Worst-Case Modeling and Simulation of an Automotive Throttle in VHDL-AMS[1]

Anton Pirker-Frühauf
KAI-Kompetenzzentrum
Automobil- und Industrie-
Elektronik GmbH Europastr. 8
A-9524 Villach, Austria
anton.pirker-fruehauf@k-ai.at
and
Institute for Computer Engineer.
Vienna University of Technology

Karsten Schönherr
Robert Bosch GmbH
Gasoline Systems
P.O. Box 300240
D-70442 Stuttgart, Germany

Arnaud Laroche
Georg Pelz
Infineon Technologies AG
Automotive Power
Am Campeon 1-12
D-85579 Neubiberg, Germany

Abstract

This paper details the development of a virtual prototype for an automotive electro-mechanical subsystem – the throttle as used in an engine management function. This is applied to assess the subsystem on a virtual platform, i.e. through simulation. Special emphasis is on the modeling methodology necessary to accomplish sufficient precision and performance at a time. Moreover, the interaction of mechanics, electronics and thermal processes is illustrated. The model is validated by comparison with measurements. Last but not least, it is shown, how worst-case modeling extends the simulation coverage with regard to fabrication-induced component property variations.

1. INTRODUCTION

During the last decade, the development cycle for a new car and its electronics has been dramatically shortened. On the other hand, the respective system complexity has substantially increased. The most promising strategy to cope with these challenges is to assess virtual prototypes, i.e. simulation models, on a simulation workstation. This holds for a point in time, where models of all system components are available, while real prototypes are not. But even if a subsystem can be completely set up on a workbench, simulation still is valuable, as it provides full controllability and observability. On the workbench, observation is at least substantial measurement effort, while in some cases, e.g. transient junction temperature of power MOSFETs, measurement is almost impossible. Even more, worst-case behavior of the spec parameters of electronics and mechanics cannot be evaluated on real prototypes. For instance, it is not possible to assess the influence of the fabrication-induced property variations, e.g. the friction of a mechanical load or the slew rate of power stage. The virtual prototypes open a perspective for these worst-case evaluations, at least if the models support to set certain parameters to minima or maxima, as defined in the component spec.

The paper illustrates the modeling of a complete, automotive electro-mechanical subsystem – a throttle valve – comprising a power bridge, an electric motor, a gearbox and a mechanical load. The model is formulated in VHDL-AMS, which is a suitable description language for electronics, mechanics and many other physical domains. The model is validated through comparison with measurements.

In general, a certain simulation is associated with a respective choice of block model property values. If there is a discrete resistor, we have to select a certain value for its resistance. Unfortunately, there is no single correct value to do so, as we have a minimum and a maximum boundary with a related underlying dispersion to reflect the fabrication tolerances of the resistor. The same holds for many more component-related properties. With a power bridge chip with some protections and diagnostics, we easily end up with some 50 or 100 of these properties. Not all of them will have a major impact, but at least theoretically all of them have a potential impact. Here are some (but certainly not all) of the important parameters that we have to evaluate according to their given bounds:

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Environment	Battery voltage
	Ambient temperature
Power bridge	Slew rate
	On resistance
	Impedance
	Over-current limit
	Over-temperature limit
	Free-wheeling behavior
	…
DC motor	Armature resistance
	Armature inductance
	Torque constant / back EMF constant
	Armature friction
	Armature inertia
	…
Gear	Inertia
	Friction
	…
Mechan. load	Inertia
	Friction
	Position of stop
	…

Now, the required system behavior needs to be guaranteed for any allowed choice of these parameters. Often, the worst case is located at a parameter boundary. In this case, it would be sufficient to simulate all permutations of mix/max choices of parameters. In this way, the above 18 parameters lead to 2^{18}, i.e. more than 260000 simulations. Even worse, some of the above parameters are not one-dimensional, e.g. impedance or free-wheeling behavior, On top, nobody guarantees that the worst case really is located at a parameter boundary!

But there are even further problems to cope with. The models need to support the respective parameters. Think for instance of a gear's wear. The respective slack between the tooth-wheels may play a big role, and if we want to see it in simulation, we would need to put the effect into the respective model. The same holds for the power electronics.

