Field Weakening Control of a PM Electric Variable Transmission for HEV

Yuan Cheng***, Alain Bouscayrol†, Rochdi Trigui*, Christophe Espanet** and Shumei Cui***

Abstract – This paper presents the control of a Permanent Magnet Electric Variable Transmission (PM-EVT) for Hybrid Electric Vehicles (HEVs). Consisting of two electric machines, the EVT realizes the power split function in an electromagnetic way rather than in a mechanical way. A specific PM-EVT has been designed for Toyota Prius II. The control scheme of the entire vehicle is deduced using the Energetic Macroscopic Representation methodology. The energy management strategy yields local control references. A specific attention is paid for the field weakening for wide speed range. Simulation results are provided to illustrate the EVT modeling and control.

Keywords: EV and HEV, Electric variable transmission, Synchronous machine, Field weakening

1. Introduction

With an increasing attention to the electric vehicles and hybrid electric vehicles (EVs and HEVs), many novel concepts have been presented to enhance the performance of electric drive [1-5]. The electric variable transmission (EVT) is one of these concepts, which realizes the series-parallel function in an electromagnetic way rather than in a mechanical way. It consists of two concentrically arranged electric machines. By controlling their speed and torque, an such a powertrain enables a continuously variable transmission (CVT), a starter and a generator [6-10].

Due to high efficiencies and power density, the permanent magnet synchronous machines (PMSMs) have already been the primary choice for EV and HEV [11, 12]. Therefore, PMSMs have also been considered to be applied into the EVT concept for performances improvements. In this paper, such an EVT is called PM-EVT in order to distinguish it from other types of EVT.

In previous studies [13-17], different PM-EVT structures have been analyzed. The control of an EVT is a complex task because of the different couplings between both machines. Moreover, for vehicle applications, it is desirable that the electric drive works over a wide speed range [18-20]. In the design process of PM-EVT, steady state operations with field weakening are studied, but mainly for the machine connected to the wheels [7, 9]. A dynamical control using field weakening for a single machine is studied in [21], but no detail is given on the field weakening algorithm and no dynamical results are provided. In order to compare the EVT-based solution with a planetary-gear train solution, a PM-EVT has been specifically designed for Toyota Prius II [22, 23]. A first control scheme has been defined for this new series-parallel HEV using EMR (Energetic Macroscopic Representation) [24]. Indeed, EMR is a graphical description for the control of complex energetic systems [25, 26] and has been successfully applied to different HEVs [27-29].

This paper proposes the dynamical control of PM-EVT for HEV application over a wide speed range. A field weakening control is implemented for both machines. Specific simulations are provided to analyze the field weakening of the EVT. Simulation of the complete vehicle demonstrates the ability of the EVT and its control to be integrated in a vehicle and its energy management.

In Section II, the studied PM-EVT is introduced and the operation modes are discussed. In Section III, the global system modeling using EMR is presented. Then an inversion-based control scheme is deduced from its EMR. Section IV is devoted to the field weakening operation of the EVT and also the energy management of the vehicle. In section V, simulation results on the different EVT modes are presented including field weakening. Simulations of a complete driving cycle are then presented.

2. PM-EVT and Magnetic Interference Analysis

A specific PM-EVT has been designed for Toyota Prius II in order to enable future comparison between the EVT-based and the planetary gear solutions for the same vehicle [23]. A field weakening of both machines of the EVT is required. In that aims, the magnetic interference between
both machines has to be studied especially if independent field weakening is required for the two machines.

2.1 Studied PM-EVT

The studied PM-EVT (Fig. 1) consists of two concentrically arranged PM machines. The outer machine EM2 consists of a stator and the outer part of an outer rotor. The inner machine EM1 consists of an inner rotor and the inner part of an outer rotor. Two layers of permanent magnets are attached on both surfaces of the outer rotor. The inner rotor is connected to the shaft of the internal combustion engine (ICE), and the outer rotor to the final drive gear. Such a PM-EVT has been designed [22] based on the technical specifications of Toyota Prius II [30-32]. The main parameters are given in Table 1.

