specified functional requirements. The aforementioned inequality Equation (8) set forth the power constraints for electric machines from the power matching perspective. It is recommended that following

condition be satisfied when designing and selecting characteristic parameters for a four-branch gear system.

$$\frac{K_b(K_a+1)}{K_b-K_a} \leq 2.75 \quad (11)$$

5

Additionally, for restricting the rotational speed of electric machines, particularly at high speed regime, it is further recommended that the following relationship holds true.

$$K_b \leq 2 \quad (12)$$

It should be pointed out that the electric machine referred in this disclosure is a generic term; it refers to both electric motor and electric generator.

15 INDUSTRIAL USEFULNESS

The parts and components required by the aforementioned embodiments and variants of current invention can be readily made by industrial manufacturing means. This warrants that the multi-mode electro-mechanic variable speed transmission is obtainable. Said transmission can be operated under at least two different power split modes, and thus is capable of avoiding internal power circulation and offering higher power transmission efficiency. Said transmission can provide, in a wide range, independent and continuous output to input speed ratio change and power regulation, extending significantly operation range. The new multi-mode electro-mechanical variable speed transmission reduces power demand on electric machines, making the construction of the transmission simple, more compact, and low cost. The transmission is capable of proving continuous speed change from reverse to full stop and to forward, without the need for vehicle launching device. It significantly improves the overall fuel efficiency of the vehicle.

30

CLAIMS

1. A multi-mode electro-mechanical variable speed transmission comprises a gear system, an input shaft, an output shaft system, a first electric machine, a second electric machine; and at least one torque transfer device;
5 said gear system includes at least one planetary gear set having at least a first co-axial rotatable component, a second co-axial rotatable component, and a third co-axial rotatable component;
 said output system includes at least one drive shaft;
10 said first electric machine connects to the first co-axial rotatable component of the at least one planetary gear set with a constant speed ratio;
 said output system connects to the second co-axial rotatable component of the at least one planetary gear set with a constant speed ratio;
 said input shaft connects to the third co-axial rotatable component of
15 the at least one planetary gear set with a constant speed ratio;
 said second electric machine connects selectively through said at least one torque transfer device to one of the co-axial component of the at least one planetary gear set with a first constant speed ratio, and to another co-axial component of the at least one planetary gear set with a second constant speed ratio, wherein the first and second constant speed ratios are different.
20
2. The multi-mode electro-mechanical variable speed transmission according to Claim 1 wherein the second electric machine selectively couples in a direct connection to one of the co-axial rotatable components of the at least one planetary gear set with a first constant speed ratio, and in an indirect connection through another planetary gear set to another co-axial rotatable component of the at least one planetary gear set with a second constant speed ratio; the first and second constant speed ratio are different.
25
3. The multi-mode electro-mechanical variable speed transmission according to Claim 2 wherein said at least one planetary gear set is a four-branch planetary gear set having a first co-axial rotatable component, a second co-axial rotatable component, a third co-axial rotatable component and a fourth co-axial rotatable component; the second electric machine selectively couples in a direct connection to the fourth co-axial rotatable component of the four-branch planetary gear set with a first constant speed ratio, and in an indirect connection through another planetary gear set to the second co-axial rotatable component of the four-branch planetary gear set with a second speed ratio; wherein the first and second constant speed ratio are different.
30
35
4. The multi-mode electro-mechanical variable speed transmission according to Claim 3 wherein the transmission further include a first stationary member; said another planetary gear set is a three-branch planetary gear set having a first, a second and a third co-axial rotatable components; the first co-axial rotatable component of the three-branch planetary gear set couples to the first
40

stationary member; the second co-axial rotatable component of the three-branch planetary gear set couples to the second co-axial rotatable component of the four-branch planetary gear set; the second electric machine selectively couples to the third co-axial rotatable component of the three-branch planetary gear set and to the fourth co-axial rotatable component of the four-branch planetary gear set.

5. The multi-mode electro-mechanical variable speed transmission according to Claim 4 wherein the transmission further include a second torque transfer device and a second stationary member; the second torque transfer device conditionally couples the input shaft and the third co-axial rotatable component of the four-branch planetary gear set to the second stationary member.
6. The multi-mode electro-mechanical variable speed transmission according to Claim 5 wherein the transmission further include a third torque transfer device and a third stationary member; the third torque transfer device selectively couples the fourth co-axial rotatable component of the four-branch planetary gear set to the third stationary member.
7. The multi-mode electro-mechanical variable speed transmission according to Claim 5 wherein the first torque transfer device is a dog-clutch having at least two engagement positions; the second torque transfer device is a one-way clutch capable of providing reaction torque to said at least one planetary gear set and preventing input shaft from orating in reverse direction.
8. The multi-mode electro-mechanical variable speed transmission according to Claim 3 wherein: the maximum continuous power rating of said electric machines is P_{em} , the maximum power at the input shaft is P_{in} ; said four-branch planetary gear set is represented a four-knot lever diagram wherein the inter-distance between the first and third knots measures K_b units, the inter-distance between the second and third knots measures K_a units, the inter-distance between the third and the fourth knots is a unit; the characteristic parameters of the four-branch planetary gear system K_a , K_b satisfy following relationship:

$$\frac{K_b(K_a + 1)}{K_b - K_a} \leq \left(\frac{1 + \frac{P_{em}}{P_{in}}}{1 - \frac{P_{em}}{P_{in}}} \right)^2 .$$