2. ELECTRONICS MODELING

Seen from the electronics angle, the throttle subsystem is mostly determined by the power bridge. Figure 1 shows a typical block diagram of a so-called eGas[2] power bridge. Most prominent are the big MOSFETs of the power stage on the right. Here, the modeling needs to be as precise as possible, because this part determines the interaction between electronics and mechanics and in this way, the overall subsystem behavior. In our case, this means that the modeling of the power stage is set up as close to physics as possible. Special effects like the Miller capacitances definitely are to be taken into account.

On the other hand, the gate drivers, the protection features and the SPI[3] communication can be abstracted to a certain degree, to provide for simulation speed.

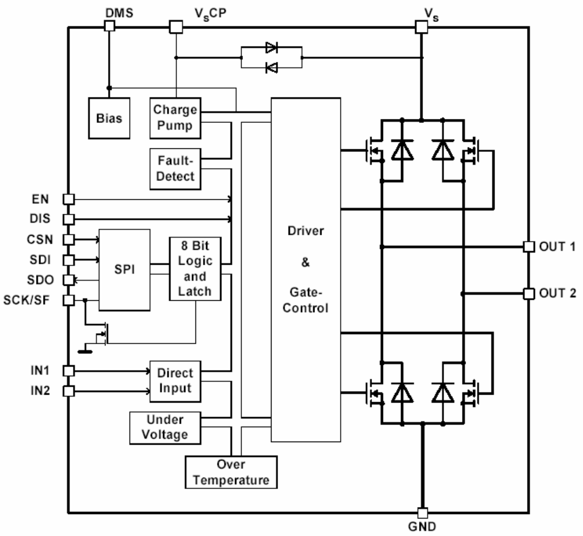

Figure. 1. Block diagram of the power bridge.

Apart from the regular features, some secondary effects have to be taken into account. In our case, this definitely holds for self-heating, as a typical current value of the bridge would be 5A DC. Self-heating has to be evaluated taking into account the thermal paths to the board and beyond, as well as the ambient temperature. Moreover, the thermal sensors for over-temperature shut-off need to be plugged into the thermal network, to ensure that the thermal protection is functional and fast enough to prevent damages.

All modeling up to this point is typical in the sense that all the circuit's properties as defined in the specification happen to be somewhere within the given window. Now let us look on how to set up a model, that for certain parameters can be put to a minimum or maximum. The big difficulty in that is

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[2] eGas: electronic gas/accelerator pedal

[3] SPI: Serial peripheral interface

the correlation between parameters, i.e. we cannot change one parameter without changing others. If behavioral models are physics-based, this is very likely. Basically, the physical equations form a connection between the parameters, e.g. changing the on-resistance of a power MOSFET will have an impact on the resulting slew-rate. On the other hand, in our case the models need to be physics-based – at least for the power stage – to closely reflect the resulting interaction between electronics and mechanics.

Apart from the correlation-induced problems, other worst-case modeling, e.g. setting up over-current or over-temperature thresholds is pretty simple. Here just the respective value has to be brought into the model.

In general, if the respective property directly appears in the model equations, it can be directly set through a generic. If this is not the case, we introduce a dimensionless generic value which can assume values from -1 to 1. Setting this generic to -1 will put the respective property to its minimum, setting it to 1 will put the property to maximum.

3. MECHANICS MODELING

An automotive throttle is a mechanism to control the flow of air into a combustion engine. This in turn enables to control the engine's power output. The mechanical part of a throttle, which is built into today's cars, comprises the following parts: DC-motor, gear, spring and the valve.

