Electronic Power Management for Bicycles

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«battery management system», «converter circuit», «energy system management», «pwm», «renewable energy system», «sensor less control», «single phase system», «automotive electronics», «Energy Control Unit (ECU)»

Abstract

This paper discusses the power management of an electronic light- and tachometer system for bicycles. The system uses a conventional hub dynamo as energy source. An accumulator battery is charged via a microprocessor controlled AC-DC converter. We develop a circuit model of the hub dynamo. In order to maximize the output power load matching is performed. A simulation analysis as well as measuring results show that the presented solution is more efficient than classical power supply arrangements and offers the basis for new features. We develop a suitable AC-DC converter topology and show its practical performance.

Introduction

The last few years hub dynamos have become popular for supplying the front and rear lights of bicycles [1]. Light sensor controlled switches and automatic gear change have been invented though the technique of supplying the energy for the light has stayed the same. The headlight goes down as soon as the bicycle stops, only the weak light of a LED continues to shine.

A suitable power management together with an on-board battery offers several advantages: First of all electric power is continuously available, further far more energy can be taken from the generator by electronic load adaptation and no external charging like in battery lights is necessary.

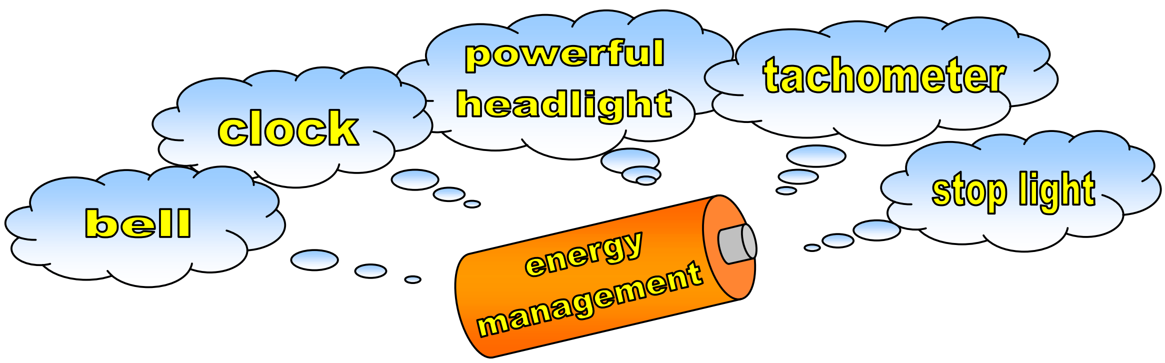

Fig.1: Combinable features forming an all-in-one device on the basis of energy management

So the power management can be the basis for more powerful lighting and for other desirable functions. A tachometer, a mile-counter, a clock, an electronic bell, a thermometer or even a stop light can be realised with very few additional effort. No speed sensor will be necessary, and the wiring remains restricted to the single phase supply line of the hub dynamo. Its AC-frequency indicates speed and acceleration.

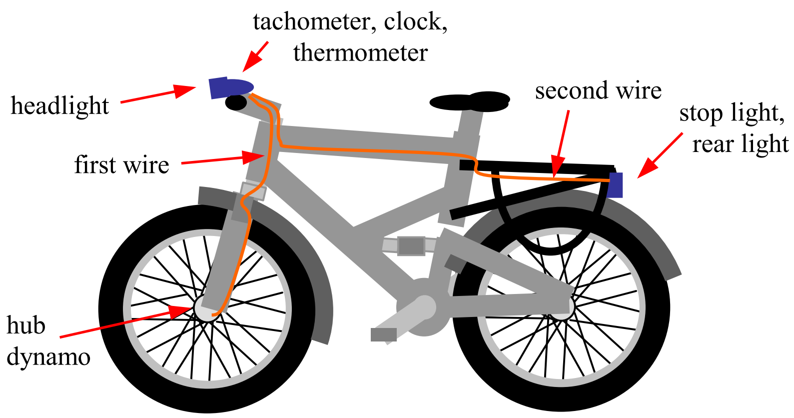

Fig.2: New technique though a classic topology

The paper is organized as follows. First an electrical model of the hub dynamo is developed. Using this model we perform load matching in order to maximize the dynamo's output power. The matched load is realized via an AC-DC converter and the phase correction by a capacitor. We describe the control scheme of the AC-DC-converter and demonstrate measuring results.

