

Modeling and Simulation for Green and Renewable Energy

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Abstract

This paper focuses on the use of Modeling and Simulation in the design and verification process for Renewable and Green Energy. First the role of electrical energy is discussed and second samples are given where modeling and simulation can be applied. Samples include wind and solar power, Hybrid Electrical Vehicles (HEV) and Fuel Cell simulations.

Introduction

Green Energy will effect the quality of our life in the near future. With limited fossil energy resources available, it is only a matter of time when we will change our focus on renewable and clean green energy.

There are many discussions going on about the type of energy storage and transportation. The two main candidates for storage and transportation are hydrogen and electricity. Since electrical energy is the most practical to generate and transport, it is favored over hydrogen. However storage of electrical energy is more difficult and requires other physical means for storage. For high energy levels, water storage on different altitudes is a proven technology. For automotive and mobile applications, batteries, super capacitors, or mechanical flywheels become more practical. Fuel cells for automotive applications and even for small mobile apparatus are in development.

A combination of efficient energy storage in the form of hydrogen and generation of electricity by fuel cells seems to be the most promising alternative to fossil energy resources. However the practical question remains, where do we get the power to produce H₂

Focus of the paper

The main focus is on electrical energy is during generation and transport. Storage is required for peak shaving and automotive and mobile applications. In this paper we will focus on the generation, transport, storage and control of electrical energy. Samples are given for high power and automotive applications as well as for low power levels such as White Led drivers. The focus is directed towards applications applying renewable and green energy for generation, transport, storage and use.

What is Green Energy?

Every now and then, new buzzwords start to appear and this is also true for electrical engineering. The term Green Energy can be associated with environment-friendly generation, transport, storage and use of energy. If we compare the use of electrical energy for railway

applications with a steam locomotive, the advantage of electrical energy for preserving the environment is evident. However, where is this electrical energy produced? You can not simply get it like other natural energy resources like coal or oil. Remember that burning coal, oil and methane produces a substantial part of the electrical energy that we use today. And we are not so fond of nuclear power, mainly to its waste problem! These are all fossil energy resources that are not part of our definition of Green Energy. Solar power, wind power, and the natural flow of water are resources that comply with our definition of Green Energy. Since the natural fossil energy resources are limited on this planet, we have to put our focus on green power generation like solar and wind power.

Taking into consideration the environment-friendly character of electrical energy, we can state that at least for transport, storage and use, electrical energy is our favorite. In the next sections we will discuss the generation, transport storage and use of electrical energy.

Generation of electrical energy

If we look at electrical energy, we can state that it is Green Energy, when it comes to transport storage and use. Only the generation of electrical energy with using fossil energy resources such as solar or wind power can be considered Green Energy. Also a Fuel Cell is considered as Green Energy, but remember that somewhere the hydrogen has to be produced.

Transport of electrical energy

Transport of electrical energy seems to be very simple, just use some cables, and the job seems to be done. This seems to be true on short or medium distances, but transporting electrical energy from one continent to another is a major challenge and losses during transport become significant.

Storage of electrical energy

Storage of electrical energy is possible for low power. For example, batteries are common in use, but have serious limitation when it comes to power level, life time, production and pollution due waste. Also the energy density/ weight ratio is far less compared to fossil energy resources. As an example, a liter of gasoline will get you much further than a fully charged battery if 1Kg.

On a larger scale, hydrogen could be stored more easily and could be generated from electrical energy. Storage in the form of mechanical power such as with a flywheel for automotive applications only found serious use in public transport. Super capacitors are a promising component,

but still partly in the development stage. Storage in the form of hydrogen seems to be the most promising candidate for the future.

Use of electrical energy

The use of electrical energy is straightforward and well accepted. There are exceptions in certain areas, for example such automotive, aeronautics, space exploration, industrial heating and welding and heating of buildings, where due to storage and the high power level requirements, electrical energy is not very practical.

Solar Power

Solar Power seems to be the most efficient way of generating energy from the sun, but the production of solar cells is expensive and environment-unfriendly. Furthermore, the efficiency of the solar cell is low. In this sample the non-linear characteristic of the solar cell is simulated, showing the current dependency of the output voltage. The solar cell is a current source up to its nominal power. As soon as the maximum power is reached, the current drops to lower levels. In this sample, current levels up to 3A are possible, up to 120 Watt.

