Identification and Controls of Electrically Excited Synchronous Machines

Hansjörg Kapeller Anton Haumer Christian Kral Franz Pirker Gert Pascoli
Arsenal Research
Giefinggasse 2, 1210 Vienna, Austria

phone +43–50550–6606, fax +43–50550–6595, e-mail: hansjoerg.kapeller@arsenal.ac.at

Abstract

Three-phase generators for traction applications are exposed to extreme mechanic and electric stress. Yet, the operating life has to be ensured for a period of 30 years. Therefore, technical optimization as well as focusing on today's and future aspects of environmental protection is required. Based on that, the development processes focuses on the minimization of losses over the entire operational range (usual speed range 600 and 2100 rev/min) and the reduction of masses. Both results in a considerably energy saving of the drive train operation. In many cases electrically excited synchronous machines feed diode rectifiers. The effects of this operation mode, particularly with regard to losses due to the harmonics, should be simulated just in the beginning of the design process for optimization.

Keywords: traction applications; three-phase generators; electrically excited synchronous machines; diode rectifiers

1 Introduction

The main objective of the paper is the development of an electromagnetic simulation tool in order to optimize operational characteristics. The particular focus of the investigation is the estimation of the losses caused by harmonics due to the rectifier. The innovative simulation tool is based on the object oriented language Modelica. For performing the Modelica simulations the simulation tool Dymola is used. The electromagnetic behavior of the traction generator can be modeled for typical operation modes using the simulation tool Dymola and the comprehensive Modelica Standard Library.

2 Model of the Controlled Synchronous Machine

For the Modelica Standard Library a model of an electrically excited synchronous machine with constant reactances is developed using space phasor theory ([1], [2]). In the presented paper the standard model of the electrically excited synchronous machine is used. Yet, for a more detailed investigation, the standard model can be extended such way that magnetic saturation in direct axis (d-axis) is taken into account [3].
The main synchronous generator is excited by an auxiliary synchronous generator (with rotating three-phase winding and stationary excitation) via a rotating rectifier bridge. The model of the integrated excitation equipment consists of a simplified model of a synchronous machine and a three phase diode rectifier bridge. A PID controller provides excitation for the auxiliary synchronous excitation machine.

2.1 Controller of the Excitation Equipment and Design Rules

In order to achieve appropriate terminal voltages of the traction generator under different operating conditions, it is necessary to implement an excitation voltage controller for the auxiliary excitation generator, which in turn determines the excitation voltage and current of the main generator, respectively.
The choice and the design of the controller (PI or PID controller) has to be performed after identifying the controlled system. The controller design significantly depends on this identification.

Identification of the Controlled System If a step-function is applied to the input of the system (i.e. excitation voltage of the auxiliary excitation generator), the response (i.e. the terminal voltage of the main

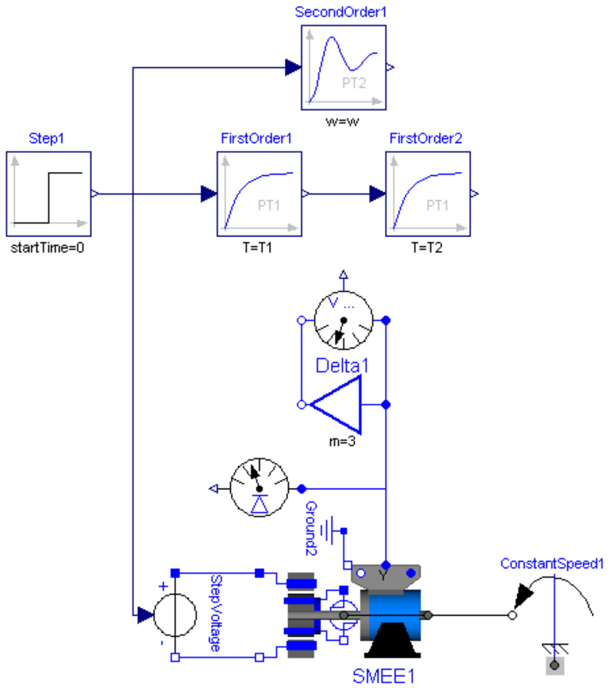

Figure 1: Scheme of the controlled system and approximation with delay elements. The identification is done with the simulation tool Dymola.