2.2 Analysis of the speed and torque ranges

Four operation modes have been analyzed in [8]: CVT mode, starter mode, generator mode and pure electric mode. The principle of EVT working in a CVT mode is reviewed in the torque-speed plane [33, 34]. For an optimal consumption, the ICE has to operate in the best consumption area (\(T_{opt}, \Omega_{opt}\)) (*). But the vehicle requires a different operation point at the wheels (\(T_{wh}, \Omega_{wh}\)) (*). Therefore, the EVT needs to provide complementary torque and speed in order to ensure the drive cycle with the best consumption (Fig. 2). As the machine EM1 is connected to the ICE shaft, it will have the same torque in steady state: EM1 can only act to provide a complementary speed. As machine EM2 is connected to the wheel, it has the same rotation speed as the wheels: it can only act to provide a complementary torque. Because the torque of ICE is only positive and the velocity of the vehicle is most

of the time positive, each machine of the EVT has mainly to ensure a two quadrant operation. For example, in Fig. 2.a, EM1 is in motor mode (positive speed and torque) and EM2 is generator mode (positive speed and negative torque).

The studied EVT has been designed in order to replace the planetary gear and the two electrical machines of Toyota Prius II. Thus, the speed and torque ranges of the Prius have been used as technical requirements (Fig. 3). All quadrants are considered symmetrical in the torque-speed plane. The rated speeds of both machines are the same (2000 rpm), but the maximum speeds are quite different (3600 rpm for EM1 and 6500 rpm for EM2). The rated torques have about the same range (120 Nm for EM1 and 100 Nm for EM2). The rated powers are deduced from these requirements (25 kW for EM1 and 21 kW for EM2). Thus the over-speed range of EM2 is nearly twice the one of EM1, so that this second machine will work more often using field weakening. Independent field weakening operations are thus a mandatory feature.

Because of the integrated structure of the EVT, the magnetic coupling between the two machines exists and influences the energetic behavior of the EVT. Moreover, the control of the EVT has to enable an easy and independent field weakening of each machine for operation.
in all the speed ranges, so that it is preferable that the magnetic interferences of the two PM machines can be neglected. This key point is addressed in the next paragraph.

2.3 Analysis of the speed and torque ranges

Due to the fact of sharing a common outer rotor, a magnetic interference could occur between EM1 and EM2. It could affect the EVT performance. In order to evaluate this magnetic interference, a finite element analysis is adopted based on the Flux2D software. Two types of interference are studied. The first one deals with the interference between the two PM fields and the second one deals with the two armature fields.

Firstly, the change of the no-load airgap flux densities with the variation of the magnet relative position is investigated (Fig. 4). It is concluded that, for the designed PM-EVT, the interference has little effect on the inner and outer machines, which can be ignored in the global modeling. When only inner magnets exist, the maximum flux density of the inner airgap $B_{\text{in}}$ is constantly 0.831 T (Fig. 4.a). Comparatively, when inner and outer magnets co-exist, the maximum reduction of $B_{\text{in}}$ is only -2%. The same situation occurs with the outer airgap flux density $B_{\text{out}}$. A detailed analysis is described in [23].

Secondly, the inductance matrix is calculated highlighting the magnetic coupling of the six windings, (i.e. windings of the inner rotor and of the stator, see Fig. 1). The computation has been achieved assuming a linear $B$-$H$ curve, since it is the worst case (magnetic saturation will decrease the magnetic permeability of the iron and then increase the reluctance between the two air-gaps). If we note $\Psi_{\text{in}}$ and $\Psi_{\text{out}}$ respectively the magnetic fluxes of the inner rotor and of the stator, and $i_{\text{in}}$ and $i_{\text{out}}$ respectively the currents of the inner rotor and of the stator, then the inductance matrix is expressed as follows:

$$
\begin{bmatrix}
\Psi_{\text{in}} \\
\Psi_{\text{in2}} \\
\Psi_{\text{in3}} \\
\Psi_{\text{at}} \\
\Psi_{\text{at2}} \\
\Psi_{\text{at3}}
\end{bmatrix} = L_0
\begin{bmatrix}
in \\
-0.24 & 1 & -0.24 & \epsilon_{14} & \epsilon_{15} & \epsilon_{16} \\
-0.24 & -0.24 & 1 & \epsilon_{24} & \epsilon_{25} & \epsilon_{26} \\
-0.24 & 1 & \epsilon_{34} & \epsilon_{35} & \epsilon_{36} & \epsilon_{at3} \\
\epsilon_{14} & \epsilon_{24} & \epsilon_{34} & 0.23 & -0.08 & -0.08 & \epsilon_{at1} \\
\epsilon_{15} & \epsilon_{25} & \epsilon_{35} & -0.08 & 0.23 & -0.08 & \epsilon_{at2} \\
\epsilon_{16} & \epsilon_{26} & \epsilon_{36} & -0.08 & -0.08 & 0.23 & \epsilon_{at3}
\end{bmatrix}
$$

Where $L_0 = 21.4 mH$ and the absolute value of the per unit mutual inductances, $\epsilon_{ij}$, are always lower than $10^{-8}$. From the coefficients of the matrix, the magnetic coupling between the different windings can be neglected.