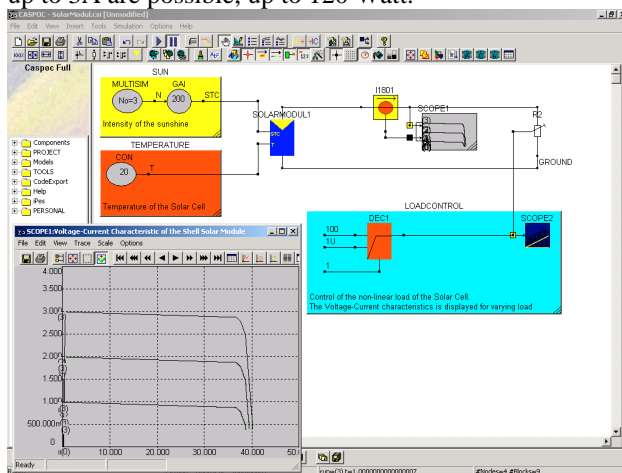


Figure 1: Solar Cell characteristics.

Wind Power

Wind Power is very popular nowadays, because of the high power that can be achieved in an efficient way. If we model the energy produced by wind power, we have to model all components in the system. First the wind turbine has to be modeled, including the mechanical drive train, such as shafts, gearboxes and bearings. Second the electrical machine, mostly a synchronous machine, is modeled in detail and connected to a model of the power electronics, such as AC-DC or back to back converters (AC-DC-AC with variable frequency). The control of the wind turbine needs special attention. The pitch control is important, since the efficiency is greatly influenced by the pitch of the rotor blades. In the simulation shown in figure 2, the wind power is converted into electrical energy by a synchronous generator and rectifier. The scope shows the DC link voltage and the load current. The Synchronous

generator is modeled by using a detailed two-phase model in the stator reference frame (1).

$$\frac{d}{dt}i_d = \frac{1}{L_d}v_d - \frac{R}{L_d}i_d + \frac{L_q}{L_d}p\omega_r i_q$$

$$\frac{d}{dt}i_q = \frac{1}{L_q}v_q - \frac{R}{L_q}i_q - \frac{L_d}{L_q}p\omega_r i_d - \frac{\lambda p\omega_r}{L_q}$$

$$T_e = 1.5p[\lambda i_q + (L_d - L_q)i_d i_q] \quad (1)$$

where (all quantities in the rotor reference frame are referred to the stator)

- L_q, L_d q and d axis inductance's
- R Resistance of the stator windings
- i_q, i_d q and d axis currents
- v_q, v_d q and d axis voltages
- ω_r Angular velocity of the rotor
- λ Amplitude of the flux induced by the permanent magnets of the rotor in the stator phases
- p Number of pole pairs
- T_e Electromagnetic torque

The power electronics is modeled by ideal switch models. Use can be made of dynamic models for the diodes, or models including the reverse recovery effect. The load is modeled by a series RL impedance.

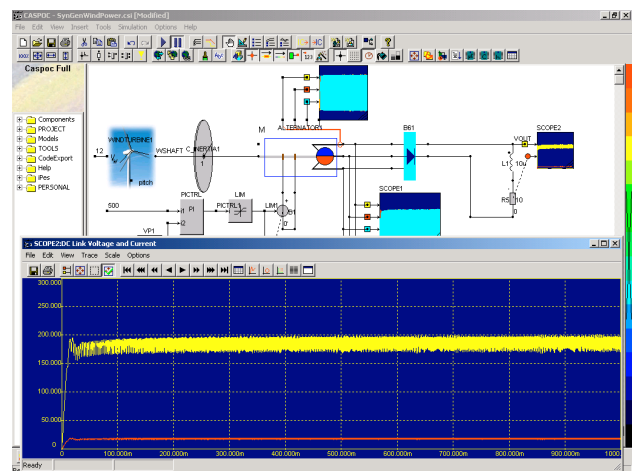


Figure 2: Wind Energy, The scope shows the DC Link Voltage and Current.

