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Electro-mechanical Differentials for Reduction of Self-generated Wind-up Torques in DBW AWD Propulsion Mechatronic Control Systems

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Abstract

This paper deals with the concept of ‘*passive*’ and ‘*active*’ electromechanical (E-M) differentials in automotive mechatronics, in particular, for reduction of ‘*self-generated wind-up torques*’ in drive-by-wire (DBW) all-wheel-drive (AWD) propulsion mechatronic control systems. Self-generated wind-up torques are created by differing dynamic wheel-tire diameters, kinetic slip between front-wheel-drive (FWD) and rear-wheel-drive (RWD) units during cornering and kinetic slip between the driven wheels or steered, motorized and/or generatorized wheels (SM&GW) of one FWD or RWD unit. However, dissimilar transmission ratios for FWD and RWD units of a rigid DBW AWD propulsion mechatronic control systems, which also could create high self-generated wind-up torques, are usually not selected. The self-generated wind-up torques emerging in the DBW AWD propulsion mechatronic control system can only be reduced by power that linearly increases with the wheel angular speed. This power loss, in fact, cannot be utilized as tractive power for the all-terrain (on/off-road) all-electric vehicles (AEV), that is, battery electric vehicles (BEV) and fuel cell electric vehicles (FCEV) as well as hybrid-electric vehicles (HEV). The generated power loss increases the electrical energy economy and/or specific fuel consumption (SFC), the wear and tear (W&T) of all DBW AWD propulsion mechatronic control system components, and the wheel-tire wear. Under extreme circumstances, over heating and overload can significantly moderate the fatigue life and lead to an early failure of all DBW AWD propulsion mechatronic control system components.

Keywords: battery electric vehicle, fuel cell electric vehicle, hybrid-electric vehicle, differential, generator, motor

1 Introduction

The application for full-time/part-time **drive-by-wire (DBW) all-wheel-driven (AWD)** propelled **all-electric vehicles (AEV)**, i.e., **battery electric vehicles (BEV)** and **fuel cell electric vehicles (FCEV)** as well as **hybrid-electric vehicles (HEV)** may grow rapidly over the next few years. This is due to in-creasing demand for AEVs and/or HEVs with higher performance and power. Benefits of AEVs and/or HEVs are not limited to environmental impact benefits. The attractiveness of AEVs and/or HEVs may be increased if the most remarkable advantage of AEV’s or

HEV’s is applied: **electromechanical/mechanoelectrical (E-M/M-E)** motors/generators can control the generated torque or voltage, respectively, with a better and precise dynamic performance, when compared with **external combustion engines (ECE)** or **internal combustion engines (ICE)**. This major capability of electric drives can be applied in the control of the effective traction force applied between wheel-tire and on/off road surface. The AEV or HEV stability and safety can be improved, allowing a better performance in limit conditions when compared with conventional automotive vehicles.

Recently, nearly everyone automotive vehicles present **traction control systems (TCS)** combin-

ed and/or **antilock braking systems** (ABS) or **electronic stability program** (ESP).

TCSs systems are designed to prevent spinning of driven wheels when an excessive throttle is applied.

For now, ABSs are included in order to assure that driven wheels do not lock in braking actions. When it is detected that a wheel will lock, ABS reduces the **fluidomechanical brake** (FMB) pressure or **electromechanical brake** (EMB) voltage, respectively, allowing the wheel angular velocity return to the slip level range necessary for near-optimum braking performance.

TCSs and/or ESPs are fundamental in order to improve the vehicle steerability and stability and to reduce stopping distances. However, they are expensive and bulky and, sometimes, the performance is not the expected. These ABS and/or TCS as well as ESP objectives can be implemented in AEV's or HEV's in a much more easier and adapted way. The natural ability of electric drives to control the generated torque and the introduction of an independent control of the traction wheel drives (two and/or four) can allow an high-performance traction control with a low cost, quick response and easy to design implementation. An automotive vehicle topology like the proposed one allows a much more simplified mechanical structure of the vehicle and an effective traction control may allow to reduce the energy consumption, namely by diminishing energy losses from the friction between the wheel-tires and the on/off road surface during sliding, improving the wheel-tires lifetime.

In reference [1] the author shows that with two wheel drives and two separate conventional or in-wheel-hub E-M/M-E motors/generators it is possible to eliminate the **mechano-mechanical** (M-M) differential and implement an **electro-mechanical** (E-M) differential.

With an assumption of difference between the adhesion coefficients on the left and right side of the automotive vehicle, it is necessary to sense the real values of the wheel angular velocity and the real value of the vehicle velocity in both sides, in order to analyze the possible sliding of the automotive vehicle. With the acquisition of these values, the torque in each driven wheel or **steered, motorized and/or generatorized wheel** (SM&GW) could be controlled, making possible the steerability and stability of the automotive vehicle. This is the task of the traction control algorithm to be introduced.

It is well known that the distribution of gross tractive effort (thrust) and slip between the front and rear driven wheels or SM&GWs of full-

time/part-time DBW AWD AEVs or HEVs has considerable effect on the efficiency of operation.

A conventional M-M **four-wheel driven** (4WD) automotive vehicle has numerous disadvantages in contrast to an M-M **two-wheel-driven** (2WD) automotive vehicle its **specific fuel consumption** (SFC) is poorer, it is heavier, due to the presence of the driveshaft and other components, and it also requires a floor tunnel for the driveshaft to pass through.

The attractiveness of DBW AWD automotive vehicles has grown in the last decade. Most automotive vehicle manufacturers have released '*all-terrain*' or '*on/off-road*' automotive vehicles to take advantage of the public's fascination with 4WD propulsion. But it's not just the traditional **sport utility vehicle** (SUV) and 4×4 automotive vehicles that have made a contribution to the growth. Although each automotive vehicle manufacturer tends to use its own name for its chassis systems for branding reasons, the author is generally able to divide DBW AWD propulsion mechatronic control systems into three basic groups.

- ❖ Full-time DBW AWD propulsion;
- ❖ Part-time DBW AWD propulsion.;
- ❖ Full-time/part-time DBW AWD Propulsion.

Full-time DBW AWD propulsion mechatronic control system operates as the name suggests.

At all times torque is supplied to all driven wheels or SM&GWs, all of the time.