Modelling the hub dynamo

The dynamo is a permanently magnetized claw-pole generator with a single-phase coil. Our dynamo was a Shimano NX-30. Its stator contains 14 pole pairs thus providing 14 electrical periods per one mechanical turn of the generator.

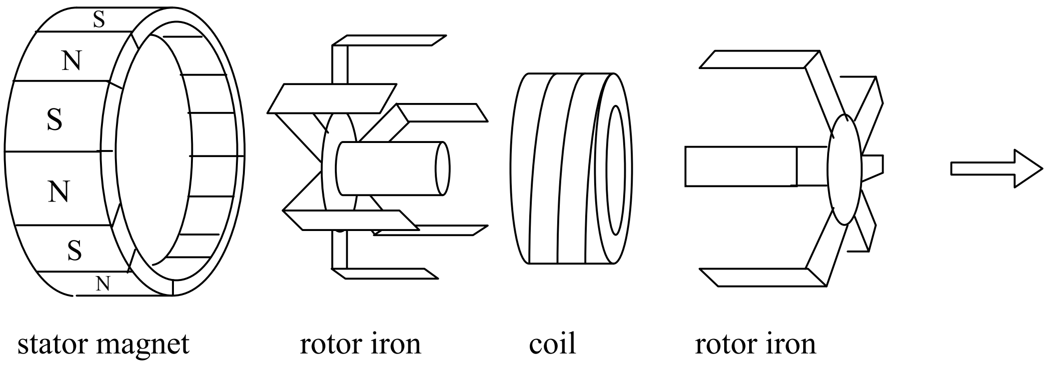

Fig.3: Assembly of a hub dynamo

In order to develop an equivalent circuit of the generator we first measure its rms output voltage in dependence on the frequency for different load cases (Fig. 4)
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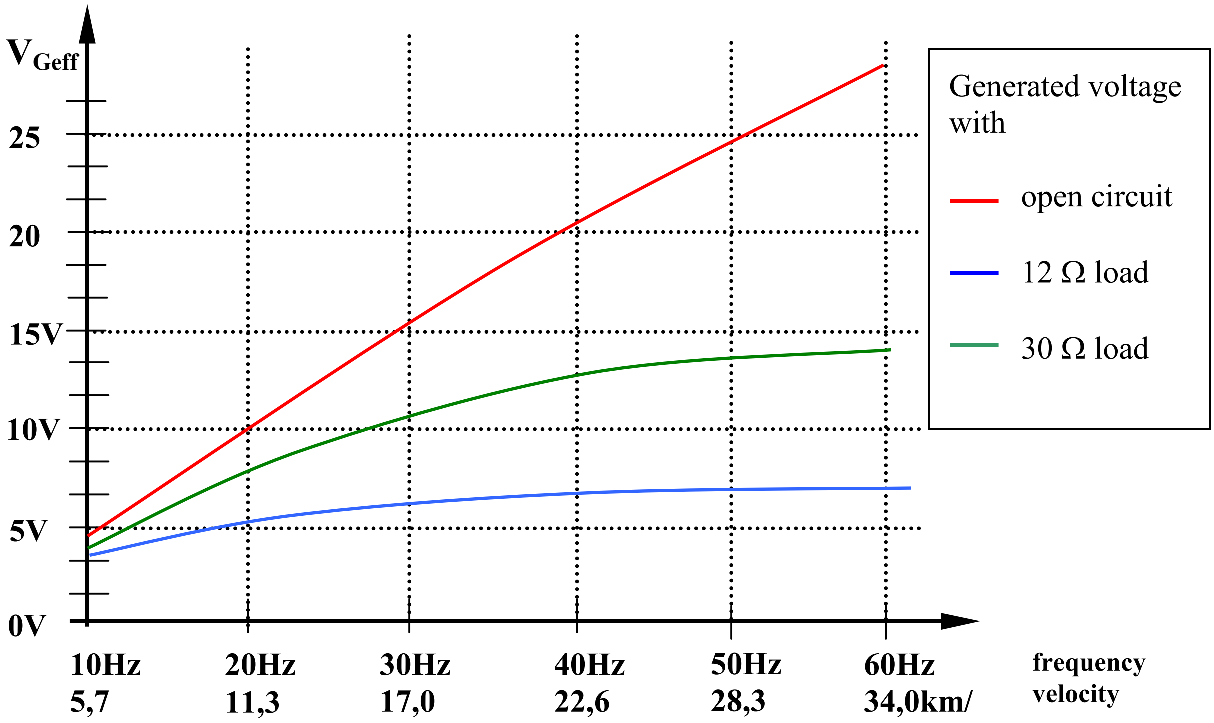