The wind turbine model should include the effects of wind speed, and pitch of the rotor blades. A general equation for the output power of the wind turbine is given by (2)

$$P_m = c_p(\lambda, \beta) \frac{\rho A}{2} v_{wind}^3 \quad (2)$$

where

P_m	Mechanical output power of the turbine (W)
c_p	Performance coefficient of the turbine
?	Air density (kg/m^3)
A	Turbine swept area (m^2)
v_{wind}	Wind speed (m/s)
?	Tip speed ratio of the rotor blade tip speed to wind speed
?	Blade pitch angle (deg)

The parameter c_p is given by the manufacturer of the wind turbine and is either modeled by a function, or by a look-up table. Figure 3 shows the parameter c_p for various pitch angles dependent on the tip speed ration.

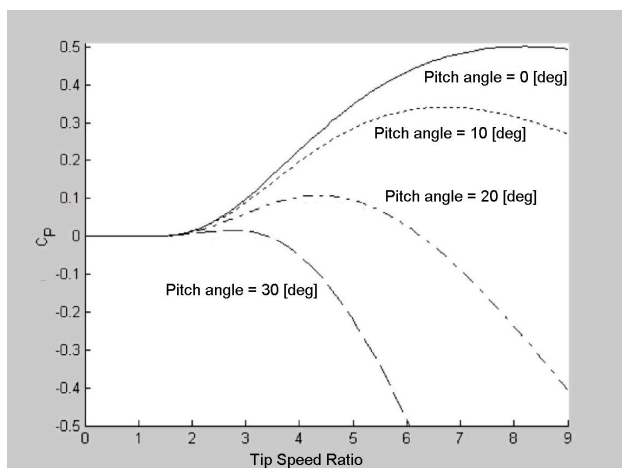


Figure 3: Parameter c_p as function of the Pitch angle and Tip Speed Ratio.

Ocean Wave Energy

A Wave Generator is a Linear Synchronous Generator that is driven by the waves in the ocean. A first demonstration model is build near the Portuguese coast, where wave energy is converted into electrical energy. The model would contain a linear synchronous generator with permanent magnets model (1), just as was used for the wind power application. Instead of using v_r in equation (1), the linear velocity v_r of the wave generator is used.

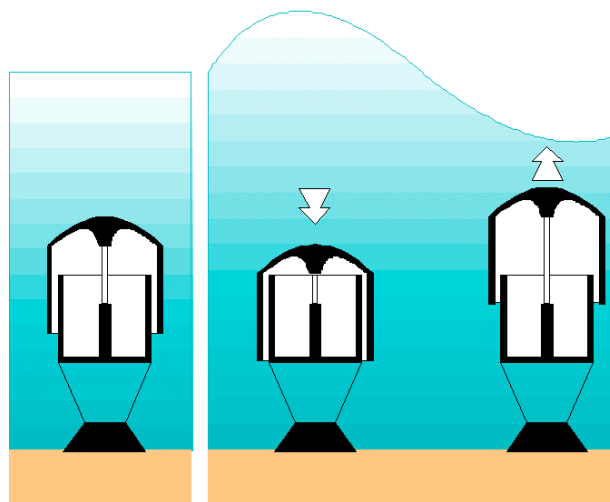


Figure 4: Wave Swing Generator; Synchronous machine with permanent magnet excitation.

The difficulty in the design is the fact that the air-gap in the linear generator is rather large, due to the robust nature of the wave swing generator. Depending on the water pressure above the wave swing, the wave swing is either pressed down or going up.

Hydro Power

Hydropower is common for many years in countries that have mountains and water. The water flows downhill from the mountain and by regulating the water and leading it through a water turbine, a synchronous generator can be driven. The concept is proven and modeling is mainly concentrating on the generators that are DC machines, synchronous machines or sometimes induction machines. Hydropower is a cheap, clean and efficient way of generator electrical energy, without producing any waste.

Water resource Power

The principle that is used for generating electrical energy from hydropower can also be used for storing energy. Instead of producing electrical energy, the water turbines are used to pump water to a higher altitude. In this way electrical energy is stored in an efficient and clean way. The electrical energy is recovered in the same way as Hydropower is generated, by using the same water turbines. Modeling is here required for the electrical machines and the power electronics for connection to the main grid.