The **human and/or telerobotic-driver** (H&TD) usually has several options available to them that affect the operation of this mechatronic control system depending on the conditions that are encountered.

In normal operation (such as driving on a bitumen asphalt on-road surface) the **front-wheel drive** (FWD) and **rear-wheel drive** (RWD) units are split by an **electro-mechanical** (E-M) differential, which allows them to operate at different values of the wheel angular velocity when required - for example, when cornering.

In most automotive vehicles there may be the option of '*diff lock*'. This locks up the centre **inter-wheel-drive** (IWD) E-M differential and restricts any rotational difference between the FWD and RWD driven wheels or SM&GWs. It's a feature that is commonly utilized when off-roading to gain maximum traction. There may also be the option of '*low range*'. Most of the time, it is utilized in extreme off-road surface conditions and on steep inclines, this reduces values of the wheel velocity to provide at constant power a torque multiplying effect.

Summing up, full-time DBW AWD propulsion mechatronic control systems operate off-road and on.

They use planetary or bevel gear M-M differentials or even E-M differentials to allow wheel slip on tight turns on dry pavement. Large and heavy with M-M differentials, they lost favor during the oil embargo of the 1970s.

Part-time DBW AWD propulsion mechatronic control system, for example, is the original DBW 4WD propulsion and the most basic. As with full time DBW 4WD propulsion there are several options available to the H&TD.

In normal conditions the automotive vehicle is driven in DBW 2WD propulsion, usually powering only the FWD or RWD driven wheels or SM&GWs.

Part-time DBW 4WD propulsion mode may be selected either by an electronically controlled changeover switch.

When part-time DBW 4WD is selected, torque is split evenly between the four driven wheels or SM&GWs. Part time DBW 4WD vehicles tend not to have centre IWD E-M differentials between the FWD and RWD units. This limits the use of part time DBW 4WD to off-road use because use of this feature on bitumen asphalt surfaces (where wheel-tires have good traction) may cause excess stress and damage to the drivetrain, termed '*self-generated wind-up*'.

This paper deals with the concept of '*passive*' and '*semi-active*' and/or '*active*' E-M differentials, in particular, for suppression of so-termed '*self-generated wind-up torques*' in full-time/part-time DBW AWD propulsion mechatronic control systems. Self-generated wind-up torques are created by differing dynamic wheel-tire diameters, kinetic slip between FWD and RWD units during cornering and kinetic slip between the driven wheels or SM &GW of one FWD or RWD unit. However, dissimilar transmission ratios for FWD and RWD units of a rigid DBW AWD propulsion mechatronic control systems, which also could create high self-generated wind-up torques, are usually not select-ed. Most part-time DBW 4WD vehicles have the option of '*low range*' for extreme off-road conditions.

Part-time DBW AWD propulsion is in some ways similar to the full-time DBW 4WD propulsion in that it also sends torque to all four driven wheels or SM&GWs constantly. These mechatronic control systems never have the option to operate in DBW 2WD propulsion, and unlike the DBW 4WD propulsion, the centre IWD E-M differential between the FWD and RWD cannot be locked. The E-M differentials do, however,

have ability to limit slippage between the FWD and RWD units if a low traction situation is encountered.

Full-time DBW AWD systems also lack the '*low range*' feature that is common in most part-time DBW 4WD propulsions.

Summing up, part time DBW 4WD propulsion mechatronic control systems operate in DBW 4WD propulsion when they're off-road and DBW 2WD propulsion drive on the highway. Since gaining popularity on military vehicles in World War II, they have appeared in many configurations.

Part-time DBW 4WD propulsion mechatronic control systems are lighter and offer better overall kilometerage (mileage), but generate undesirable wind-up torque effects on dry pavement if left in the DBW 4WD propulsion mode.

The best of both worlds, namely full-time/part-time mechatronic control systems incorporate E-M differentials, but typically must be manually shifted from 4WD to 2WD propulsion.

Active wind-up torque-reduction system (AWTS) is one of the first automatic full-time/part-time DBW 4WD propulsion to use mechatronic control and no passive M-M and/or E-M differentials.

2 DBW 4WD hybrid-electric vehicle

DBW AWD vehicles tend to be more '*vehicle*' like than obvious off-roaders. Accordingly, it may be decided to utilize E-M DBW 4WD automotive vehicle to optimise (minimize) these disadvantages and to ensure adequate DBW 4WD performance in actual driving, for instance, as an AEV and/or HEV shown in Figure 1.

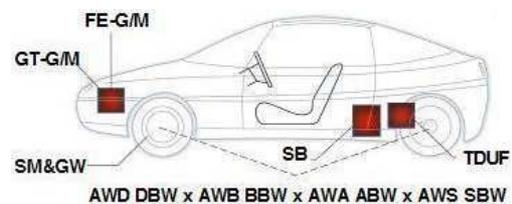


Figure 1: Series HE transmission arrangement for the high performance, all-round energy-efficient, HEV termed the *Poly-Supercar*

The high-performance, all round energy-efficient, mechatronically-controlled tri-mode HEV termed the *Poly-Supercar*, shown in Figure 1, may be an advanced ultra-light hybrid that means it may be electrically-powered by a high-density

mechanical energy-storing high-angular-velocity **twin-disc ultraflywheel** (TDUF) pack that may be backed up by **primary energy sources** (PES), a small hydrogen (metal-hydrate) combustion automotive **gas turbine-generator/motor** (GT-G/M) that is based on the **Fijalkowski turbine boosting** (FTB) system, or the **Fijalkowski engine-generator/motor** (FE-G/M) and electrified highway or powered roadway designed to extend the HEV's range.

The two SM&GW on each side of the HEV's hull wheeled-unit may have an independent **absorb-by-wire** (ABW) **four-wheel-absorbed** (4WA) suspension.

The two front SM&GWs and the two rear SM&GWs are driven and/or absorbed individually by four DC-AC/AC-DC macrocommutator **interior permanent magnet** (IPM) magneto-electrically-excited in-wheel-hub motors/generators, respectively, and angular velocity of each SM&GW may be arbitrarily controlled by driver-vehicle and terrain-vehicle real time expert system, incorporating mathematical model following **fuzzy-logic** (FL) programmable and **neural-network** (NN) learning motion mechatronic control of an HEV [1].