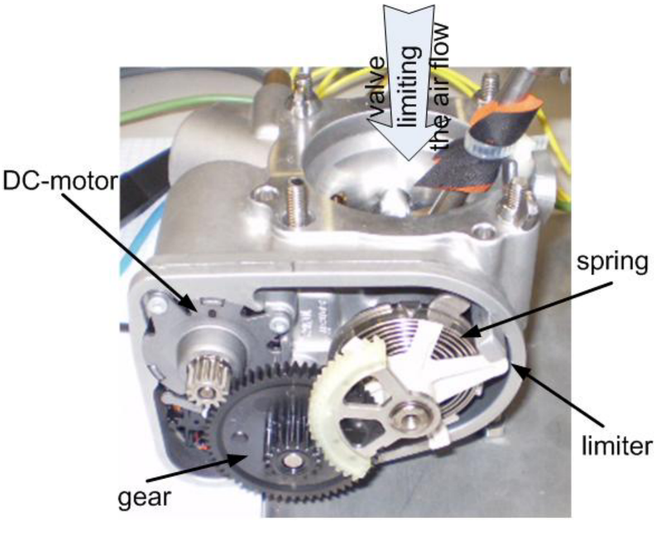

Figure. 2. A typical car throttle.

Apart from the regular functionality, we have to consider some side effects like the friction because the components are not ideal. Furthermore, the stops limit the angular movement to some certain range.

The DC-motor transforms the electrical energy into magnetical and then into mechanical energy. Thus we are talking about an electromechanical device. In the model representation, the motor's electrical and mechanical conservation laws are explicitly formulated in the model's equations.

The torque T depends on the current which is provided at the electrical nodes and the torque constant minus the losses through the movement of the motor. The torque equation for the model,

$$T = -K_T i + D\omega + J\frac{d\omega}{dt}. \qquad (1)$$

describes the net torque production of the motor as the difference between the generated torque ($K_T i$) and the torque losses, $D\omega$ (viscous damping loss) and $Jd\omega/dt$ (internal losses). Similarly, the electrical equation for the model,

$$V = K_E\omega + Ri + L\frac{di}{dt}. \qquad (2)$$

illustrates that the input voltage is equal to the sum of the back-EMF ($K_E\omega$), the motor's winding resistance voltage drop (Ri) and the winding inductance voltage drop (Ldi/dt). Note that $K_T=K_E$ when SI units are used in the motor definition.

In VHDL-AMS, a so-called *entity* describes a component model's interface, while an *architecture* provides for the internal implementation. To attach the external pins of a component model to the internal equations in the architecture descriptions, branch quantities are associated with the terminals. For the DC-motor, there are two electrical quantities in connection to the electrical pins p and n:

Listing 1. Describing the electrical flow

```
quantity v across i through p to n;
```

The quantity *i* is a through branch quantity, representing the current into p and out of n, while the quantity *v* provides for the voltage across these pins. As we are just dealing with the analog system behavior in our model, we restrict ourselves to simultaneous statements in the architecture. The simultaneous statements express explicit differential and algebraic equations, which describe the values of the analog quantities of the model. The continuously varying values represent the analog behavior of the system. For example, the first simultaneous statement after the *begin* keyword relates the value of the quantity *w* to the value of the quantity *theta*. VHDL-AMS provides a number of predefined attributes of quantities. These attributes together with simultaneous statements of various forms, are the most important features of VHDL-AMS for behavioral analog and mixed-signal modeling. For a given quantity *theta*, the attribute *'dot* is the derivative with respect to time. The following Listing shows the VHDL-AMS DC-motor model.

Listing 2. DC-motor model.

```
begin
   w == theta'dot;
   torque == -1.0*kt*i + d*w + j*w'dot;
   v == kt*w + i*r_wind + l_wind*i'dot;
end architecture behav;
```

4. SIMULATION

All parts of the throttle are described by a model in the VHDL-AMS language and are linked as objects to a whole system which is shown in following figure.

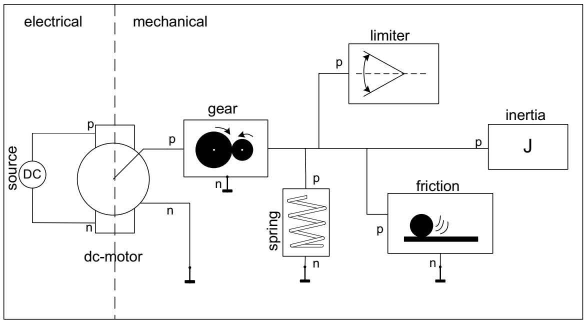

Figure. 3. Throttle model components.