In conclusion, whatever the operations of the two machines (no-load or full load, field weakening or not…), it is assumed that the two machines are totally magnetically decoupled. Independent models can thus be considered.

3. EMR and Inversion-based Control

Independent magnetic modeling of both machine can thus be considered for the studied PM-EVT. This drive is described using EMR and integrated in a complete vehicle description. The control of the EVT is deduced from its EMR and is also integrated in the complete vehicle control.

3.1 EMR of the PM-EVT HEV

EMR is a graphical description which highlights energetic properties of complex systems. All elements are connected according to the interaction principle and the scalar product of the action and reaction vectors yields the power exchanged between elements. Moreover, the physical (integral) causality is exclusively used. This property enables a systematic deduction of control schemes.

The EMR of the entire vehicle is depicted in the upper part of Fig. 5. All modeling relationships are given in Table I (left columns). Elements, which store energy like the ICE shaft (1), are described by crossed rectangles (see Appendix). Elements, which distribute energy like the parallel connection of both VSI (Voltage Source Inverters) (2), are described by overlapped squares. Elements, which convert energy without storage and distribution like VSI (3), are described by squares (mono-physical conversion) or circles (multi-physical conversion). More details on the modeling can be found in [24]. In this paper, the mechanical brake is considered and the EMR is organized in another way to better deduce the control scheme. The VSIs are modeled in averaged values, but instantaneous models could also be used [35].

As an example of EMR element, the correspondence with classical block diagram is proposed for the mass of the vehicle (11) in Fig. 6. EMR is more compact and better highlights the action/reaction variables. The EMR of the whole system show the different power flows to propel the vehicle: from the ICE, from the battery through EM1, from the battery through EM2 and from the brake subsystem.

![Fig. 4. $B_{\text{in}}$ and $B_{\text{out}}$ variation with magnet position $\Delta\beta$](image-url)
Table 2. Modeling and control relationships

<table>
<thead>
<tr>
<th>Modeling relationships with ( j \in {1,2} )</th>
<th>Control relationship with ( j \in {1,2} )</th>
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<tbody>
<tr>
<td>( \frac{d}{dt} \Omega_{\text{em}1} = \Omega_{\text{em}1} - \Omega_{\text{em}2} )</td>
<td>( T_{\text{em}1} - \text{ref} = C_{\Omega}(t)(\Omega_{\text{ice} - \text{ref}} - \Omega_{\text{ice} - \text{meas}}) + T_{\text{ice} - \text{meas}} )</td>
</tr>
<tr>
<td>( T_{\text{tot}} = I_{\text{em}1} + I_{\text{em}2} )</td>
<td>no inversion</td>
</tr>
<tr>
<td>( \Omega_{\text{em}1} = \Omega_{\text{em}2} - \Omega_{\text{ice}} )</td>
<td></td>
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<tr>
<td>( L_{\text{em}1} \frac{d}{dt} I_{\text{em}1} = V_{\text{em}1} - E_{\text{em}1} - R_{\text{em}1} I_{\text{em}1} )</td>
<td>( V_{\text{em}1} - \text{ref} = C_{j}(t)(I_{\text{em}1} - \text{ref} - I_{\text{em}1} - \text{meas}) + E_{\text{em}1} - \text{meas} )</td>
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<tr>
<td>( I_{\text{em}1} = P_{\text{em}1} \Omega_{\text{em}1} L_{\text{em}1} )</td>
<td>( I_{\text{em}1} - \text{ref} = \frac{1}{P_{\Omega}} T_{\text{em}1} - \text{ref} )</td>
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<td>( E_{\text{em}1} = P_{\text{em}1} \Omega_{\text{em}1} I_{\text{em}1} )</td>
<td>( I_{\text{em}1} - \text{ref} ) from strategy</td>
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<td>( \Omega_{\text{em}2} = \Omega_{\text{em}2} - \Omega_{\text{em}1} )</td>
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<td>( \frac{d}{dt} \Omega_{\text{em}2} = \Omega_{\text{em}2} - \Omega_{\text{em}1} )</td>
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<tr>
<td>( T_{\text{tot}} = T_{\text{em}1} + T_{\text{em}2} )</td>
<td>( T_{\text{em}2} - \text{ref} = T_{\text{tot} - \text{ref}} - T_{\text{em}1 - \text{ref}} )</td>
</tr>
<tr>
<td>( \Omega_{\text{em}2} = (k_{\text{gear}} / R_{\text{wh}}) \Omega_{\text{em}2} )</td>
<td></td>
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<tr>
<td>( F_{\text{wh}} = \left( k_{\text{gear}} / R_{\text{wh}} \right) \Omega_{\text{tot}} )</td>
<td>( T_{\text{tot} - \text{ref}} = (R_{\text{wh}} / k_{\text{gear}}) F_{\text{wh} - \text{ref}} )</td>
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<tr>
<td>( F_{\text{tot}} = F_{\text{wh}} + F_{\text{hk}} )</td>
<td>( F_{\text{wh} - \text{ref}} = k_{\text{D}} F_{\text{tot} - \text{ref}} )</td>
</tr>
<tr>
<td>( M \frac{d}{dt} \omega_{\text{ev}} = F_{\text{tot}} - F_{\text{res}} )</td>
<td>( F_{\text{tot} - \text{ref}} = C_{\Omega}(t)(\omega_{\text{ev} - \text{ref}} - \omega_{\text{ev} - \text{meas}}) - F_{\text{res} - \text{meas}} )</td>
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</table>
Coupling elements (double squares) are key elements, which split different power flows. From the same power demand of the vehicle, there are thus different possibilities.