9. The multi-mode electro-mechanical variable speed transmission according to Claim 8 wherein: said another planetary gear set is three-branch planetary gear set and is represented by a three-knot lever diagram; the inter-distance

between the first and second knots measures one unit; the inter-distance between the second and third knots measures K_s units; the characteristic parameter of the three-branch planetary gear set K_s and the characteristic parameters of the four-branch planetary gear set K_a and K_b closely satisfy one of the following relationships:

$$K_s = \frac{K_a + 1}{K_b - K_a};$$

$$K_s = K_b.$$

10. The multi-mode electro-mechanical variable speed transmission according to Claim 2 wherein said at least one planetary gear set and said another planetary gear set are co-axially aligned and positioned adjacent to each other along the axial direction.

11. The multi-mode electro-mechanical variable speed transmission according to Claim 9 wherein: the characteristic parameters of the four-branch planetary gear set K_a and K_b satisfy following relationships,

$$\frac{K_b(K_a + 1)}{K_b - K_a} \leq 2.75;$$

$$K_b \leq 2.$$

12. The multi-mode electro-mechanical variable speed transmission according to Claim 1 wherein said at least one torque transfer device has at least four engagement positions; said engagement positions are aligned adjacent to each other along an axial direction.

13. A method of designing, producing and operating the multi-mode electro-mechanical variable speed transmission includes:

design and produce a gear system having a first and a second planetary gear sets, each of the said planetary gear sets includes at least a first, a second and a third co-axial rotatable components;

design and produce an input shaft, an output system, a first electric machine, a second electric machine, a first stationary member and a first torque transfer device;

couple the first co-axial rotatable component of the first planetary gear set to the first stationary member;

couple the second co-axial rotatable component of the first planetary gear set to the second co-axial rotatable component of the second planetary gear set;

couple the first co-axial rotatable component of the second planetary gear set to the first electric machine;

couple the first second co-axial rotatable component of the second planetary set to the output system;

couple the third co-axial rotatable component of the second planetary set to the input shaft;

5 couple the second electric machine selectively through the first torque device to a co-axial component of the first planetary gear set and to a co-axial rotatable component of the second planetary gear set;

operate said multi-mode electro-mechanical variable speed transmission in at least two different power split modes based on a predetermined speed ratio of the two co-axial rotatable components of the second planetary gear set that connect to the output system and the input shaft, respectively.

14. The method of designing, producing and operating the multi-mode electro-mechanical variable speed transmission according to Claim 13 wherein: said first planetary gear set is represented by a first lever diagram having at least three knots, the inter-distance between the first and second knots measured one unit, the inter-distance between the second and third knots measures K_s units; said second planetary gear set is represented by a second lever diagram having at least four knots; the inter-distance between the first and third knots measures K_b units, the inter-distance between the second and the third knots measures K_a units, the inter-distance between the third and fourth knots measures one unit; said predetermined speed ratio SR_b is the input to output speed ratio of the gear system and is determined as

$$SR_b = \frac{K_a + 1}{K_a(K_s + 1) + 1}.$$

25 15. The method of designing, producing and operating the multi-mode electro-mechanical variable speed transmission according to Claim 13 wherein: said first planetary gear set is represented by a first lever diagram having at least three knots, the inter-distance between the first and second knots measures one unit, the inter-distance between the second and third knots measures K_{S1} units; said second planetary gear set is represented by a second lever diagram having at least three knots; the inter-distance between the first and second knots measures one unit, the inter-distance between the second and the third knots measures K_{S2} units; said predetermined speed ratio SR_b is the input to output speed ratio of the gear system and is determined as

$$35 \quad SR_b = \frac{1}{1 + K_{S1}}.$$

16. The method of designing, producing and operating the multi-mode electro-mechanical variable speed transmission according to Claim 13 wherein: design and produce the second planetary gear set to include a fourth co-axial rotatable component; couple the second electric machine selectively through

the first torque device to the third co-axial component of the first planetary gear set or to the fourth co-axial rotatable component of the second planetary gear set.

5 17. The method of designing, producing and operating the multi-mode electro-mechanical variable speed transmission according to Claim 13 wherein: couple the second electric machine selectively through the first torque device to the third co-axial component of the first planetary gear set or to the third co-axial rotatable component of the second planetary gear set.

10 18. The method of designing, producing and operating said dual-mode variable speed transmission according to Claim 13 wherein: said method further includes arrange and align the first, second planetary gear sets, the first torque transfer device and along a same axial line of rotation; arrange and align the first and second electric machines along the same axial line of rotation.

15 19. The method of designing, producing and operating said dual-mode variable speed transmission according to Claim 13 wherein: design and produce the first torque transfer device to provide at least four engagement positions arranged adjacent to each other along a axial direction.