Fig.4: Generator output voltage versus frequency for different loads

Second we analyse the voltage-time function of the dynamo (Fig.5). Besides the fundamental wave it contains significant third and fifth harmonics which can also be seen in the spectrum (Fig. 5). We approximate the measured time function by

$$V_G(t) = V_0\,(cos(\pi\ t) + 0{,}5\ cos(3\pi\ t) + 0{,}2\ cos(5\pi\ t)), \quad (1)$$

where V_0 is the peak voltage. If a resistive load is connected a low pass is obtained. It consists of the internal inductance of the generator and the load and reduces the amplitudes of the higher harmonics. The cut off frequency is $f_{gr} = R/(2\pi L) = 30Hz$ at a load of 20Ω. In consequence the higher harmonics are already damped at low turning frequency and it is sufficient to consider the fundamental wave of the output voltage (1) only.

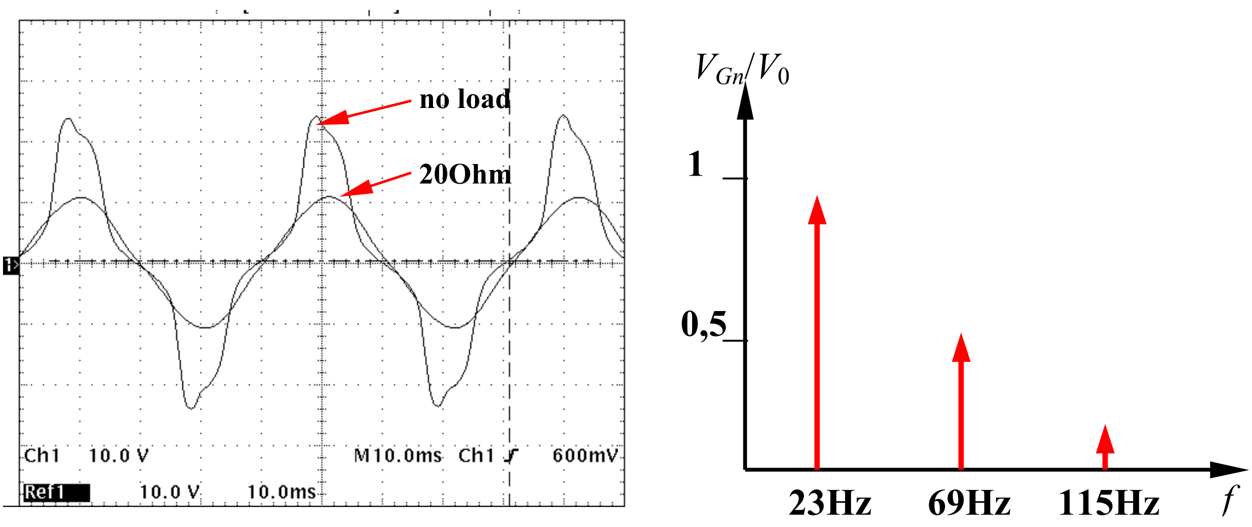

Fig.5: Voltage versus time without load and with 20 Ohm load, Time function and spectrum

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From the measurement results an equivalent network can be derived (fig. 6) with the parameters $R_{GS} = 4\ \Omega$, $L_G = 120\ mH$ and the

$$V_0 = 0{,}81V\ *\ v/(km/h). \qquad (3)$$

The frequency and the velocity are related by $f_{el} = 1{,}767\ Hz * v/(km/h)$. Further there are eddy currents in the generator's iron which can be modelled by adding a resistor R_{GP} (fig.5). It is frequency dependent. An average value of R_{GP} 55 Ω has been determined experimentally.