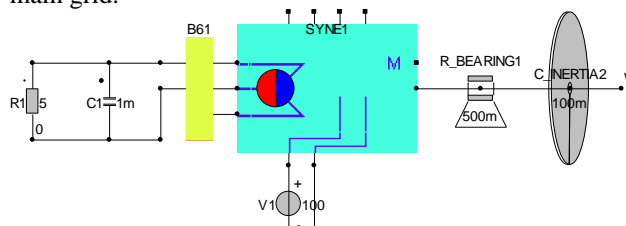


Figure 5: Synchronous generator with external excitation feeding a DC link via a rectifier.

Power Fluctuations due to the non-linear energy supply can be cancelled in various ways. Power Quality

Compensators for FACTS and Custom Power can be used and in figure 6 a control system is shown that cancels power fluctuations in a grid. The energy level is kept constant by the controlled voltage source that in reality is a voltage source inverter supplied from a DC link.

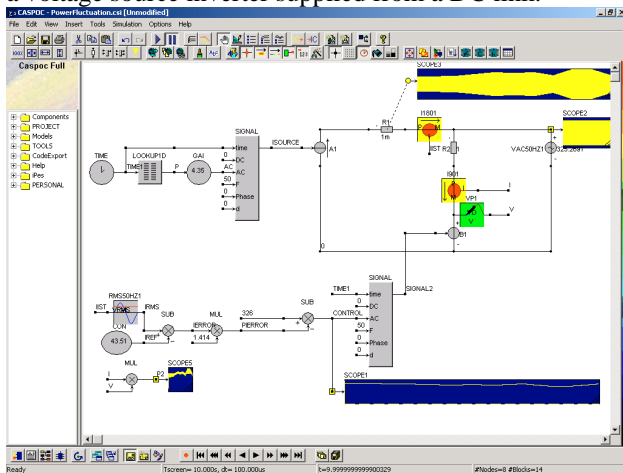


Figure 6: Canceling Power Fluctuations. The grid is modeled as a single phase in Caspoc[1].

To cancel out these power fluctuation, energy recourses are required that can react very fast. Super capacitor banks are a new way of providing this energy.

Super Capacitors

Super Capacitors or Electrochemical Double Layer Capacitors (EDLC) take advantage of the charge stored in the Electro-chemical double layer and provide extremely high capacities of more than 1000 Farads. These devices have applications in computer power back up, power electronics, electric vehicles and space flight technology. However, power and energy demands of these applications vary significantly.

Special low resistance, high-power super capacitors, suitable for applications such as switch gear or power quality are in development. Electrochemically modified glassy carbon is a promising material to be used in electrochemical capacitors. Oxidation of the surface of a glassy carbon electrode results in a porous layer with very large capacitance and fairly low internal resistance when using an aqueous electrolyte.



Figure 7: Super-capacitor for 5.7kW and an energy level of 115Joule.

In figure 7 a 24 V bipolar aqueous capacitor with a maximum power of 5.7 kW and a maximum energy of 115 J is shown. The characteristic data are given below:

Nominal Voltage	24 V
Capacitance	0.4 F
ESR	25 mohm @ 1 kHz
RC Time-constant	10 ms
Max. Energy	115 J
Max. Power	5.7 kW

One of the advantages of EDLCs is the cycle stability. With a 5V bipolar capacitor (5 cells) more than 100'000 charge/discharge cycles between 0 V and 5 V were demonstrated. During this cycle test, which lasted two months, the internal resistance as well as the capacitance changed less than 10%. The Simulation of the Super Capacitor shows the difference between discharge via the load and self discharge.

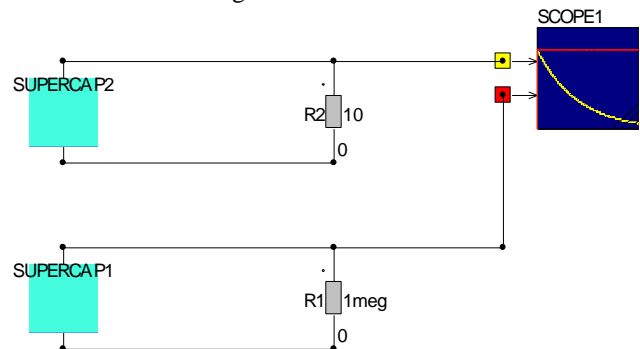


Figure 8: Simulation of the discharge in a resistive load of 10 ohms (upper schematic) and self-discharge (lower schematic).