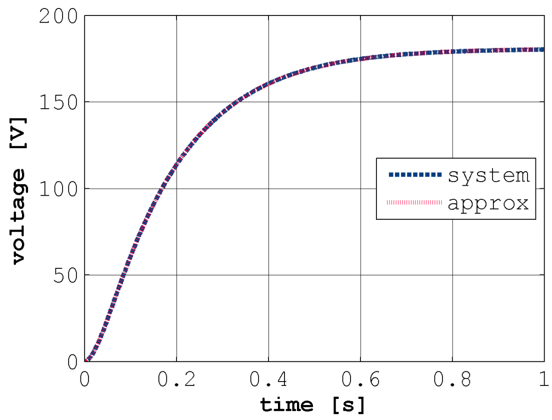

Figure 2: Step response of the real system (dashed line) and approximation with PT2-element (dotted line); criterion of least mean square is applied for optimization.

generator) can be observed. The controlled system is shown in Fig. 1 and consists of the (main) synchronous machine and the auxiliary excitation generator. From Fig. 2 it is obvious, that the analysis of the controlled system shows a non periodic second order system. The terminal voltage of the excitation synchronous generator arises with a first order delay (PT1) and the terminal voltage of the main synchronous machine arises with a first order delay, too. The system therefore appears as non periodic second order system (PT2 element). The structure of the second order controlled system is:

$$G(s) = \frac{k_S}{\left(\frac{s}{\omega}\right)^2 + 2D_S\left(\frac{s}{\omega}\right) + 1} =$$

$$= \frac{k_S}{(T_S s)^2 + 2D_S T_S s + 1} = \frac{k_S}{(1+T_1 s)(1+T_2 s)} \qquad (1)$$

k_S	gain of the controlled system
ω	oscillation frequency of the undamped assumed system
T_S	reciprocal value of the oscillation frequency of the controlled system
D_S	attenuation ratio ($D_S \geqslant 1$) aperiodic system with real singularities $s = -T_1^{-1}$ resp. $s = -T_2^{-1}$
T_1, T_2	time constants T_1 and T_2

At time zero a step-function is applied to the input of the system and the response can be compared with the output of the two series connected PT1 elements, which are equivalent to a PT2 element. The two PT1 elements have the time constant characteristics T_1 and T_2, respectively, and the resultant gain k_S. The series connected PT1 elements will be fine tuned such way that step responses of main controlled system and the step response of the series connected PT1 elements coincide. This can be done by adjusting the time constants T_1 and T_2 and the resultant gain k_S with respect to a criterion, e.g. the least mean square criterion. The comparison of both, the step response of the controlled system and the step response of the approximating (equivalent) PT2 element, is shown in Fig. 2. The use of the least square mean criterion results in a very close approximation of the system response. From the identified time constant characteristics T_1 and T_2 and the resultant gain k_S, the transfer function of the equivalent PT2-element can be estimated according to (1).

The identification of the controlled system is performed semiautomatically. In the simulation tool Dymola a first coarse setting of the time constant T_1 and T_2 and the resultant gain k_S can be set to get a first approximation of the response of the controlled system. In a postprocessing application the least mean square criterion will be performed to get correctly identified values.

Parameterization of the Controller After the identification one of the following methods respectively rules for setting the control parameters can be used:

1. tables (e.g. empirical formula „which controller to which controlled system“, see [4]),
2. analytical points of view (e.g. structure optimized controllers),
3. parameter adjustment strategies:
   (a) compensation method [5] (identification via step response, cp. Fig. 2, or via open loop frequency response, see [6])
   (b) via adjusting the control parameters in situ, if the controlled system is not critical
   (c) simulation of the closed loop and use of empirical control settings.

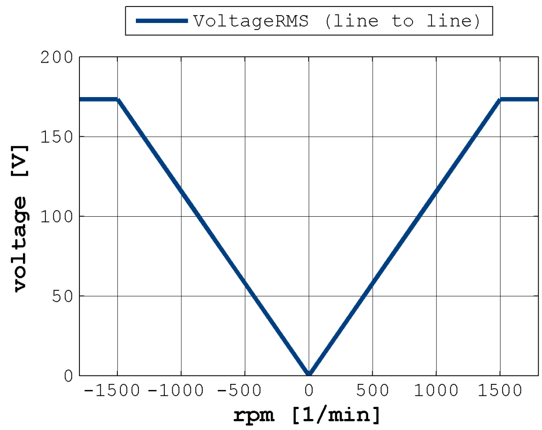

Figure 3: Dependence between desired setpoint value of the voltage and speed.