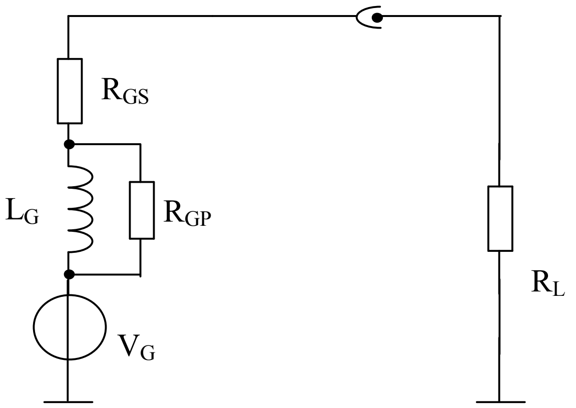
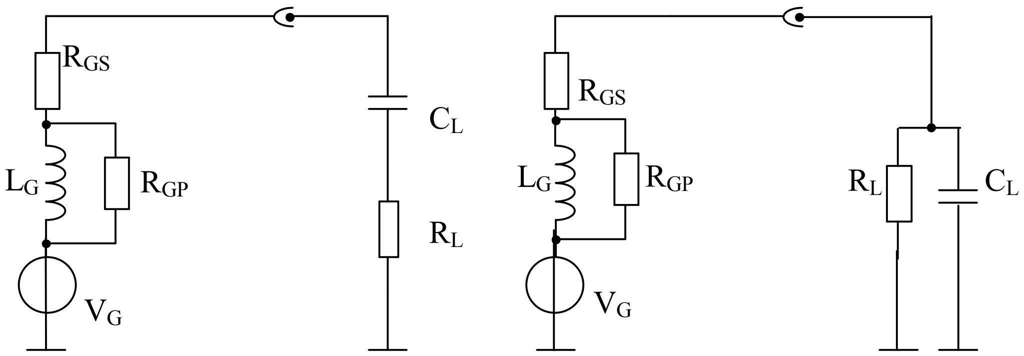


Fig.6: Equivalent circuit of the Dynamo ($R_{GS} = 4Ohm$, $L_G = 120mH$ *und* $R_{GP} \approx 55$Ohm)

Load matching

In order to maximize the dynamo output power by load matching a capacitor C_L can be connected in series or in parallel with the load (Fig. 7).



a) series compensation b) parallel compensation

Fig.7: Dynamo schematic with series an parallel phase compensation

As the capacitance is constant an adaptation for the most probable velocity is realised. E.g. for a velocity of 15 km/h (f = 25Hz) we obtain a capacitance of

$$C_L = \frac{1}{\omega^2 L_G} = 300\ \mu F \qquad (4)$$

Using all parameters fixed so far an optimal the value for R_L can be calculated for maximum output power of the dynamo. For the series compensation (Fig. 7a) the power delivered to R_L is

$$P_L = \frac{R_L V_G^2}{\left(-\frac{1}{\omega C_L} + \frac{\omega L_G R_{GP}^2}{\omega^2 L_G^2 + R_{GP}^2}\right)^2 + \left(\frac{\omega^2 L_G^2 R_{GP}}{\omega^2 L_G^2 + R_{GP}^2} + R_{GS} + R_L\right)^2} \qquad (5)$$