The model for the Super Capacitor is given below.

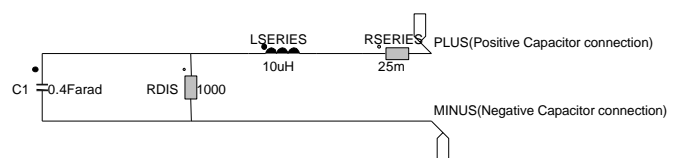


Figure 9: Equivalent circuit model for the Super Capacitor.

Here the capacitance of the Super Capacitor is modeled by C1, while RDIS models the self-discharge of the capacitor. The components L_{series} and R_{series} model the series impedance of the capacitor. For automotive applications and also in high power applications, Super Capacitors are connected in series and in parallel to get higher power levels.



Figure 10: Super Capacitor bank for automotive applications

Hybrid Electrical Vehicle

Hybrid Electrical Vehicles (HEV) are gaining attention since prices for gasoline are rising. In HEVs an electric machine is used in parallel with a gasoline powered engine. The engine is used for providing the average power for driving, while the electrical machine assists during start-up, breaking and providing power at non-nominal operation speed of the engine. In other words, the engine is operating only at nominal rpm, where it is efficient. For all other speeds, the power from the electrical machine is added to the power from the engine. There are several approaches to do this. The most simple is to mount the electrical machine on the shaft of the engine. In that case the engine speed is not constant. If the electrical power and the power from the engine have to add, and the constant speed of the engine has to be maintained, a planetary gear is used, also called a Power Split for automotive applications.

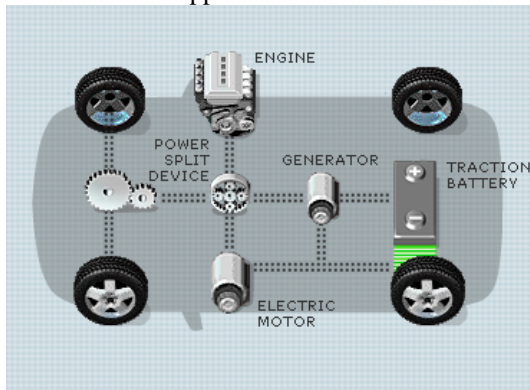


Figure 11: HEV with Engine, electric motor, generator, battery and power split.

Power Split

The Power Split is shown in the simulation below. The power from both engines is added and transferred to the outgoing shaft. The power level from the first engine is around 90kW, while the power level from the second engine is 26kW. A total of 106kW is transferred to the outgoing shaft, where a rotating mass and bearing model the load of the automotive application.

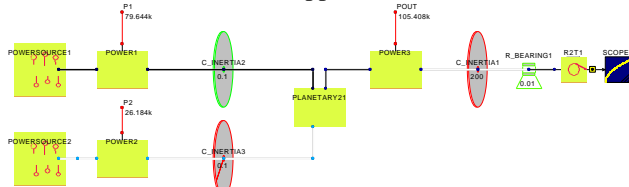


Figure 12: Power split feeding the output shaft from two engines.

To study the dynamics between the engines, power split, gear, differential and wheels, the total mechanical drive train is modeled in figure 13. Here the masses of the shafts is modeled as well as the masses and frictional losses of the wheels. By using two different values for the friction loss in the bearings at the wheels, the difference in angular speed of the driving wheels can be simulated.

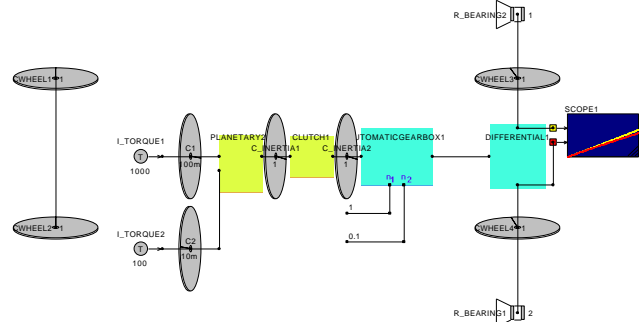


Figure 13: Mechanical drive train for a HEV.