Compensation Method In this paper the compensation method will be used. The idea behind this method is to implement the controller as an inverse function of the already identified controlled system enhanced with an additional integral time (T_K).
Then the controller of a PT2 system looks like:

$$K(s) = \frac{1}{G(s)} \cdot \frac{1}{T_K s} = \\ = \frac{2D_S T_S}{k_S T_K} \cdot \left(1 + \frac{1}{2D_S T_S s} + \frac{T_S s}{2D_S}\right) \quad (2)$$

This control structure is equivalent to a PID control structure.

$$K(s) = k_R \cdot \left(1 + \frac{1}{T_I s} + T_D s\right) \quad (3)$$

k_R	gain of the controller
T_I	integral time
T_D	derivative time

The parameters can be found by comparing the coefficients,

$$T_I = 2D_S T_S, \quad (4)$$

$$T_D = \frac{T_S}{2D_S}, \quad (5)$$

$$k_R = \frac{2D_S T_S}{k_S T_K} = \frac{T_I}{k_S T_K}. \quad (6)$$

When $T_K = T_I$ is assumed, from (4) and (6) the conherence $k_R = k_S^{-1}$ can be deduced. The transfer function of the closed loop is, however, a first order system. The value of k_R determined using the assumption $T_K = T_I$ can be used as an initial setting during the initial operation phase. It is possible to increment the gain of the controller to enhance the dynamic performance of the whole controlled system (e.g. five times the value of k_R could be a feasible setting).

Principle of the Voltage Measurement – Sensing of the Actual Value The actual value of the line-to-line voltage of the (main) synchronous machine has to be measured and compared with the speed depended, desired set point value of the voltage, as shown as in Fig. 3. The resultant deviation from the desired value feeds the voltage controller, which influences the controlled system in such a way, that the deviation from the desired value decreases.
Implementations of voltage controllers often measure the main generator voltage with a three phase measuring transformer. In practice the secondary alternating voltage is rectified, smoothed by a capacitor and then measured. This measured value corresponds with the arithmetic mean value of the rectified three-phase voltage. In the simulation environment the rectification of the secondary alternating voltage is performed by an algebraic algorithm that determines the maximum value of the absolute values of the line-to-line voltages. To minimize non linear load effects due to the rectifier or static thyristor inverters (noise), the rectified three-phase measuring voltage is low pass filtered. The attenuation characteristic of the chosen low pass filter is "critical", which means, that the low pass filter is a non-oscillating Butterworth filter (asymptotic case). Taking into account the dynamic quality factor

on the one hand and the ripple suppression on the other hand the choice of a 3rd order butterworth low pass filter is useful. The reference filter decreases the dynamic performance of the whole controlled system but it is necessary to avoid instabilities due to the superposed noise in the actual value of the main generator voltage.

Predetermined Desired Value of the Line-to-Line Voltage (Speed Dependent) Quite often the shaft of the main synchronous generator is driven by a diesel engine and the predetermined desired value of the voltage of the main generator can be derived from the mechanical speed of the generator shaft: if the absolute value of the rotational speed decreases, the desired value of the voltage of the main generator shall decrease proportionally, too. If the mechanical shaft speed is to high, the desired value of the line-to-line voltage shall be limited to the nominal generator voltage. Furthermore the desired value of the voltage is a positive quantity, because we assume that the sense of the rotation (e.g. of a diesel-driven generating set) does not change. The coherence between speed and voltage is depicted in Fig. 3.

Rectifier with Electrical Load In a standard application a traction generator feeds a diode rectifier with an intermediate circuit and the electrical load, for instance inverter fed traction motors. If the inverter is working with a very high pulse rate, it is possible to model the inverter and the traction motors as a constant-power sink. Figure 4 shows the electrically excited synchronous machine with the diode rectifier, the smoothing capacitor in the DC circuit and the modelled constant-power sink (for example 15 kW).

Mechanical Drive To simplify the simulation we assume, that the driving engine runs with constant mechanical speed, guaranteed by the speed controller of the diesel-driven generating set. The rotational speed ripple effect due to the inherent torque ripple, mainly caused by the diesel engine and, to a lesser extent, from the main synchronous generator (due to feeding the diode rectifiers), is neglected.