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It reaches its maximum for

$$R_{L,opt} = \sqrt{\frac{R_{GP}^2 + \omega^2 \left(-2\, C_L L_G R_{GP}^2 + C_L^2 R_{GP}^2 R_{GS}^2 + L_G^2 \left(1 + \omega^2 C_L^2 (R_{GP} + R_{GS})^2\right)\right)}{\omega^2 C_L^2 \left(\omega^2 L_G^2 + R_{GP}^2\right)}} \quad . \qquad (6)$$

For the parallel case we get:

$$P_L = \frac{V_G^2}{R_L \left(\left(1 + \frac{1}{R_L} \left(R_{GS} + \frac{\omega^2 L_G^2 R_{GP}}{\omega^2 L_G^2 + R_{GP}^2} \right) - \frac{\omega^2 C_L L_G R_{GP}^2}{\omega^2 L_G^2 + R_{GP}^2} \right)^2 + \left(\frac{1}{R_L} \frac{\omega L_G R_{GP}^2}{\omega^2 L_G^2 + R_{GP}^2} + \frac{\omega^3 C_L L_G^2 R_{GP}}{\omega^2 L_G^2 + R_{GP}^2} + \omega R_{GS} C_L \right)^2 \right)} \qquad (7)$$

and

$$R_{L,opt} = \sqrt{\frac{R_{GP}^2 R_{GS}^2 + \omega^2 L_G^2 (R_{GP} + R_{GS})^2}{R_{GP}^2 + \omega^2 \left(-2\, C_L L_G R_{GP}^2 + C_L^2 R_{GP}^2 R_{GS}^2 + L_G^2 \left(1 + \omega^2 C_L^2 (R_{GP} + R_{GS})^2\right)\right)}} \quad . \qquad (8)$$

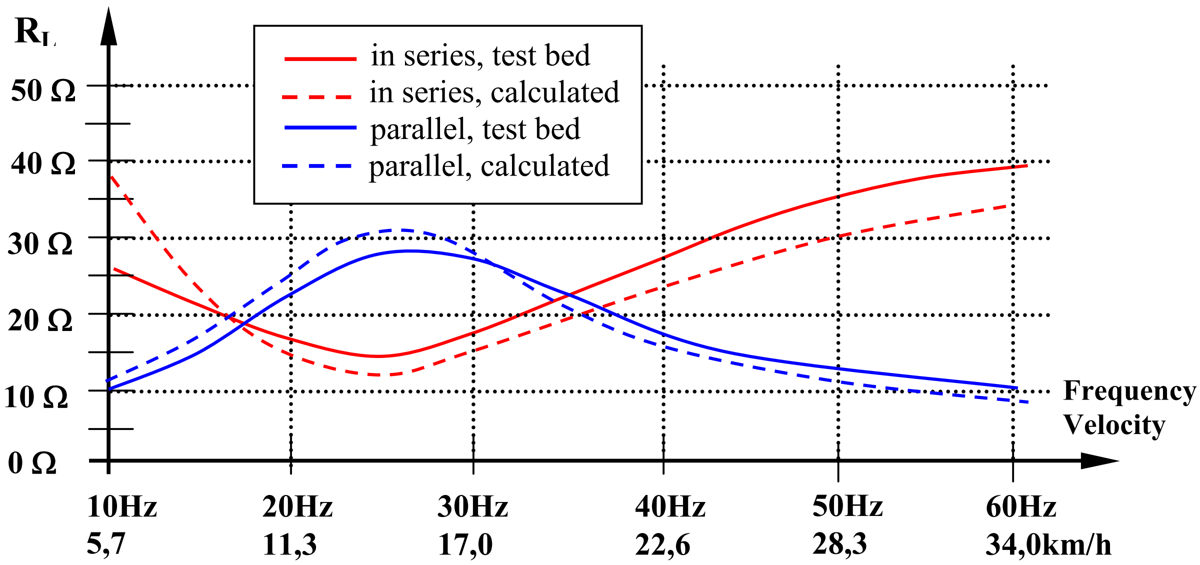

Fig.7: Optimal load resistance versus frequency according to test bed and calculation