### 3.2 Inversion-based control of the PM-EVT HEV

A control scheme can be deduced from the EMR of the system using specific inversion rules. Tuning paths are first deduced. In the PM-EVT HEV, the ICE torque $T_{\text{ice-ref}}$ is directly imposed, the modulation vector of VSI $m_{\text{volt-ref}}$ is used to impose the ICE rotation speed $\Omega_{\text{ ICE}}$ and the modulation vector of VSI 2 $m_{\text{volt2-ref}}$ is used to impose the vehicle speed $v_{\text{veh}}$. If the global control scheme is presented in [24] all the control relationships are now given in this paper (Table II). An accumulation element is inverted by a closed-loop control, such as the ICE shaft (1), which is inverted by (12), where $C_i(t)$ is a controller (P, PI or other kinds), which has to cancel the error between the speed reference $\Omega_{\text{ ICE-ref}}$ and its measurement $\Omega_{\text{ ICE-meas}}$. The distribution elements are inverted using compensation, such as (8) inverted by (18) or distribution criteria, such as the coupling of the wheel and braking forces (10), which is inverted using the distribution coefficient $k_d$ (20) in order to define the part of the mechanical and electrical braking. Other elements are directly inverted such as the wheel (9), which is inverted by (19).

The control scheme deduced by the inversion of the EMR (lower part of Fig. 5) shows the different control operations. It should be noticed that two control parts are defined: one for the velocity control and the second for the ICE speed control. Both parts are coupled by the reference torque $T_{\text{meq-ref}}$ (dashed line), which is provided by the ICE control and is considered as a disturbance by the velocity control. Moreover, some references of both controls have to be provided by a global control level, called strategy or energy management. This strategy level has to define the ICE torque and speed references, but also the $i_d$ current of both EMs and the force distribution when braking.

Despite a unique inversion-based control scheme for the system, there are different possible strategies [35]: several energy managements can be defined using the same control scheme. Moreover, a Maximum Control Structure (MCS) has been obtained by assuming all variables being measurable. Practical control schemes can be deduced from the MCS by simplifications and estimations of non-measured variables, such as estimation of (d,q) e.m.f and currents. But these further steps are not studied in this paper.

### 4. Control strategies

A field weakening strategy is defined to ensure all possible operations of the EVT. In order to implement the EVT and its own control in the studied HEV, simple energy management of the vehicle are then proposed.

#### 4.1 Field weakening strategy

A field weakening strategy is used to enable high rotation speeds when the voltages reach their maximum values. This strategy will thus reduce the machine flux using the $d$ component of the stator current, $i_d$. Because each electrical machine of the EVT are magnetically independent, the field weakening operation can be applied independently on both machines ($j=1$ or 2). Different limitation circles can be plotted depending on the voltage and current constraints:

$$i_{d,j}^2 + i_{q,j}^2 \leq I_{\text{max}}^2$$

$$v_{d,j}^2 + v_{q,j}^2 \leq V_{\text{max}}^2$$

$I_{\text{ max}}$ and $V_{\text{ max}}$ are the maximum current and voltage that inverters and EMs can support. $I_{\text{ max}}$ is determined by the inverter rating and machine thermal rating, and $V_{\text{ max}}$ is constrained by the DC bus voltage and the PWM strategy. We assume both machines have the same limitations.