2.1.1 Initial Operation Phase of the Voltage Controller

The simulation environment Dymola includes the Modelica Standard Library. This library is a standardized and free package that is developed together with the Modelica language and provides model components in many domains that are based on standardized interface definitions. One domain is the so called Machines Library. This package contains components to model electrical machines, specially three phase induction machines, based on space phasor theory.
The following types of machines, however, can be modelled:

- three phase asynchronous induction machines
- three phase synchronous induction machines
- DC machines with different excitation

In this paper machine parameters for the main synchronous machine and the auxiliary exciting synchronous generator (with rotating three-phase winding and stationary excitation) are taken from the standard model "Electrical excited synchronous induction machine with damper cage"of the Machines library.

2.1.2 Machine Parameters

Machine parameters (main synchronous generator):

- rotor's moment of inertia = 0.29 kg m^2
- number of pole pairs (Integer) = 2
- warm stator resistance per phase = 0.03 Ω
- stator stray inductance per phase $= 0.1/(2 \cdot \pi \cdot f_{Nominal})$ H
- main field inductance in d-axis $= 1.5/(2 \cdot \pi \cdot f_{Nominal})$ H
- main field inductance in q-axis $= 1.5/(2 \cdot \pi \cdot f_{Nominal})$ H
- damper stray inductance in d-axis $= 0.05/(2 \cdot \pi \cdot f_{Nominal})$ H
- damper stray inductance in q-axis $= 0.05/(2 \cdot \pi \cdot f_{Nominal})$ H
- warm damper resistance in d-axis = 0.04 Ω
- warm damper resistance in q-axis = 0.04 Ω
- nominal stator RMS voltage per phase = 100 V
- nominal frequency $f_{Nominal} = 50$ Hz
- no-load excitation current @ nominal voltage and frequency = 10 A

- warm excitation resistance = 2.5 Ω
- stray fraction of total excitation inductance = 2.5%

Excitation machine's parameters (simplified synchronous generator):

- number of pole pairs (Integer) = 3
- warm stator resistance per phase = $5/3 \cdot 0.03$ Ω
- stator stray inductance per phase = $5/3 \cdot 0.1/(2 \cdot \pi \cdot f_{Nominal})$ H
- main field inductance in d-axis = $5/3 \cdot 1.5/(2 \cdot \pi \cdot f_{Nominal})$ H
- nominal stator RMS voltage per phase = 25 V
- nominal frequency $f_{Nominal}$ = 75 Hz
- no-load excitation current @ nominal voltage and frequency = 1 A
- warm excitation resistance = 25 Ω

2.1.3 Setting of the Control Parameters

If the main synchronous machine and the auxiliary exciting synchronous generator are modeled with the parameters specified in the previous subsection, the whole system including the voltage PID controller can be arranged and simulated. For the given machine parameters, the least mean square method leads to the following parameters of the controlled system results:

$k_S = 7.2387$	gain of the controlled system
$\omega = 14.01\,\mathrm{s}^{-1}$	oscillation frequency of the undamped assumed system
$T_S = 0.071375\,\mathrm{s}$	reciprocal value of the oscillation frequency of the controlled system
$D_S = 1.39$	attenuation ratio ($D_S \geqslant 1$) aperiodic system with real singularities $s = -T_1^{-1}$ resp. $s = -T_2^{-1}$
$T_1 = 0.16841\,\mathrm{s}$	time constant T_1
$T_2 = 0.03025\,\mathrm{s}$	time constant T_2

With these numeric values the parameter settings of the voltage PID controller can be determined according to (4)–(6):

$T_I = 2D_S T_S = 0.19867\,\mathrm{s}$	integral time
$T_D = \dfrac{T_S}{2D_S} = 0.02565\,\mathrm{s}$	derivative time
$k_R = \dfrac{T_I}{k_S T_K} = 0.13815$	gain of the controller

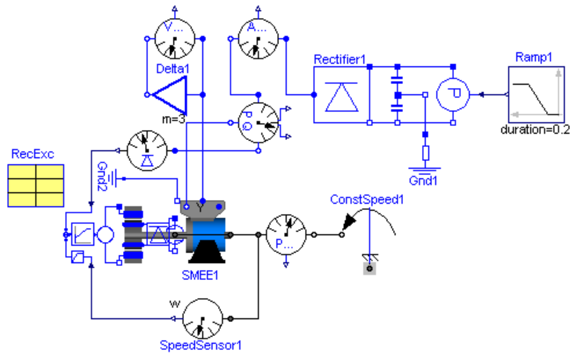

Figure 4: Closed loop with constant-power sink.