20 20. A multi-mode electro-mechanical variable speed transmission is comprised of a gear system, an output system, an input shaft, a first electric machine, a second electric machine, at least one torque transfer device and at least one stationary member;

25 said gear system includes a first and a second planetary gear sets each having at least three co-axial rotatable components; one co-axial rotatable component of the first planetary gear set couples to the stationary member and another co-axial rotatable component of the first planetary gear set couples to a co-axial rotatable component of the second planetary gear set;

said output system includes at least one drive shaft;

30 the first electric machine connects to the first co-axial rotatable component of the second planetary gear set with a constant speed ratio;

the output system connects to the second co-axial rotatable component of the second planetary gear set with a constant speed ratio;

the input shaft connects to the third co-axial rotatable component of the second planetary gear set with a constant speed ratio;

35 the second electric machine connects selectively through the at least one torque transfer device to one co-axial component of the second planetary gear set with a first constant speed ratio, and to another co-axial component of the second planetary gear set via the first planetary gear set with a second constant speed ratio, wherein the first and second constant speed ratios are different.

40 21. The multi-mode electro-mechanical variable speed transmission according to Claim 20 wherein the second planetary gear set includes a first, a second, a

third and a fourth co-axial rotatable components; the first co-axial rotatable component of the first planetary gear set couples to the stationary member and second co-axial rotatable component of the first planetary gear set couples to the second co-axial rotatable component of the second planetary gear set; the second electric machine connects selectively through the at least one torque transfer device to the third co-axial component of the first planetary gear set, and to the fourth co-axial component of the second planetary gear set.

22. The multi-mode electro-mechanical variable speed transmission according to Claim 20 wherein the transmission include a second torque transfer device; said first and second planetary gear sets, said first and second torque transfer devices, and said first and second electric machines are arranged on a same axial line of rotation; the first and second planetary gear set are arranged adjacent to each other along axial direction; the first torque transfer device, and the first and second planetary gear sets are sandwiched between the two electric machines.

23. The multi-mode electro-mechanical variable speed transmission according to Claim 20 wherein said at least one torque transfer device has at least four engagement positions; in the first engagement position, the torque transfer device couples the second electric machine to a co-axial rotatable component of the first planetary gear set; in the second engagement position, the torque transfer device couples the second electric machine to a co-axial rotatable components of the first and second planetary sets; in the third engagement position, the torque transfer device couples the second electric machine to a co-axial component of the second planetary gear set; in the fourth engagement position, the torque transfer device couples the second electric machine to a co-axial component of the second planetary gear set and another stationary member of the transmission.

24. The multi-mode electro-mechanical variable speed transmission according to Claim 20 wherein the transmission is capable of operating under multiple operation modes including two power-split modes and two fixed speed ratio modes, said operation modes are achieved through selective coupling the second electric machine to different co-axial rotatable component or components of the gear system and to stationary member of the transmission.