Using E-M differential's torque and/or angular velocity controls of the outer SM&GWs as well as current and/or voltage controls of the inner SM&GWs can increase the lateral motion control effect especially at recuperating braking with the inner SM&GWs acting as the AC-DC macrocommutator in-wheel-hub generators, because the front gravitational forces on the HEVs become greater than the respective rear ones. At the same creep, this leads to greater horizontal (longitudinal and lateral) forces.

The experimental proof-of-concept DBW AWD propulsion mechatronic control systems utilized on AEVs or HEVs satisfy nearly all the same essential requirements as for the running gear systems utilized on conventional automotive vehicles, namely:

- ❖ To apply an E-M DBW AWD propulsion mechatronic control system to a complete number of SM&GWs;
- ❖ To allow the outer side of the curve a positive propelling (driving) torque and at the inner side – a negative dispelling (braking) torque, achieving their maximum value for pivot skid steering;
- ❖ To occupy the minimum volume within the space envelope of the AEV or HEV;
- ❖ To distribute the mass of the AEV or HEV over relatively spacious ground surface or soil area.

The requirements first may contribute to the very good soft soil performance of HEVs. The feature third may tend to conflict with requirements first.

The **artificial intelligence** (AI) **central processing unit** (CPU) corrects the steering position needed to balance the off-centre thrust during SM&GWs are actuated during braking and/or cornering. An HE DBW 4WD propulsion function, with or without locked FWD and RWD as well as IWD E-M differentials can be selected through the H&TD. The DBW 4WD propulsion mechatronic control system's AI CPU selects these modes automatically if the SM&GWs are spinning during acceleration or locked during braking.

3 Steered, motorized and/or generatorized wheel (SM&GW)

The circular shape of in-wheel-hub E-M/M-E motor/generator is not extraordinary, but the main parts are reversed. As a rule a conventional E-M/M-E motor/generator consists of a ring-shaped part that does not move, termed an outside stator, through which an armature current runs, developing magnetic forces that turn the shaft that runs inside it, the inside rotor.

For years, automotive scientists and engineers have discussed construction an E-M/M-E motor/generator in which the shaft (inside stator) is fixed and the ring (outside rotor) turns.

If the shaft (inside stator) were to serve as an axle, and the ring (outside rotor) were to have a wheel-tire attached, the result would be in-wheel-hub E-M/M-E motors/generators that serve as electric wheels, termed SM&GWs (see Fig. 2).

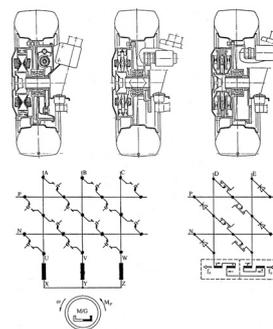


Figure 2: Principle layouts of three dissimilar independent-sprung, planetary gearless, SM&GWs with rotary DC-AC/AC-DC macrocommutator (unwound outer rotor and wound inner stator) in-wheel-hub E-M/M-E motors/generators and tubular linear DC-DC macrocommutator drum-, disc- or ring-brake actuator E-M motors

Such an arrangement would have only one moving part, and would eliminate the parts of the drivetrain, which transfers power from the prime mover to the driven wheels.

For instance, it would eliminate the M-M differential, gears that allow an automotive vehicle's wheels to turn at slightly different values of the wheel angular velocity when cornering.

With an in-wheel-hub E-M/M-E motor/generator on each SM&GW, values of the wheel angular velocity or the armature voltage, respectively, could be independently controlled.

Electric wheels, so-termed SM&GWs would also be a simple way of making an automotive vehicle with the full-time/part-time DBW 4WD propulsion mechatronic control system. And if one SM&GW started to slip in acceleration or braking, a CPU could determine that far faster than existing TCS or ABS as well as ESP.

Those benefits could be approximated by any automotive vehicle that used one E-M/M-E motor/generator for each SM&GW. But the SM&GW goes two steps further. First, it squeezes into the SM&GW a macroelectronic commutator termed the DC-AC/AC-DC macro-commutator that is acting as inverter/rectifier, which changes the **direct current** (DC) from the CH-E/E-CH storage battery into **alternating current** (AC) for supplying the E-M motor, and vice-versa changes the AC from the M-E generator into DC for charging the CH-E/E-CH storage battery.

Converting the current elsewhere in the automotive vehicle would require running long AC cables to the E-M/M-E motor/generator.

Running DC cables from the CH-E/E-CH storage battery or TDUF to the SM&GW and converting the power there to AC increases efficiency.

In addition, some mechatronic procedures can make the E-M motors turn at values of the vehicle velocity fast enough to run the automotive vehicle without gears. The result is to drop the gearbox, a source of mass and friction.

Unlike automotive vehicles with **external combustion engine** (ECE) or **internal combustion engines** (ICE), most AEVs and/or HEVs do not require variable transmissions, but sometimes they do necessitate a gearbox of some kind.

4 Full-time/part-time DBW 4WD propulsion

Principle layout of a **hybrid-electric** (HE) transmission arrangement for the aforementioned HE

DBW 4WD propulsion mechatronic control system is shown in Figure 3.

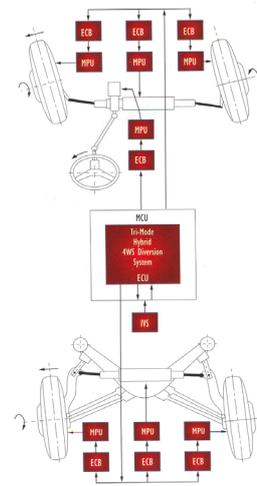


Figure 3: Principle layout of an HE transmission arrangement for the HE 2WD and/or 4WD DBW propulsion mechatronic control system

While the basic principles of the E-M transmission arrangements for the DBW 2WD and/or 4WD propulsion mechatronic control system remain the same for virtually all categories of HEVs, the actual arrangements vary – for instance, some may have DBW 2WD propulsion, that is either FWD or RWD, and other DBW 4WD propulsion.

Another requirement for the DBW 4WD propulsion stems from the fact that, when the HEV is cornering, the outer driven wheels or SM&GWs must roll faster than the inner ones that may be traversing circles of smaller radii, yet their mean value of the wheel angular velocity, and mean value of the vehicle velocity, may be required to remain constant.