Assuming steady-state at high speed operation, the voltage on the stator resistance can be ignored. Therefore, from (5) and (6), the voltage limit equation is reduced to (Fig. 7):

$$\left( i_{d,j} + \frac{\phi_{\text{pmj}}}{L_{s,j}} \right)^2 + i_{q,j}^2 \leq \left( \frac{V_{\text{max}}}{p_p \Omega_{\text{meq}} L_{s,j}} \right)^2$$
where $L_{stj}$ and $\phi_{pmj}$ are respectively the stator inductance and the PM flux of EM $j$. The more the rotation speed increases, the more the limitation of current decreases. The maximal voltage is also depending of the PWM strategy and the battery voltage, which can vary during the vehicle operation. For the chosen PWM strategy (classical Space Vector PWM), the maximum voltage in the $(d,q)$ frame relationship is:

$$V_{\text{max}} = \frac{u_{\text{bat-meas}}}{\sqrt{2}}$$ \hspace{1cm} (25)

Thus, the voltage limit circle changes with operation points, especially in the applications of electric vehicles, where the energy source is limited and the motor operation is quite constrained. Therefore, the field weakening control must be considered over all the speed range [37-39].

The machine torque machine (6) depends only on the $q$-axis current because EM1 and EM2 are surface mounted machines without saliency. Thus, when there is no voltage limitation, a maximum-torque-per-ampere (MTPA) strategy can be normally adopted (no current in the $d$-axis). It assures that, for a required torque level, the minimum stator current magnitude is applied.

With the increasing motor speed or current, the back EMF becomes higher. When it reaches the voltage limit, the field weakening must be conducted. For PMSMs, field weakening is implemented by injecting into the stator windings a negative $d$-axis current to counter the PM flux. A simple field weakening algorithm is implemented for both EM1 and EM2 (Fig. 8). The stator voltage magnitude $V_{j\text{ref}}$ is firstly calculated from the $(d,q)$ reference components. The maximum voltage is calculated from the battery voltage measurement (24). If there is no limitation, the $d$-axis current reference is imposed to zero (MTPA operation). If the voltage limitation is active, the $d$-axis current reference is imposed by solving (23):

$$i_{dj-ref} = \frac{V_{j\text{ref}}}{L_{stj}} - \frac{\phi_{pmj}}{P_{pj}}$$ \hspace{1cm} (26)

4.2 Energy management of the entire vehicle

A lot of ICE management strategies have been proposed for series-parallel HEVs [40]. A simple rule-based thermostat strategy is used to validate the control scheme.

The ICE strategy is based on the decision of both ICE ON/OFF state and the ICE operating point. The ON/OFF strategy is detailed as follows:

- ICE ON when the battery SOC gets a minimum value,
- ICE OFF when the SOC gets its maximal value,
- ICE ON when the maximal acceleration is required,
- ICE OFF when a big deceleration happens to maximize the recovery energy.

When the ICE is ON, the optimal ICE torque and speed are imposed to reduce the fuel consumption according to the iso-consumption map. More advanced strategies can be used once the control scheme has been validated.

For braking, the coefficient $k_B$ distributes the mechanical and electrical braking. A simple strategy is considered:

- $k_B = 1$ (electrical braking) when the battery SOC is lower than a maximal value,
- $k_B = 0$ (mechanical braking) when the SOC has reached this maximal value.

It should be noticed that a more complex strategy can be developed taking into account, for example, the limitations of torque of electric machines or braking profile.