35

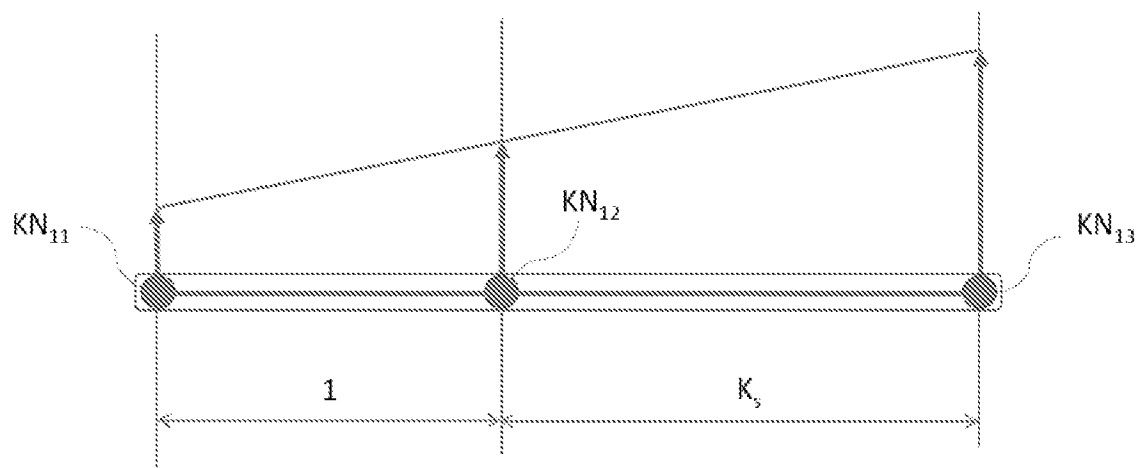


Figure 1

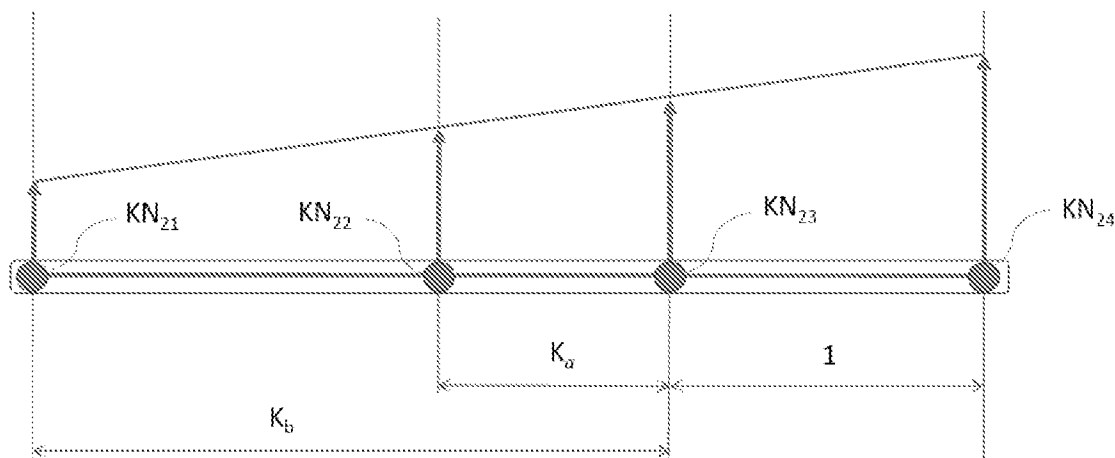


Figure 2

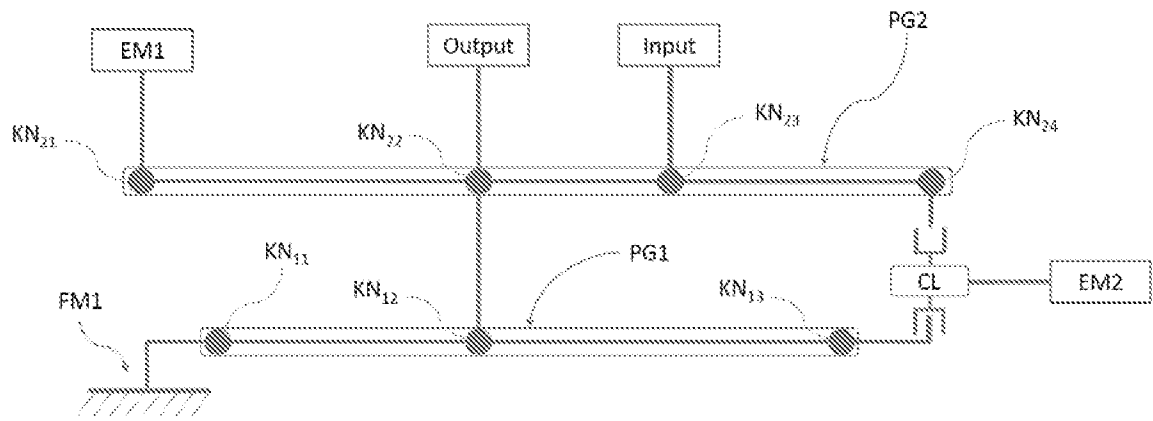


Figure 3

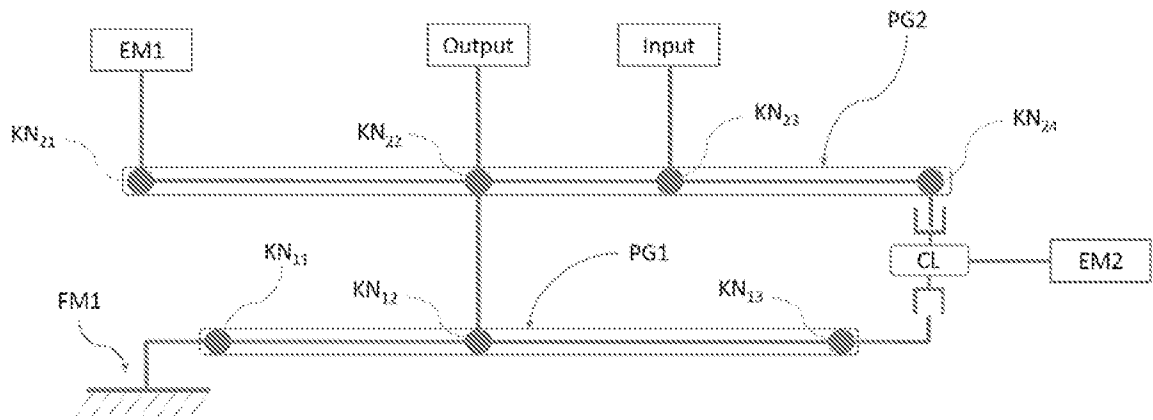


Figure 4

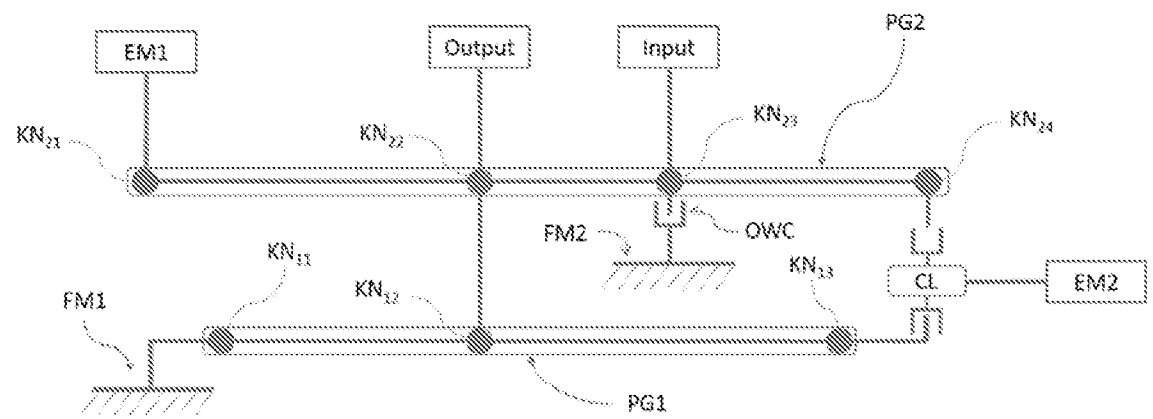


Figure 5

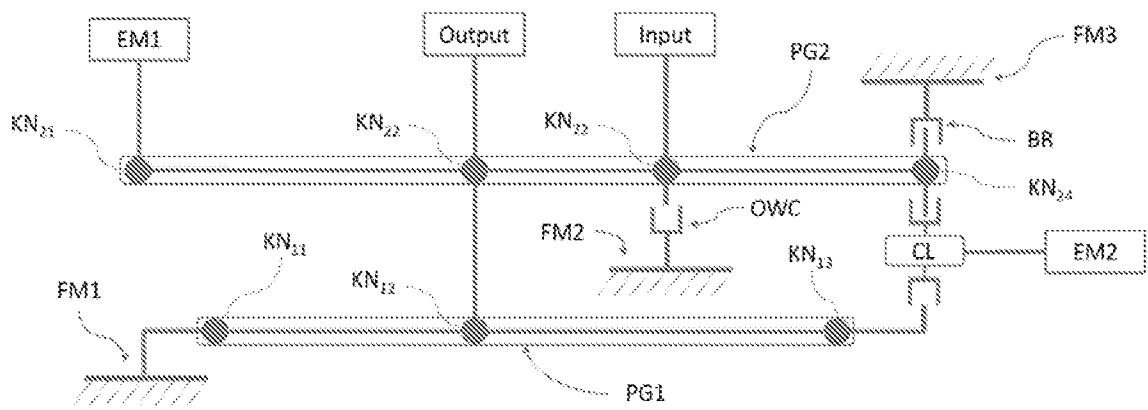


Figure 6

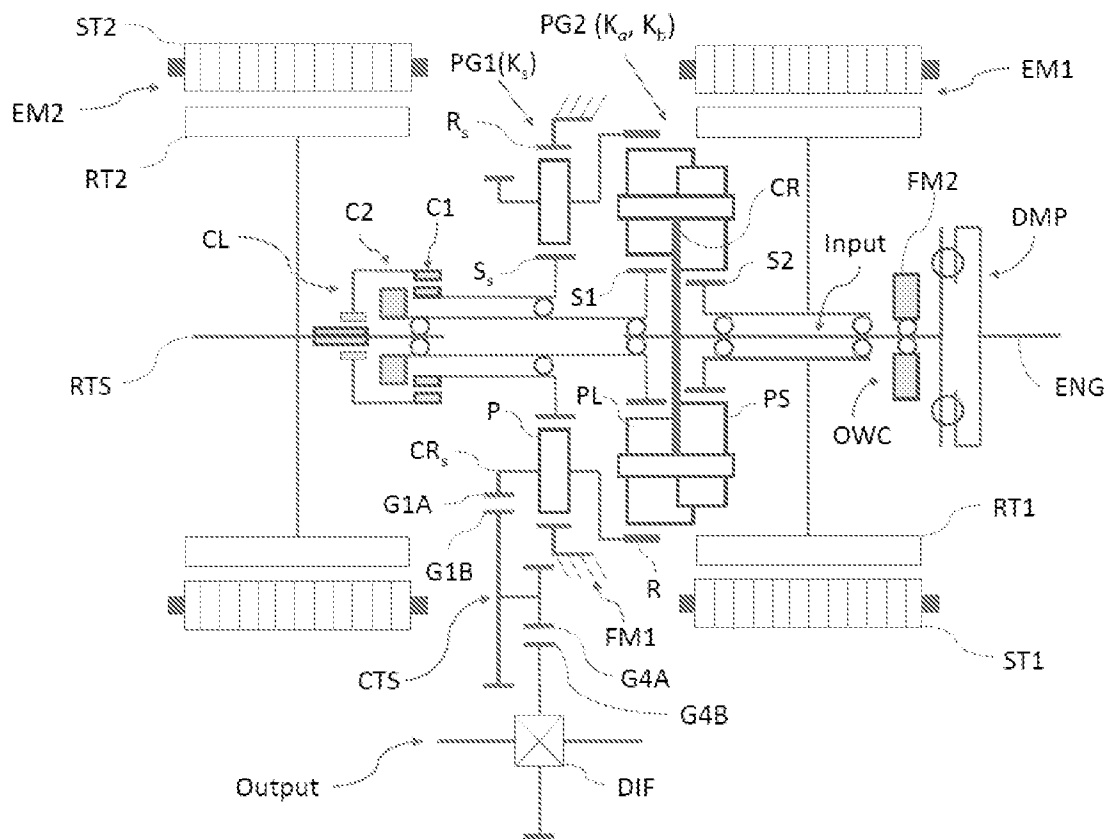


Figure 7

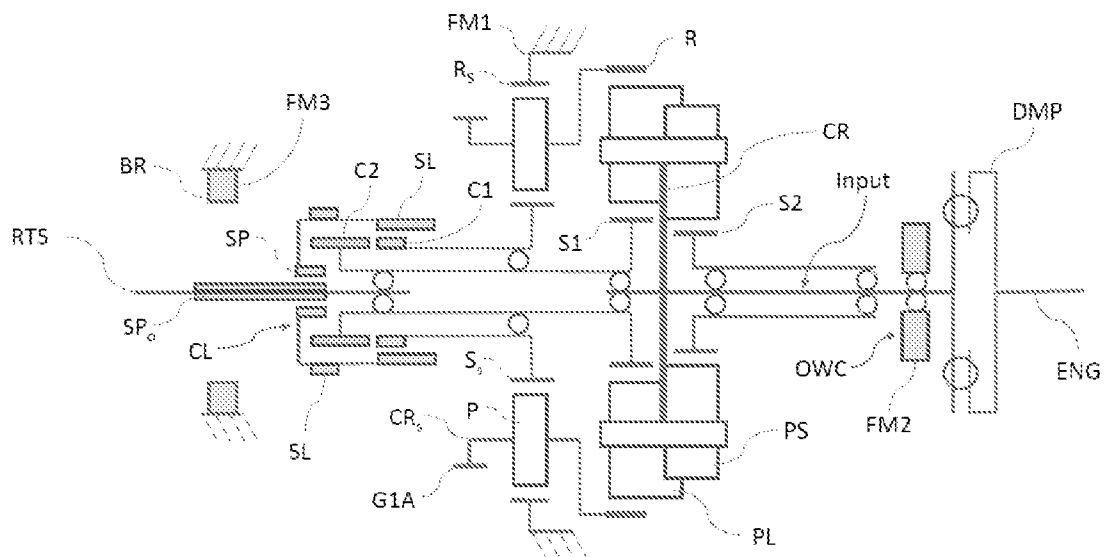


Figure 8

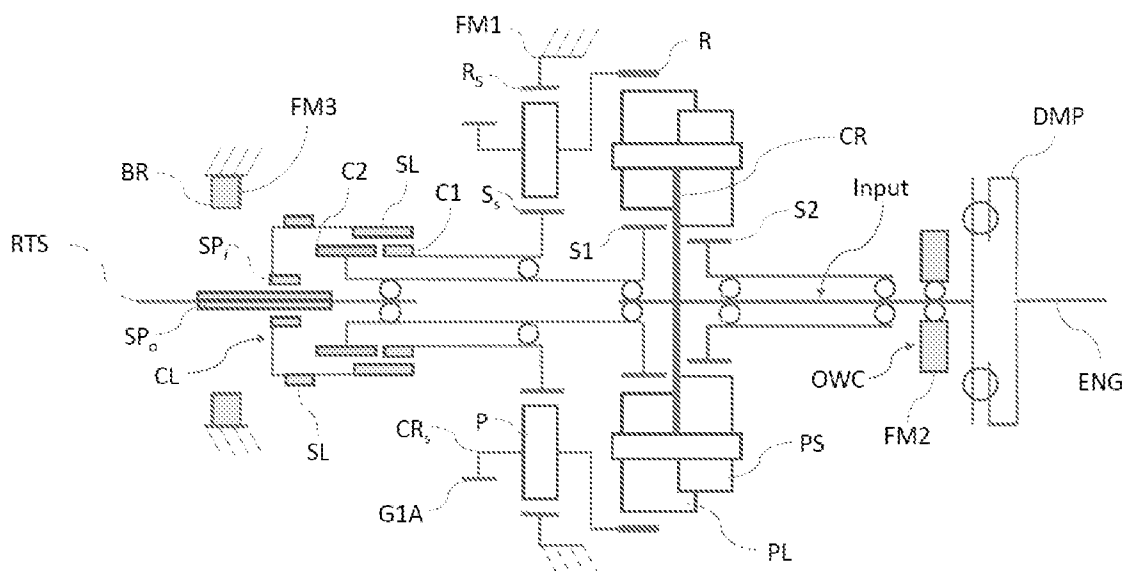


Figure 9

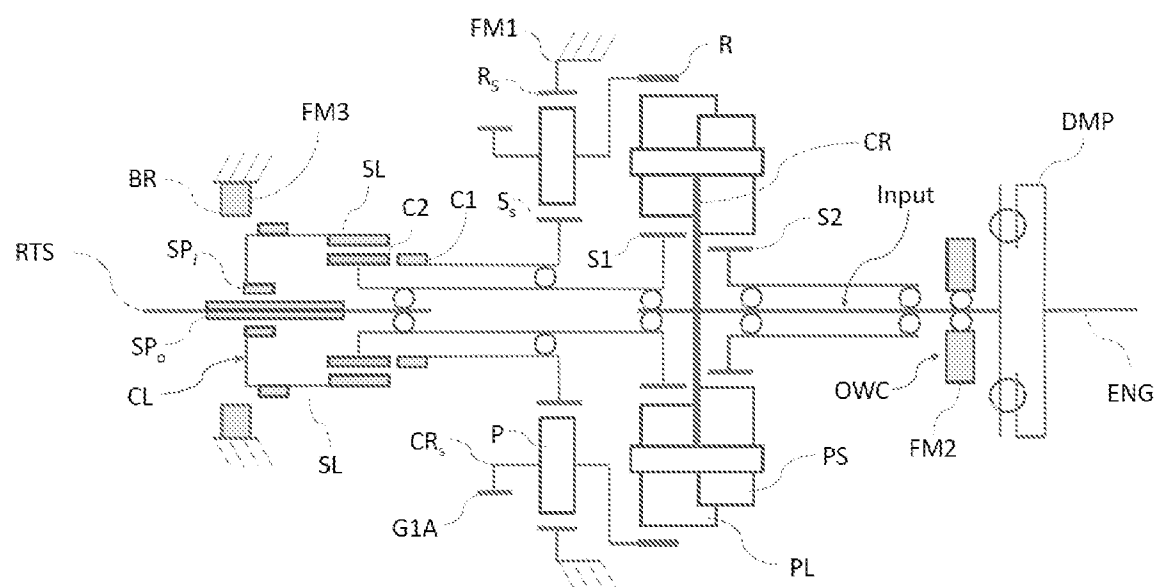


Figure 10

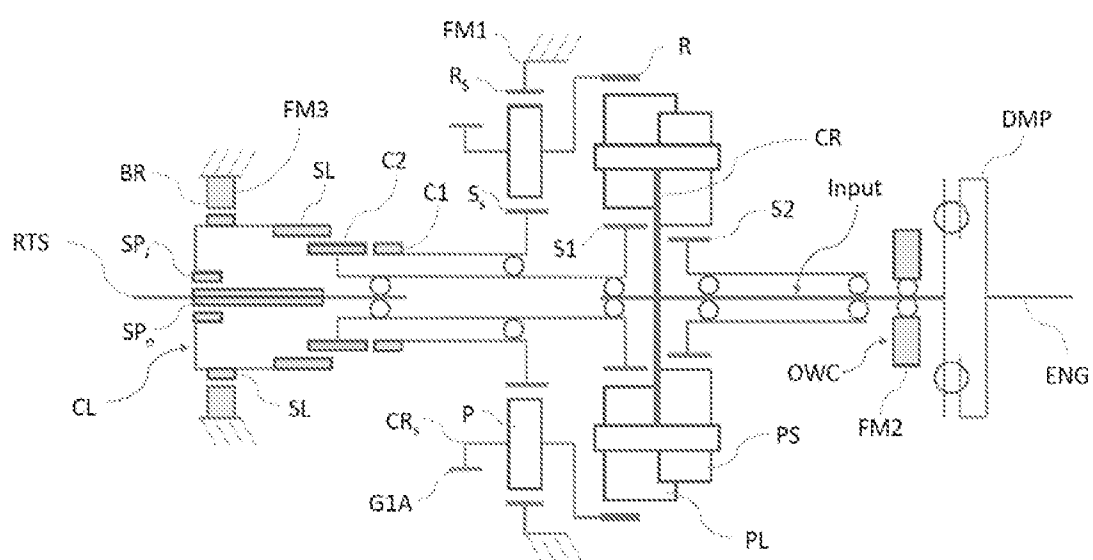


Figure 11

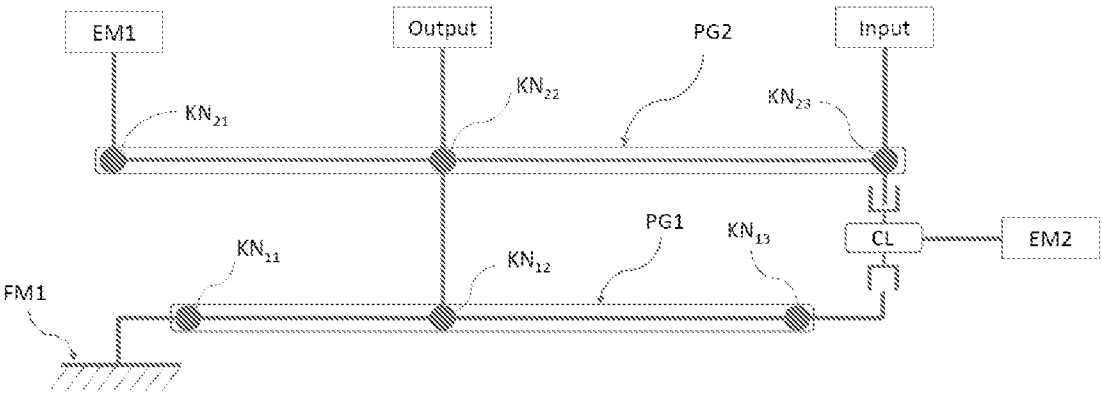


Figure 12

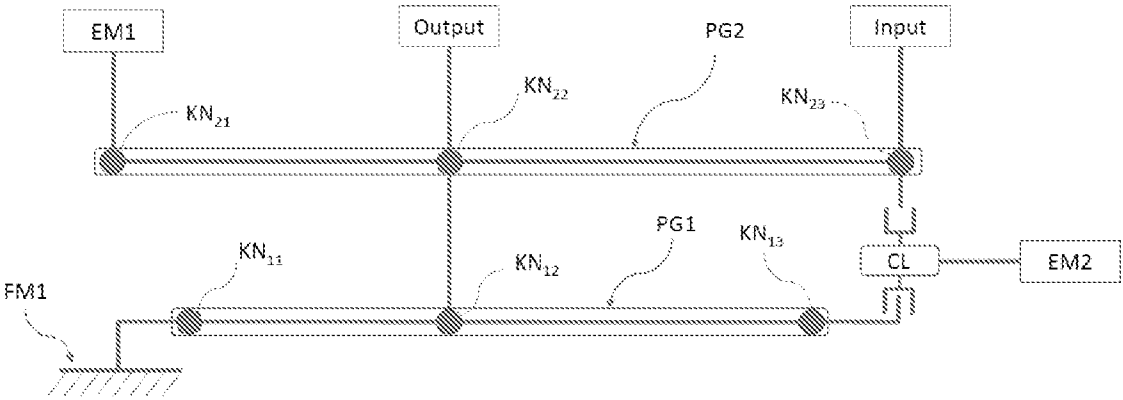


Figure 13