So far as effectiveness of traction is concerned, FWD is better than RWD, especially on difficult terrain including ice or snow. This is partly because the mass of the CH-E/E-CH storage battery on the front driven wheels or SM&GWs enables them to grip the on/off-road surface better that also apply to rear CH-E/E-CH storage battery's RWD HEVs.

Principally, however, the advantage is gained by virtue of the fact that the propulsive force, that is, tractive effort is always delivered along the line in which the front driven wheels or SM&GWs are steered. Another factor is that front SM&GWs tend so climb out of holes or ruts, whereas rear driven wheels or SM&GWs tend to thrust the front undriven wheels deeper down and, in any case, not necessarily in the sense of direction in which they are being steered.

5 Passive E-M differentials

In an AEV or HEV, passive E-M differentials are devices, usually consisting of at least two or more series electrically wiring-connected conventional or in-wheel-hub E-M/M-E motors/generators, for supplying equal torque to the driving conventional wheels or SM&GWs, even as they rotate at dissimilar values of the wheel angular velocity.

In some AEVs or HEVs, torque is simply applied equally to all driven wheels utilizing a simple driveshaft or directly to all SM&GWs. This may operate adequately when traveling in a straight line, but when changing sense of a travel direction the outer driven wheel or SM&GW necessitates traveling farther than the inner driven wheel or SM&GW. Thus, the simple solution may result in the inner driven wheel or SM&GW spinning. For common on/off-road use, such a method would result in too much damage to both the wheel-tire and on/off-road surface.

Passive E-M differentials are naturally composed of series electrically wiring-connected conventional or in-wheel-hub E-M/M-E motors/generators in which their armature windings receives input power, which is transferred to two or more side conventional or in-wheel-hub E-M/M-E motors/generators by means of usually electrical wiring connection with the 'changeover switches'. In an AEV or HEV, the two side electrically wiring connected conventional or in-wheel-hub E-M/M-E motors/generators may be utilized to transfer power to the left and right wheels or SM&GWs. When the AEV or HEV turns a corner, or one of the driven wheels or SM&GWs encounters resistance, the wheel shafts or SM&GW hubs rotate around the side with the most resistance; this rotation propels the other side driven wheel shaft or SM&GW hub with additional values of the wheel angular speed.

The most E-M differential described above, known as a passive E-M differential, suffers from one important problem, however. In an AEV or HEV, if one driven wheel or SM&GW starts to slip while the other continues traction, the slipping driven wheel or SM&GW may receive most of the power. This means that if one driven wheel or SM&GW is spinning on ice while the other is still in contact with the bitumen asphalt road, acceleration of the driven wheel shaft or SM&GW hub may only create the slipping driven wheel or SM&GW to spin faster and very little power may reach the driven wheel or SM&GW with good traction.

Similarly, if one driven wheel or SM&GW is lifted off the ground, nearly all the power may

go to the driven wheel or SM&GW that is off the ground; not a optimistic prospect for on/off-road automotive vehicles. Such a loss of traction is sometimes termed 'diffing out'. E-M differential mechanism has two **degrees of freedom** (DOF), and the state of the mechanism depends on two constraints. In an AEV or HEV, the first constraint is the E-M/M-E motor/generator, and the second is the frictional kinematic chain between the two driven wheels or SM&GWs and the ground. When the two driven wheels or SM&GWs slip on the ground, the second constraint becomes weaker or disappears. The passive E-M differential also becomes undetermined and transmits less or no power. For full-time/part-time DBW 4WD propulsion mechatronic control and recovery of the second constraint, various mechanisms are utilized. One solution is utilizing of the changeover switch for locking centre **inter-wheel drive** (IWD) E-M differential that employs an option for allowing the E-M/M-E motors/generators to be locked by changing over the electrical wiring connection between FWD and RWD units from series to parallel, causing either driven wheels or SM-&GWs to turn at the same value of the wheel angular speed regardless of which has more traction; this is equivalent to removing the centre IWD differential entirely. For instance, a 4WD AEV or HEV may have at least two E-M differentials (one for each pair of driven wheels or SM-&GWs) and possibly a centre IWD E-M differential to apportion power between the FWD and RWD units. HEVs without a centre IWD E-M differential should not be driven on dry, paved roads in AWD propulsion mode, as small differences in values of the angular velocity between the FWD and RWD units of the AEV or HEV create a torque to be applied across the transmission. This phenomenon is known as 'self-generated wind-up' and can create damage to the transmission. On loose on/off road surfaces these differences are absorbed by the slippage of the on/off-road surface. An IWD E-M differential option can also be utilized to give the difference between two input FWD and RWD units. Taken literally AWD means all four driven wheels or SM&GWs can be driven, but there is some ambiguity as to just what 'driven' means. If a centre IWD E-M differential is utilized between the FWD and RWD units then all driven wheels or SM&GWs share equal torque (unless one slips and a centre IWD E-M differential lock takes over).

5.1 Operation of passive E-M differential

The application for full-time/part-time DBW 4WD propelled AEVs or HEVs may grow rapidly over the next few years. This is due to increasing demand for AEVs or HEVs with higher performance and power. It is well known that the distribution of gross tractive effort (thrust) and slip between the front and rear driven wheels or SM&GWs of full-time/part-time DBW 4WD HEVs has considerable effect on the efficiency of operation. The function of a series electrical wiring connection is to transfer the drive electrical energy from the **electrical energy source (EES)** to both the front and/or rear SM&GWs.

The centre IWD E-M differential, in the series electrical wiring connection, is also necessary to distribute the drive equally between the front and/or rear SM&GWs, and to allow for the fact, when the AEV or HEV is driven in a circle, the mean values of the wheel angular velocity of the front SM&GWs are different from those of the rear SM&GWs and therefore the values of the wheel angular velocity of the two FWD and RWD units must differ too. Other factors include different degrees of **wear and tear (W&T)** and, perhaps, different values of the wheel-tire pressure.

Provision is usually made for locking this IWD E-M differential out of operation to improve the performance and reliability of traction when the AEV or HEV is driven on slippery ground.