Inverter and PMSM

Figure 14 shows the simulation [5] of the complete electrical and mechanical drive train for a HEV. Here the inverter is modeled using ideal switch models to achieve a fast simulation. The harmonics due to the Pulse Width Modulation (PWM) of the inverter appear on the torque produced by the Permanent Magnet Synchronous Machine (PMSM). This torque pulsation will effect the dynamics of the entire mechanical drive train. The control for the power electronics can be designed and optimized in a complete model where the power electronics, PMSM and mechanical drive train are modeled, see fig. 14 and 18.

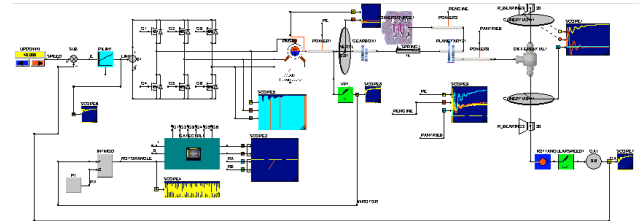


Figure 14: Simulation of the electrical and mechanical drive train in a HEV.

Battery

A battery in automotive applications is modeled by a large capacitor with internal self-discharge parallel resistor and an internal series resistance. The model resembles that of the equivalent circuit model from figure 9. Compared to Super Capacitor, the capacitance is much larger, but the internal resistance is much higher. Super Capacitors can not store the same amount of energy as lead-acid batteries, but can provide energy in a shorter period.

For example as Engine start-up assist, the Super Capacitor is used to provide the high power demand in a very short time. Compared to lead-acid batteries, Super Capacitors can provide very high amounts of current during a short period.

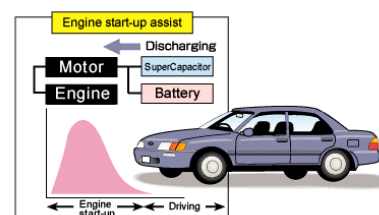


Figure 15: Engine Start-up assist by paralleling a lead acid battery with a Super Capacitor.

Fuel Cell

Fuel cells generate power through an electrochemical process, much like a battery. They convert chemical energy to electrical energy by combining hydrogen from fuel with oxygen from the air. Hydrogen fuel can be supplied in two ways - either directly as pure hydrogen gas or through a "fuel reformer" that converts hydrocarbon fuels such as methanol, natural gas, or gasoline into hydrogen-rich gas.

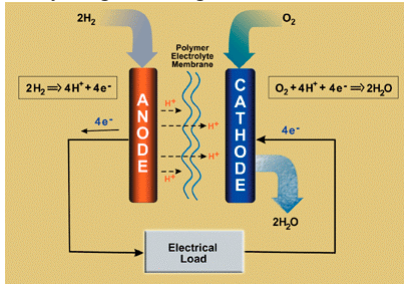


Figure 16: Fuel cells with two electrodes and electrolyte.

The quantitative evaluation of a galvanic power source can be made in several ways, including cell voltage at fixed discharge current density, energy density, power density, or discharge capacity. A common way to express the performance of a fuel cell is the steady-state voltage versus current (or current density), viz. polarization curve.

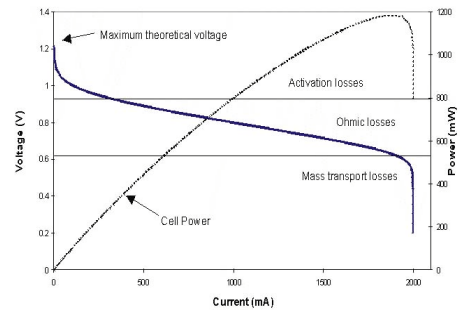


Figure 17: Voltage-Current relation for a Fuel Cell.

The Voltage-Current relation for a Fuel Cell is modeled by a non-linear voltage source that is current dependent.