5. Simulations and validation

First simulation results are carried out on Matlab/Simulink® using the designed PM-EVT and the parameters of Toyota Prius II [32] (Table 3).

| Table 3. Simulation parameters of Toyota Prius II |
|------------------------------|-----------------|-------------|
| Vehicle weight/kg | 1360 | Battery energy/kWh | 1.3 |
| Rolling radius/m | 0.3 | Battery voltage/V | 2016 |
| Frontal area/m² | 1.746 | Final drive ratio | 4.113 |
| Rolling resistance | 0.0054 | ICE engine/kW | 57 |
| Air friction coeff. | 0.26 | Planetary gear | 2.6(78/30) |

5.1 Simulation of the EVT and its control

Two EMs have been independently controlled. Specific speed and torque profiles are imposed to highlight the different operations, especially field weakening of both machine (Fig. 9). The four operations defined in section II are proposed: each machine is in motor or generator mode.
As described in Fig. 2, the EM1 torque is always positive and its speed could be either positive (motor) or negative (generator). It is the same for the EM2 speed (always positive) and torque. From Fig. 9(c) and Fig. 9(d), we can see that for both EM1 and EM2, without field weakening, the \( i_d \) currents are null. During the field weakening, negative \( i_d \) currents are imposed. The required torques are imposed in consequence of the speed demands (Figs. 9(c) and Fig. 9(d)). For the Interior PM machines (IPM machines), both \( i_d \) and \( i_q \) contribute to the torque.

Due to the same design rated speed, the field weakening happens to EM1 and EM2 when their speeds are greater than 2000 rpm. But in fact, as mentioned in section IV, the field weakening control depends not only on the motor speed, but also on the load conditions and the machine parameters. Due to the ever-changing loads and limited energy supply, the field weakening is activated sometimes when the speed is lower the rated speed 2000 rpm. As an example, the starting point of field weakening for EM2 happens at 1900 rpm (Fig. 9(d)).

Because of the same rated speed, the field weakening of both EMs, starts at the same speed. But due to different designs, the \( i_d \) currents should perform differently -384A for EM2 and -128 A for EM1.

Separate operation modes can be achieved with the proposed inversion-based control for both machines of the EVT. Moreover, independent field weakening are also possible.

### 5.2 Simulation of the entire vehicle

The EVT and its control are now integrated in a complete vehicle simulation. The U.S. Urban Dynamometer Driving Schedule (UDDS) is used with, maximum speed of 91 km/h (Fig. 10(a)).

When the power demand is not high and the battery has enough power, the vehicle operates in a pure EV mode with EM2 as the only propulsion power, such as intervals “A” and “D”. Because the speeds of two EMs are not high, the field weakening is not activated (Fig. 10(j)). Meanwhile, the ICE and EM1 do not work.

With the increasing power demand, the ICE is activated and operates at its optimal curve, such as interval “B”. Both EM1 and EM2 work without the field weakening because of the low speed.

In interval “C”, the vehicle speed reaches up to 91km/h and the EM2 maximum speed reaches 3300 rpm. The field weakening is thus applied and a negative \( i_d \) current is imposed to EM2 But because of its low speed, no field weakening is activated for EM1.

In interval “E”, due to higher speeds for both EM1 and EM2, both field weakening are imposed (Fig. 10(i), Fig. 10(j)).

In this vehicle application, the field weakening is activated during short periods, which results in few supplementary losses due to these operations. But, thanks to field weakening, all operation modes can be ensured without an over-sizing of the battery. The designed EVT is thus well adapted to the Toyota Prius in terms of driving cycles and dynamical performances.

### 6. Conclusion

A PM-EVT has been designed for Toyota Prius II for
future comparisons with the planetary gear solution. Independent operations are required for both machines of the EVT in order to ensure all the operation modes of the vehicle. Because of the specific design, independent field weakening must be ensured by both machines. The magnetic design of the PM-EVT leads to a weak magnetic interference between both machines, which results in an independent control of each machine. A simple weakening strategy has been implanted. A specific simulation of the PM-EVT demonstrates that both EMs can operate independently over their base speed. The simulation of the complete vehicle shows that the EVT control can be easily implemented in the vehicle energy management. The designed EVT is thus able to replace the planetary train solution in the studied driving cycles. More advanced strategies can be now developed and a comparison with the planetary gear solution will be proposed in future works.

Acknowledgements

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References

Appendix: Pictograms of Energetic Macroscopic Representation (EMR)

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<th>Source element (energy source)</th>
<th>Accumulation element (energy storage)</th>
<th>Indirect inversion (closed-loop control)</th>
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<tbody>
<tr>
<td>Mono-physical conversion element</td>
<td>Mono-physical coupling element (energy distribution)</td>
<td>Direct inversion (open-loop control)</td>
</tr>
<tr>
<td>Multi-physical conversion element</td>
<td>Multi-physical coupling element (energy distribution)</td>
<td>Coupling inversion (energy criteria)</td>
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</tbody>
</table>


[30] S. Sasaki. Toyota’s Newly Developed Hybrid Power-


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