2.2 Simulation Results of the Three-Phase Generator for a Traction Application

Using the simulation environment Dymola it is possible to simulate and test the command action (Fig. 5) of the closed loop (Fig. 4) for plausibility reasons. At time zero, the auxiliary exciting synchronous generator and the main synchronous machine (without electrical load) will be accelerated until the mechanical nominal speed of the traction application is reached (= 1500 min^{-1}). After the transient, the value of the desired line-to-line voltage will be achieved (rms phase-to-phase voltage is equal to $\sqrt{3} \cdot 100\,\mathrm{V}$). In Fig. 5 the actual rms values of the filtered and the unfiltered line-to-line voltages are displayed. Using a constant power sink model, 1s later, a load step from 0 to 15 kW, is applied. The effect of the voltage ripple and the harmonic losses caused by the full bridge rectifier are discussed in the following section.

3 Simulation of the Harmonic Losses

The estimation of the harmonic losses due to the current ripple is performed with the entire model shown in Fig. 4. In particular, the observation of additional harmonic losses in the stator winding and the excitation circuit of the main synchronous machine is of interest, because in the beginning of the design process it is important to know, how these additional harmonic losses influence the size of the machine and if the reduction of masses is possible. As depicted in Fig. 6, the stator current shows a significant current ripple. Are serious additional harmonic losses the consequence? The higher the losses the higher is the thermal stress and the larger is the resultant size of the generator. If the simulation legitimates that these additional losses are not relevant, a reduction of masses is suggested and

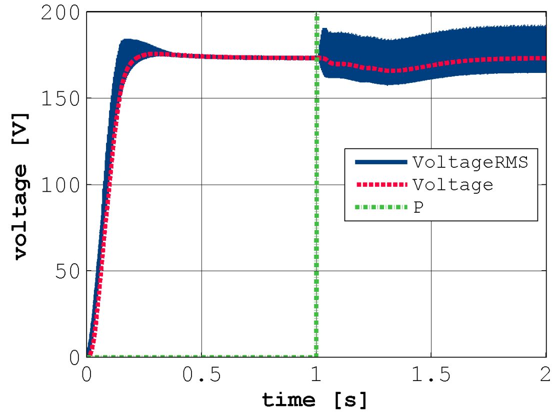

Figure 5: Observation of the unfiltered and filtered (smooth curve) voltage between the terminals: command action of the closed loop if an increase of power occurs (from 0 kW to 15 kW; activation of the constant-power sink after 1 s).

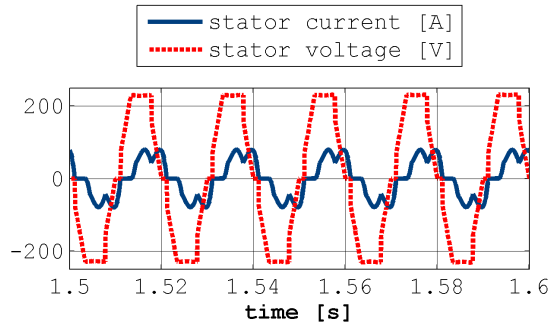

Figure 6: Current ripple due to diode switching effects. The observation of additional harmonic losses in the stator winding and the excitation circuit of the main synchronous machine is of interest.

this results in a considerably energy saving of the drive train operation.
The voltage ripple due to effects caused by the full bridge rectifier can be observed in Fig. 5 during the transient in the beginning of the simulation and after applying a load step from 0 to 15 kW. The salient distortion in the intermediate circuit voltage arise due to currents in the stator winding, caused by the mechanical load or the inherent moment of inertia of the entire rotating masses, and from switching events of the rectifying diodes (Fig. 6). A theoretical work about rectifying effects like current ripples and voltage distortion caused by converters can be found in [7].
The assumptions for the simulation of the harmonic losses are:

- main synchronous machine with constant reactances
- excitation synchronous generator with rotating rectifier bridge
- voltage controller with optimized parameters
- rectifier bridge on load side

Further boundary conditions:

- constant mechanical speed $= 1500$ rpm
- desired rms phase-to-phase voltage is equal to $\sqrt{3} \cdot 100\,\mathrm{V}$

This results in a corresponding intermediate circuit voltage of 233.9 V according to:

$$\frac{V_{DC}}{V_{RMS}} = \frac{6}{2\pi} \int_{-\frac{2\pi}{12}}^{\frac{2\pi}{12}} \sqrt{2} \cos(x)\, dx = \sqrt{2}\frac{3}{\pi} \qquad (7)$$

- load step from 0 to 15 kW by means of a power sink

The observation of the intermediate circuit voltage and current during the above mentioned increase of power is depicted in Fig. 7. During the initial no load operation ($t < 1$ s), the current of the intermediate circuit is zero and the intermediate voltage reaches the peak value of the rectified terminal voltage. When the machine is loaded with 15 kW ($t > 1$ s), the intermediate current increases and the intermediate voltage reaches 233.9 V, according to the desired pre-set value of the rectified terminal voltage, as determined by (7). The simulation result in Fig. 7 shows, that with the controlled synchronous machine the desired intermediate circuit voltage under load conditions can be reached and that the current in the DC link arise accordingly.

Discussion of the Simulation Results The stator current ripple and the square wave form of the stator voltage (note: *not* sinusoidal) depicted in Fig. 6, suggest a further inspection of the simulation results. By means of a harmonic distortion factor estimation, the additional losses can be estimated.

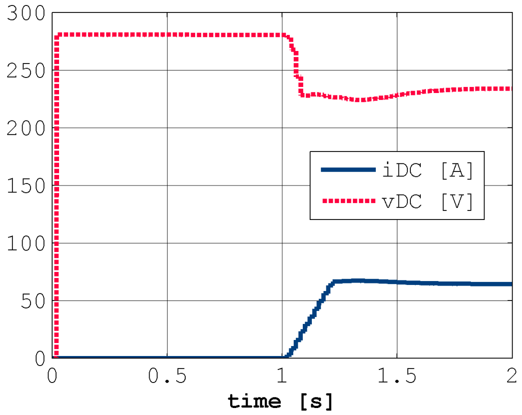

Figure 7: Observation of the intermediate circuit voltage and current if an increase of power occurs (from 0 kW to 15 kW; activation of the constant-power sink after 1 s).

The total harmonic distortion factor (THD) of the current in the stator winding of the main synchronous machine can be calculated by:

$$THD_s = \sqrt{\frac{\sum_{\nu=2}^{\infty} I_{s\nu}^2}{I_{s1}^2}} = 30\%$$

This results in additional harmonic losses about 9% in the main synchronous machine.
The total harmonic distortion factor (THD) of the current in the excitation circuit of the main synchronous generator can be calculated according to:

$$THD_e = \sqrt{\frac{\sum_{\nu=1}^{\infty} I_{e\nu}^2}{I_{e0}^2}} = 7.6\%$$

This results in additional harmonic losses about 0.6% in the excitation winding of the main synchronous generator.
These results are discovering, that the entire additional harmonic losses are not so severe and can be neglected when starting the design process of traction generators.

4 Conclusion

In this paper an electrically excited synchronous machine feeding a diode bridge rectifier, as used in traction applications, is investigated. The effects of this operation mode, particularly with respect to losses due to the harmonics, can be simulated in the beginning of the design process for revealing possible optimizations. The presented innovative simulation model is based on the object oriented language Modelica. Based on the simulation tool Dymola with the provided comprehensive Modelica Standard Library, the electromagnetic behavior of the traction generator can be modelled for typical operation modes. To achieve appropriate terminal voltages of the traction generator under such typical operation conditions, it is necessary to implement an excitation voltage controller for the auxiliary excitation generator, which in turn determines excitation voltage and current of the main generator, respectively. The choice and the design of the controller has to be performed after identifying the controlled system. The identification is performed applying a step response. The control parameter are determined using the compensation method. After that it was possible to simulate the entire traction generator model. The analysis of the additional harmonic losses due to the full bridge rectifier shows, that the entire additional harmonic losses are not so severe and can be neglected in the beginning of a design process for traction generators.

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