References

- [1] Bauer P. Understanding the Power Quality Problems and Compensators, Proceedings PCIM 2004, page 503-508, ISBN 3-928643-39-8
- [2] Sasaki S., Sato E., Okamura M., The motor Control Technologies for the Hybrid Electric Vehicle, PCIM 2004, page 1-10, ISBN 3-928643-39-8
- [3] Bauer P., Gospodaric D., Hybrid Electric Car Design and Simulation., Power Systems Design Europe, 7/8-2005, www.powersystemsdesigns.com, ISSN 16136365
- [4] Bauer P., Duijsen P.J. van, Simulation Software with Open Interface, Power Electronics Europe, page 29-31,
- [5] Simulation Research, Simulation program Caspoc 2005, www.caspoc.com

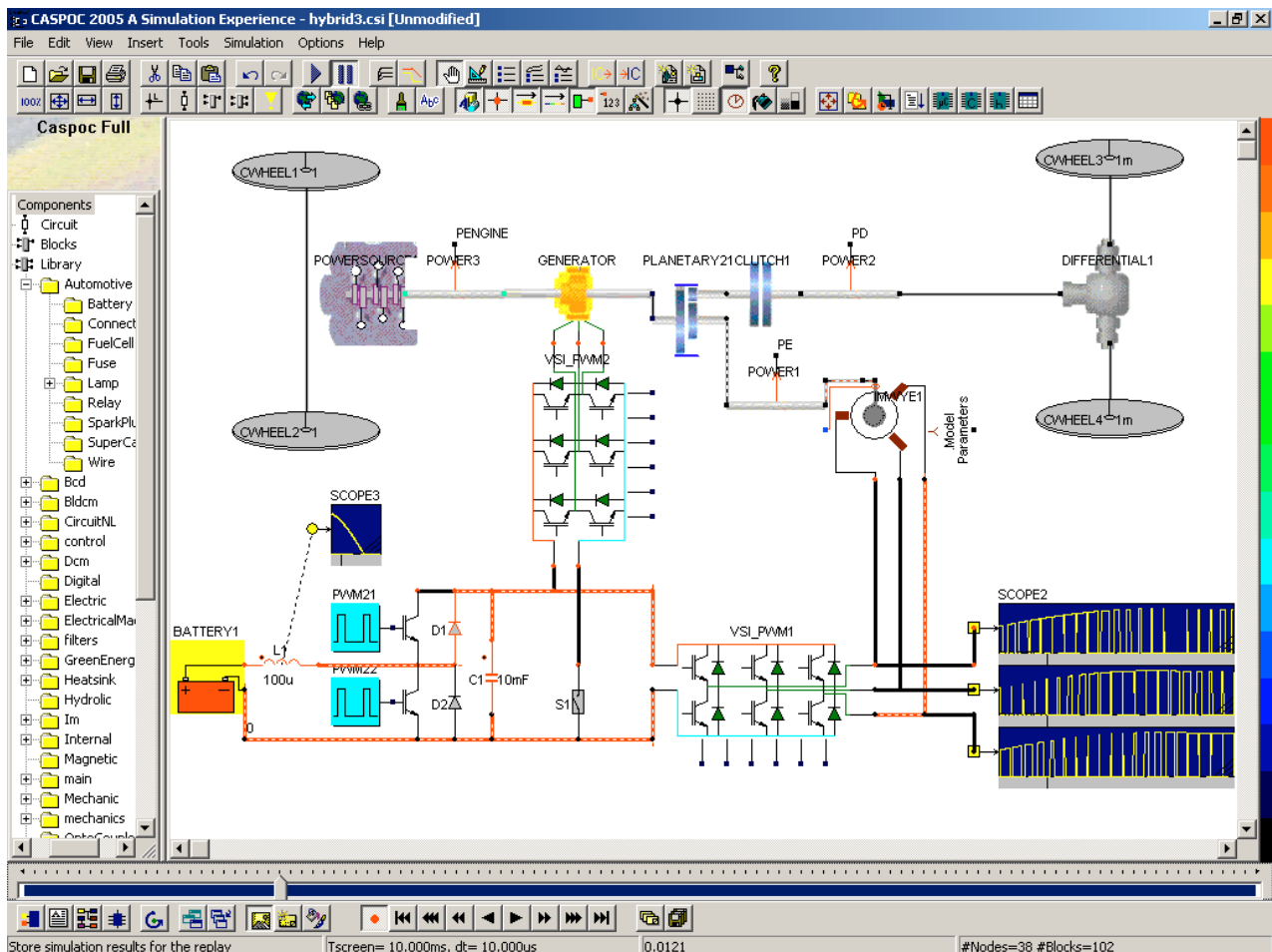


Figure 18: Simulation in Caspoc [3] of the electric and mechanical drive train in a Hybrid Electrical Vehicle.