For the input of the throttle model, we used an ideal electrical source. The figure 4 shows the current flowing through the DC-motor which corresponds to the step response after applying a certain voltage. In other words: at start-up as well as at a stop, the back-EMF is zero, which results in high currents.

Figure. 4. Current flow of DC-motor.

According to the simulation results the valve reaches the maximum opening after 110ms and the limiter prevents further rotation.

Comparing the simulation with the measurement results, figure 5 shows a reasonable correlation between the simulation and the measurement. The small deviations can be explained as follows: the oscillation on the step response of the measured curve arises from the commutation of the DC-motor. As the motor rotates the internal resistance of the brush/winding complex is varying. This is also the reason for the offset when the valve is fully open. The motor stops at an unknown position which in turn holds for the commutator and thus the resistance may differ from the measured one. Looking at the section where the limiter comes into play, it is noticing almost no damping, which explains the big oscillation. All in all, the compared results are well suited.

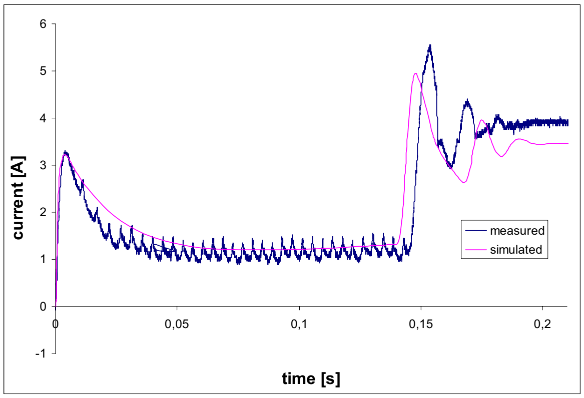

Figure. 5. Simulation and measurement results.

In Figure 6, we give some simulation results for worst-case simulations. It shows throttle displacement (over its full range from stop to stop) vs. time and gives a pretty good idea on the sensitivity of the results in the light of environmental and component property variations. The upper three curves show the dependence on supply voltage. The three curves in the middle illustrate the impact of temperature (only modeled for the power circuit). Finally, the bottom curves were accomplished for varying the torque constant by ±20%.

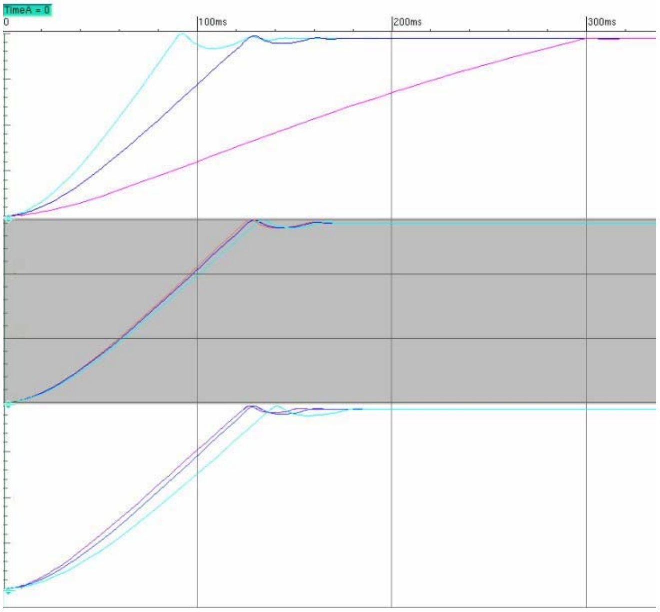

Figure. 6. Best / typical / worst case simulations;
throttle displacement (full range from stop to stop) vs. time
top: battery voltage = 18 V / 13 V / 8 V
medium: temperature = -40°C / 25°C / 150°C
bottom: torque constant kt= kt+20% / kt / kt-20%

5. CONCLUSION

The paper details the modeling and simulation of an automotive, electro-mechanical subsystem – the throttle – which is of prevalent importance for the engine management. It details, how this virtual prototype can be used to assess this subsystem with a substantially reduced number of experiments on a real workbench, which are costly and limited in scope. A special emphasis is on worst-case considerations on the basis of the above behavioral models.

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