INTERNATIONAL SEARCH REPORT

International application No.

PCT/CN2015/079062

A. CLASSIFICATION OF SUBJECT MATTER

F16H 3/76(2006.01)i

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

F16H;B60K

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

WPI; EPODOC; CNPAT; CNKI; electro mechanical, variable, speed, ratio, planetary, gear, first, second, two, machine?, motor

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2010261565 A1 (AI, XIAOLIN ET AL.) 14 October 2010 (2010-10-14) description, paragraphs 41-51 and figure 4	1
A	CN 102003506 A (GM GLOBAL TECHNOLOGY OPERATIONS, INC.) 06 April 2011 (2011-04-06) the whole document	1-24
A	CN 101004211 A (UNIVERSITY CHONGQING) 25 July 2007 (2007-07-25) the whole document	1-24
A	CN 101386302 A (TOYOTA MOTOR CORP.) 18 March 2009 (2009-03-18) the whole document	1-24
A	JP 2007085436 A (TOYOTA MOTOR CORP.) 05 April 2007 (2007-04-05) the whole document	1-24
A	JP 2004125047 A (AISIN AI CO., LTD.) 22 April 2004 (2004-04-22) the whole document	1-24

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents:

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“O” document referring to an oral disclosure, use, exhibition or other means

“P” document published prior to the international filing date but later than the priority date claimed

“T” later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