For HEVs intended mainly for operation on soft ground, the centre IWD E-M differential may be omitted from the drive E-M powertrain line, but some means of disengaging DBW 4WD propulsion, leaving only single pair of SM&GWs to do the driving, is generally provided to utilize if the AEV or HEV is required to operate on metalled roads. As it is well known from the principle of *Ackermann's steer-by-wire (SBW) two-wheel steered (2WS)* conversion mechatronic control systems, the front SM&GWs always tend to roll further than the fixed-geometry rear SM&GWs, because their radius of turn is always larger, a parallel electrical wiring connection (cabling) may be interposed between the EES as well as FWD and RWD units and the IWD E-M differential may be omitted from the drive E-M powertrain line (see Fig. 4).

In practice, this usually takes the form of two separate FWD and RWD units, single on each front and rear SM&GWs on which there are rotary controls that can be locked by the H&TD, but they have to stop and get out doing so.

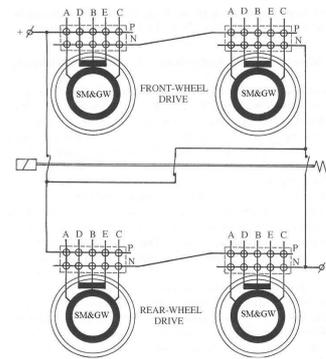


Figure 4: Elementary wiring connection for the full-time/part-time DBW 4WD E-M transmission arrangement with the torque proportioning passive FWD and RWD as well as IWD E-M differentials

As soon as the H&TD again drives the AEV or HEV on the firm ground, however, the H&TD must remember to unlock the FWD and RWD units. Should the rear SM&GWs lose traction, on the other hand, and therefore tend to rotate further than the front ones; the drive may automatically be transferred to the front SM&GWs even if they are in the freewheeling mode.

5.1 Mathematical model of passive E-M differentials

At the start it is assumed that at each driven wheel or SM&GW is affected an equal influence from the external forces and the vehicle mass. If the DC-AC macrocommutator IPM magneto-electrically excited in-wheel-hub motors have the same armature current, the generated torques are the same and also the applied forces or torques to the on/off road surface. In this circumstance the right and left driven wheels or SM&GWs rolls at the same values of the wheel angular velocity and the HEV has a straight trajectory.

On the other hand, if the forces or torques that the right driven wheels or SM&GWs apply to the on/off road surface are different from the forces or torques applied by the left driven wheels or SM&GWs the vehicle trajectory describes a dissimilar one. It is considered that the applied forces or torques to the on/off road surface generated from the left driven wheels or SM&GWs are higher than the applied forces or torques from the right driven wheels or SM&GWs, and the AEV or HEV turn right.

Note that this circumstance may be the consequence of a variation in the steering angle command, but also could appear as the result of dissimilar on/off road surface conditions under the right and left side driven wheels or SM&GWs.

To formulate the mathematical model of passive E-M differential, two successive intervals may be analyzed, namely:

First interval - In this interval the applied wheel forces or torques from each driven wheel or SM&GW are the same ($F_{fl} = F_{fr} = F_{rl} = F_{rr}$).

The resultant forces or torques applied to the AEV or HEV is in the x axis with value $F_x = F$ and in the y axis with value $F_y = 0$.

Second interval - In this circumstance the applied wheel forces or torques at the on/off road surface are dissimilar at the left and right sides ($F_{fl} \neq F_{fr} \neq F_{rl} \neq F_{rr}$), resulting a total force with components in x and y axes. In this interval the left driven wheels or SM&GWs travel a longer distance and the right driven wheels or SM&GWs travel a shorter distance when turn right.

5.1.1 Vehicle absolute resistant force

A vehicle absolute resistant force F_{va} of the AEV or HEV is the sum of the rolling resistance F_{vr} , Stokes force or viscous friction F_{vf} , aerodynamic drag F_{va} and climbing resistance F_{vc} , namely [2]:

$$F_{va} = F_{vr} + F_{vf} + F_{va} + F_{vc} \quad (1)$$

The vehicle rolling resistance

$$F_{vr} = \mu m_v g \text{ sign } v_v \quad (2)$$

where: μ - the rolling resistance coefficient caused by the wheel-tire deformation and contact with the on/off road surface);

m_v - the vehicle mass;

g - the gravitational acceleration constant;

v_v - the vehicle velocity

The adhesion coefficient or friction coefficient may be defined by

$$\mu = \frac{F_w}{\frac{1}{4} m_v g} \quad (3)$$

where F_w - the force that each driven wheel or SM&GW may transmit to the on/off road surface.

In order to give physical meaning to the rolling resistance coefficient, it is necessary to guarantee the circumstance expressed by

$$\mu = \begin{cases} +\mu & \text{if } v_w > v_v \text{ and } v_v > 0 \\ +\mu & \text{if } v_w < v_v \text{ and } v_v < 0 \\ -\mu & \text{if } v_w < v_v \text{ and } v_v > 0 \\ -\mu & \text{if } v_w > v_v \text{ and } v_v < 0 \end{cases} \quad (4)$$

The Stokes force or viscous friction

$$F_{vf} = k_A v_v \quad (5)$$

where: k_A - the Stokes coefficient;

v_v - the vehicle velocity.

The resistance of the air acting upon the vehicle is the aerodynamic drag

$$F_{va} = k_D v_v^2 \quad (6)$$

where k_D - the aerodynamic drag coefficient.

The climbing force (positive) or the downgrade force (negative)

$$F_{vc} = P \sin \delta = m_v g \sin \delta \quad (7)$$

where: P - the vehicle weight force

δ - the steep inclines' angle.

5.1.2 Vehicle velocity

If the left side values of the vehicle velocity \bar{v}_{fl} and \bar{v}_{rl} is equal to the right side values of the vehicle velocity \bar{v}_{fr} and \bar{v}_{rr} , then the vehicle velocity \bar{v}_v may be considered equal to those values of the vehicle velocity.

On the other hand, if the AEV or HEV is describing a circle, the left and right values of the vehicle velocity are dissimilar

$$(\bar{v}_{fl} \neq \bar{v}_{fr} \neq \bar{v}_{rl} \neq \bar{v}_{rr}).$$

Therefore, the vehicle velocity may be considered the average value of both values of the vehicle velocity, namely:

$$\bar{v}_v = \frac{\bar{v}_{fl} + \bar{v}_{fr} + \bar{v}_{rl} + \bar{v}_{rr}}{4} \quad (8)$$

To calculate the left and right side values of the vehicle velocity, it is considered that the vehicle mass is equally distributed on both sides and also the absolute resistant force.

The right side values of the vehicle velocity may be expressed by

$$\bar{F}_{fr} - \frac{\bar{F}_{va}}{4} = \frac{m_v}{4} a_{fr} \Rightarrow a_{fr} = \frac{4}{m_v} \left(\bar{F}_{fr} - \frac{\bar{F}_{va}}{4} \right) \quad (9a)$$

$$\bar{F}_{rr} - \frac{\bar{F}_{va}}{4} = \frac{m_v}{4} a_{rr} \Rightarrow a_{rr} = \frac{4}{m_v} \left(\bar{F}_{rr} - \frac{\bar{F}_{va}}{4} \right) \quad (9b)$$

$$v_{fr} = \int_0^t a_{fr} dt \quad (10a)$$

$$v_{rr} = \int_0^t a_{rr} dt \quad (10b)$$

Similarly for the left side values of the vehicle velocity:

$$\bar{F}_{fl} - \frac{\bar{F}_{va}}{4} = \frac{m_v}{4} a_{fl} \Rightarrow a_{fl} = \frac{4}{m_v} \left(\bar{F}_{fl} - \frac{\bar{F}_{va}}{4} \right) \quad (11a)$$

$$\bar{F}_{rl} - \frac{\bar{F}_{va}}{4} = \frac{m_v}{4} a_{rl} \Rightarrow a_{rl} = \frac{4}{m_v} \left(\bar{F}_{rl} - \frac{\bar{F}_{va}}{4} \right) \quad (11b)$$

$$v_{fl} = \int_0^t a_{fl} dt \quad (12a)$$

$$v_{rl} = \int_0^t a_{rl} dt \quad (12b)$$

5.1.3 Driven wheel or SM&GW dynamics

The mechanical hyposystem equation of dynamics, in the conventional or in-wheel-hub motor referential, used to describe each driven wheel or SM&GW propulsion may be expressed by

$$J_m \frac{d\omega_m}{dt} = \begin{cases} 0 & \Leftrightarrow \omega_m = 0 \\ M_{em} - M_s & \Leftrightarrow \omega_m \geq 0 \end{cases} \quad (13)$$

where: J_m – the moment of inertia of the vehicle from the conventional or in-wheel-hub motor referential;

ω_m – the motor angular velocity;

M_{em} – the electromechanical torque generated by conventional or in-wheel-hub motor;

M_s – the static load torque at the conventional or in-wheel-hub motor referential.

The electromechanical torque generated by conventional or in-wheel-hub motor may be defined by

$$M_{em} = L_{af}^* i_{f0} i_a \quad (14)$$

where: L_{af}^* – the motor rotational coefficient of the mutual-inductance;

i_{f0} – the motor magnetic field current;

i_a – the motor armature current.

The motor rotational coefficient of the mutual-inductance may be defined by

$$L_{af}^* = \frac{\partial L_{af}}{\partial \alpha} \quad (15)$$

where: L_{af} – the motor mutual-inductance;

α – the displacement angle of a carbon collector brushes of the mechano-commutator or the control angle electrical valves of the macrocommutator.

Due to the use of a reduction gear for conventional driven wheel with the respective transmission the following relations for the wheel angular velocity may be defined

$$\omega_w = \frac{\omega_m}{i} \quad (16)$$

where: ω_w – the wheel angular velocity;

i – the transmission ratio;

and the wheel torque may be defined by

$$M_w = M_m i \eta \quad (17)$$

where: M_w – the wheel torque;

η – the transmission efficiency.

The static load torque at the conventional or in-wheel-hub referential is defined by

$$M_s = \frac{M_{rw}}{i} = \frac{R}{i} F_{va} \quad (18)$$

where: M_{rw} – the static load torque at the conventional motor shaft or in-wheel-hub motor;

R – the wheel-tire radius.

Note: For an in-wheel-hub motor the transmission ratio $i = 1$.

The full amount moment of inertia of the AEV or HEV from the conventional or in-wheel-hub motor referential may be defined as a sum of motor shaft or hub inertia, respectively, and the equivalent moment of inertia corresponding to the vehicle mass, namely:

$$J_m = J_w + J_v \quad (19)$$

The driven wheel shaft or SM&GW hub moment of inertia may be defined by

$$J_w = \frac{1}{2} m_w \frac{R^2}{i^2} \quad (20)$$

The equivalent moment of inertia corresponding to the vehicle mass may be defined by

$$J_v = \frac{1}{2} m_v \frac{R^2}{i^2} (1-s) \quad (21)$$

$$= \frac{1}{2} m_v \frac{R^2}{i^2} \left(1 - \left| \frac{v_w - v_v}{\max\{v_w, v_v\}} \right| \right)$$

where: s – the slip, i.e., the relative wheel velocity and vehicle velocity difference.

The slip, i.e., the relative wheel velocity and vehicle velocity difference may be defined by

$$s = \left| \frac{v_w - v_v}{\max\{v_w, v_v\}} \right| \quad (22)$$

The value of the slip depends of the generated motor torque and also of the on/off road surface conditions.

If the adhesion coefficient of the on/off road surface is high then the slip is usually low. If adhesion coefficient may be neglected, the contribution of the vehicle mass to the full amount moment of inertia may be calculated by the following equation:

$$\Delta T_c^* = 0 \Leftrightarrow T_{c\text{input}}^* = T_{c\text{output}}^* \quad (23)$$

$$4 \times \frac{1}{2} J_v \omega_m^2 = \frac{1}{2} m_v v_v^2 \quad (24)$$

$$J_v = \frac{1}{2} m_v \frac{R^2}{i^2} \quad (25)$$

The electrical hyposystem equation of dynamics, in the conventional or in-wheel-hub motor referential, used to describe each driven wheel or SM&GW propulsion may be expressed by

$$L_a \frac{di_a}{dt} + R_a i_a + \Delta u_a \text{sign} i_a + L_{af}^* i_{f0} \omega_m = u_a \quad (26)$$

where: L_{af}^* – the rotational coefficient of the mutual-inductance

L_a – the armature self-inductance;

- R_a – the armature resistance;
 Δu_a – the armature voltage drop on carbon collector brushes of the mechanocommutator or electrical valves of the macrocommutator;
 i_a – the armature current;
 i_{f0} – the exciter magnetic field current;
 ω_m – the motor angular velocity;
 u_a – the armature voltage.