“X” document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

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“&” document member of the same patent family

Date of the actual completion of the international search

28 December 2015

Date of mailing of the international search report

26 January 2016

Name and mailing address of the ISA/CN

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INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/CN2015/079062

Patent document cited in search report			Publication date (day/month/year)	Patent family member(s)	Publication date (day/month/year)
US	2010261565	A1	14 October 2010	US 8734281 B2	27 May 2014
				CN 101451596 B	11 January 2012
				CN 101451596 A	10 June 2009
				US 9108624 B2	18 August 2015
				US 2014221153 A1	07 August 2014
				WO 2009079917 A1	02 July 2009
				US 2015292600 A1	15 October 2015
CN	102003506	A	06 April 2011	US 2011053724 A1	03 March 2011
				US 8226515 B2	24 July 2012
				CN 102003506 B	02 July 2014
				DE 102010034832 A1	25 August 2011
CN	101004211	A	25 July 2007	CN 100476253 C	08 April 2009
CN	101386302	A	18 March 2009	US 8370034 B2	05 February 2013
				DE 102008041924 A1	23 April 2009
				CN 101386302 B	09 May 2012
				JP 2009067257 A	02 April 2009
				US 2009076693 A1	19 March 2009
				JP 4957475 B2	20 June 2012
JP	2007085436	A	05 April 2007	None	
JP	2004125047	A	22 April 2004	None	