5.1.4 Passive E-M differential for DBW 4WD propulsion

A mathematical model of the passive E-M differential for full-time/part-time DBW 4WD propulsion mechatronic control system may be formulated from the Eq. (26) by multiplying it by (4) four identical driven wheels or SM&GWs, with an assumption of operation at constant value of the motor armature current ($i_a = const$), due to the fact of series wiring connection (see Fig. 4), namely:

$$4 \times (R_a i_a + \Delta u_a \text{sign} i_a + L_{af}^* i_{f0} \omega_m) = 4 \times u_a \quad (27)$$

After substitution to Eq. (25) that

$$4 \omega_m = \omega_{fl} + \omega_{fr} + \omega_{rl} + \omega_{rr} \quad (28)$$

and simple algebraic conversions, the mathematical model of DBW 4WD propulsion with a passive FWD and RWD as well as centre IWD E-M differentials for steady-state may be defined by

$$\omega_{fl} + \omega_{fr} + \omega_{rl} + \omega_{rr} = \frac{u_a - R_a i_a - \Delta u_a \text{sign} i_a}{L_{af}^* i_{f0}} \quad (29)$$

5.1.5 Passive E-M differential for DBW 2WD propulsion

A mathematical model of the passive FWD or RWD E-M differential for DBW 2WD propulsion mechatronic control system may be formulated from the Eq. (26) by multiplying it by (2) two identical driven wheels or SM&GWs, with an assumption of operation at constant value of the motor armature current ($i_a = const$), due to the fact of series wiring connection (see Fig. 4), namely:

$$2 \times (R_a i_a + \Delta u_a \text{sign} i_a + L_{af}^* i_{f0} \omega_m) = 2 \times u_a \quad (30)$$

After substitution to Eq. (26) that:

$$\text{for FWD unit: } 2 \omega_m = \omega_{fl} + \omega_{fr} \quad (31)$$

$$\text{for RWD unit: } 2 \omega_m = \omega_{rl} + \omega_{rr} \quad (32)$$

and simple algebraic conversions, the mathematical model of DBW 4WD propulsion with a passive FWD, RWD and centre IWD E-M differentials for steady-state may be defined

for FWD unit:

$$\omega_{fl} + \omega_{fr} = \frac{u_a - R_a i_a - \Delta u_a \text{sign} i_a}{L_{af}^* i_{f0}} \quad (33)$$

for RWD unit:

$$\omega_{rl} + \omega_{rr} = \frac{u_a - R_a i_a - \Delta u_a \text{sign} i_a}{L_{af}^* i_{f0}} \quad (34)$$

In Figure 7 is illustrated a steady-state characteristic of the wheel angular velocity as a function of the wheel torque for DBW 2WD propulsion with the FWD or RWD differential.

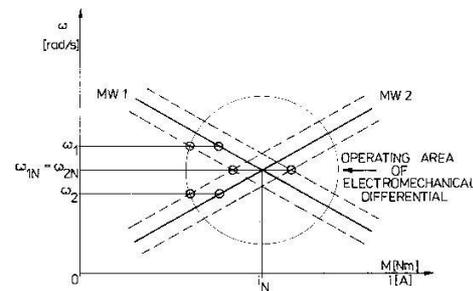


Figure 5: Wheel angular velocity ω vs. wheel torque M for FWD or RWD E-M differential

6 Semi-active and/or active E-M differentials

A relatively new technology is the mechatronically-controlled semi-active or active E-M differential. An on-board CPU utilizes inputs from multiple sensors, including yaw rate, steering angle, and lateral acceleration and adjusts the distribution of torque to compensate for undesirable handling behaviors like understeer.

Semi-active and/or active E-M differentials may be common in the AEVs and HEVs, though they may be applied in coming years. One of the first uses of this technology on an automotive vehicle was an AWTS on the *Poly-Supercar* [1]. This E-M differential was actually equipped with a changeover switch placed next to a FWD E-M differential, not an integrated system. Fully integrated semi-active and/or active E-M differentials may be utilized on the DBW 4WD AEVs and HEVs. The second constraint of the E-M differential is passive – it is actuated by the friction kinematics chain through the ground. The difference in torque on the wheel-tires (caused by turns or bumpy ground) drives the second DOF,

(overcoming the torque of inner friction) to equalize the propulsion torque on the driven wheel-tires. The sensitivity of the E-M differential depends on the inner friction through the second DOF. All of the E-M differentials (so-termed 'semi-active' and/or 'active' as well as 'passive') utilize changeover switches and brakes for restricting the second DOF, so all suffer from the same disadvantage – decreased sensibility to a dynamically changing environment. The sensibility of the on-board CPU mechatronically-controlled E-M differential is also limited by the time delay created by sensors and the response time of the conventional or in-wheel-hub E-M/M-E motors/generators.

6.1 Operation of the semi-active and/or active E-M differential

The self-generated wind-up torques emerging in the full-time/part-time DBW AWD propulsion mechatronic control system can only be reduced by power that linearly increases with the wheel angular velocity. This power loss, in fact, cannot be utilized as tractive power for the all-terrain (on/off-road) AEVs, that is, BEVs and FCEVs as well as HEVs. The generated power loss increases the electrical energy economy and/or SFC, the W&T of all passive DBW AWD propulsion mechatronic control system components, and the wheel-tire wear. Under extreme circumstances, over heating and overload can significantly moderate the fatigue life and lead to an early failure of all DBW AWD propulsion mechatronic control system components.

In comparison, semi-active and/or active full-time/part-time DBW AWD propulsion mechatronic control systems with the AWTSs are much more refined and can provide optimum DBW AWD performance and response under all driving conditions (see Fig. 6).

Furthermore, the active full-time/part-time DBW AWD propulsion mechatronic control system is designed to operate 'in unison' with other security mechatronic control systems such as TCS or ABS as well as ESP. The AWTS is mechatronically-controlled externally by a CPU. The latter utilizes electronic sensor inputs and a microprocessor controller in order to manage the DBW AWD torque transfer. In the case of traction loss or demand for torque, the CPU sends an electric current signal to the microprocessor controller in the AWTS. The microprocessor controller generates an auxiliary input electric current signal that attracts the DC-AC/AC-DC macrocommuta-

tors in the conventional and/or in-wheel-hub E-M/M-E motors/generators and engages them. Based on the available input torque, the torque in the E-M/M-E motors/generators is amplified by means of the armature current increase.

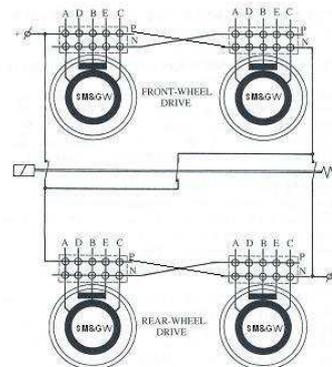


Figure 6: Elementary wiring connection for the full-time/part-time DBW 4WD E-M transmission arrangement with the torque proportioning active FWD and RWD as well as IWD M-E differentials with the active wind-up torque-reduction system (AWTS)

As the next step, it may engage the conventional and/or in-wheel-hub E-M/M-E motors to transmit torque to the RWD unit.

The torque-split FWD (fore) and RWD (aft) needed not be 50 : 50. If it is necessary, the mechatronic control law may be of dissimilar algorithms and apply different rules to their respective output SM&GWs.

For instance, some 4WD rally cars used 40 : 60 or 30 : 70 torque-splits. A centre-IWD E-M differential lock on a full-time DBW 4WD is open to manipulate. If it is engaged on firm road surfaces it can cause SM&GWs' transmission self-generated wind-up torques and rapid wear.

If it is not engaged on loose road surfaces the SM&GWs and changeover switch may over-heat and fail. It is quite strong enough if used correctly. In most cases, AWTS's control strategies predict what the H&TD intentions are and deliver torque transfer before slip or wind-up occurs. The result: an enhancement in vehicle traction, stability and driving comfort. On the motorway, the AWTS automatically reduces power transfer to the RWD wheels or SM&GWs to improve energy economy. Additional inputs to the active DBW AWD propulsion mechatronic control system's CPU such as available conventional and/or in-wheel-hub E-M/M-E motors' torques, lateral acceleration and yaw rates allows the H&TD to exploit the capability of active full-time/part-time DBW AWD propulsion mechatronic control systems even further. These aspects are able to boost the automotive vehicle's capability and predictability.

Furthermore the AWTS hardware can be utilized across multiple applications. Through slight changes to the software, the semi-active and/or active full-time/part-time DBW AWD propulsion mechatronic control system can be adapted to provide performance tuning for an SUV or the stability and traction required for a mini-van.

Summing up, the AWTS is an 'intelligent', semi-active and/or active mechatronic control system that continuously distributes conventional and/or in-wheel-hub E-M/M-E motors' torques between the FWD and RWD units, giving optimum handling, stability and grip in all driving conditions – from fast bends to slower corners, in dry or wet weather.

6.2 Active wind-up torque-suppression system (AWTS)

The AWTS hardware consists of a **power take-off unit** (PTU) in the FWD unit that transmits SM&GWs' torques through wirings to the RWD that includes a **torque transfer device** (TTD) and the optional changeover switch. Both are controlled by the on-board CPU. The TTD is activated as soon as the automotive vehicle is placed in DBW. Rear SM&GWs are applied and ready to transfer torque before acceleration begins. This anticipatory function leap-frogs many advanced technologies that require the detection of wheel slip or driveline rotation before the RWD drive is activated. The enhanced functionality provides maximum traction immediately for smooth, strong acceleration from a standstill without the possibility of any drivetrain hesitation. During driving, torques delivery between the FWD and RWD units is varied by an on-board CPU in the TTD, which increases or reduces the values of the armature voltage on the DC-AC macrocommutator IPM magnetoelectrically-excited in-wheel-hub motors to progressively engage or disengage RWD unit. The degree of slip determines the amount of torque transmitted. The CPU function in unison with the DC-AC macrocommutator IPM magnetoelectrically-excited in-wheel-hub motors/generators, E-M transmission and ABS/ESC control modules.

7 Conclusions

Mounting the in-wheel-hub E-M/M-E motors/generators inside the SM&GWs allows for controlling each SM&GW individually, which improves handling.

It also eradicates the necessity for the M-M differentials and drive shafts and therefore allows for passive, semi-active and active E-M differentials and extraordinary freedom in designing automotive vehicles.

A tenacious disadvantage of SM&GWs with the in-wheel-hub E-M/ M-E motors/generators has been the mass that they add to each wheel, which unfavorably influences comfort and road-holding performance. But advanced technology prevails over this disadvantage by utilizing the E-M/M-E motors/generators to absorb vibration. The E-M/ E-M motors/generators themselves function as vibration shock absorbers (dampers). Their own vibration offsets the vibration from the on/off road surface and wheel-tires, allowing for better traction and a more-comfortable ride than are possible with other in-wheel-hub or electric propulsion systems.

Passive full-time/part-time DBW AWD propulsion mechatronic control systems do not require any external mechatronic control. The passive E-M differential transfers a fixed torque proportionally to the speed difference across the driveline. This inevitably leads to a compromise between traction, driveline '*self-generated wind-up*' and vehicle stability.

The four in-wheel-hub E-M/M-E motors/ generators mechatronically-controlled by AWTS may run as direct drive E-M transmission for smooth running with minimal '*self-generated wind-up torques*'.

References

- [1] B.T. Fijalkowski, Intelligent Automotive Systems: Development in Full-time Chassis Motion Spheres for Intelligent Vehicles. Chapter 5 in the book "*Advanced Vehicle and Infrastructure Systems – Computer Application, Control and Automation* (Ch. Nwagboso, Ed.) Wiley & Sons, Chichester, New York 1997.
- [2] T.D. Gillespie, *Fundamentals of Vehicle Dynamics*, Society of Automotive Engineers, Inc., Warrendale, Pa, 1992.

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