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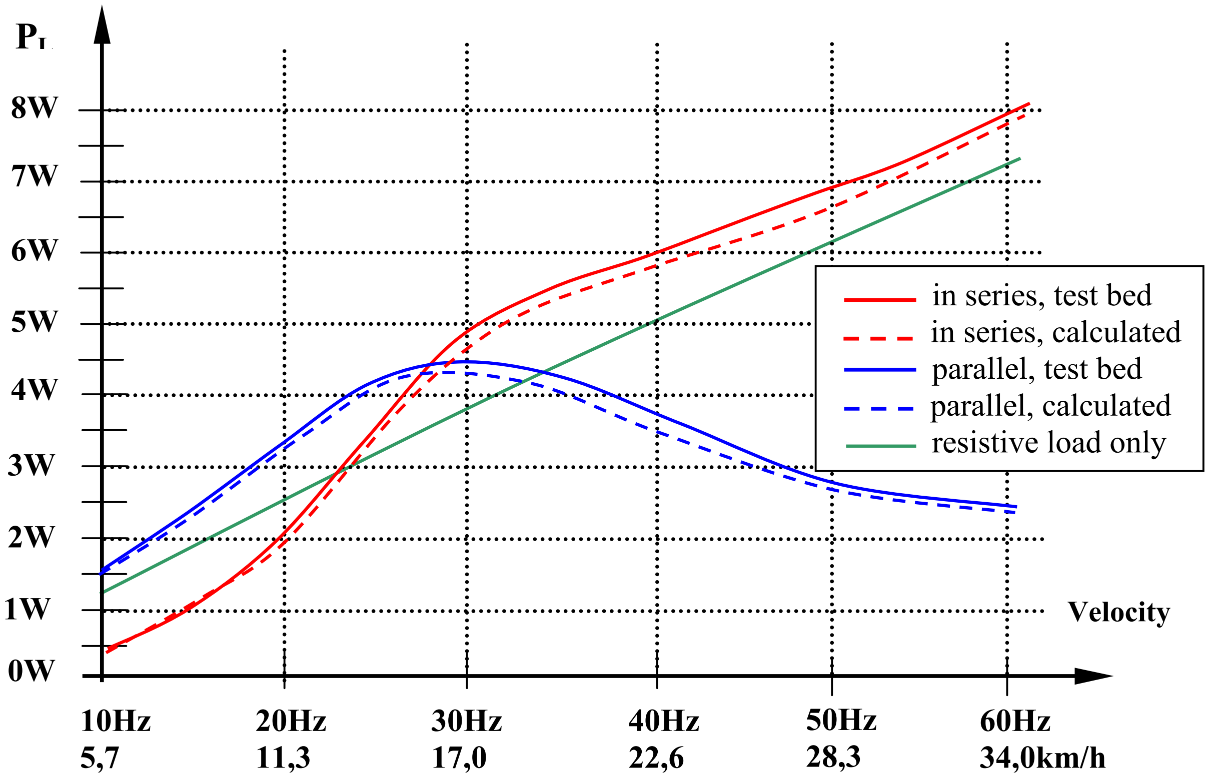

Fig.8: Output power versus frequency according to test bed and calculation

Fig. 7 depicts the calculated and measured optimal load resistance versus frequency for the parallel and series compensation. The corresponding dynamo output power is depicted in fig. 8. It can be seen, that parallel compensation should be preferred for low frequencies and series compensation for high frequencies. This is a good compromise as the effort is low and the convertible power is about 1Watt (that is 25%) higher than without phase compensation.

Load control unit

The load control unit has two tasks:

- selection of parallel or series compensation in dependence on the frequency and
- adjustment of the optimal load resistance.

The load control unit is realized by an AC-DC converter based structure. In order to adjust the converter input resistance the AC input voltage is controlled via the converter's duty cycle (fig.9). The optimal input voltages for the parallel and series configurations are depicted in fig. 9 for the two phase compensation cases. For comparison the open-circuit voltage is shown as well (green line). The yellow straight line corresponds to the linear dependence between frequency and input voltage which has been used in the design of the control scheme.

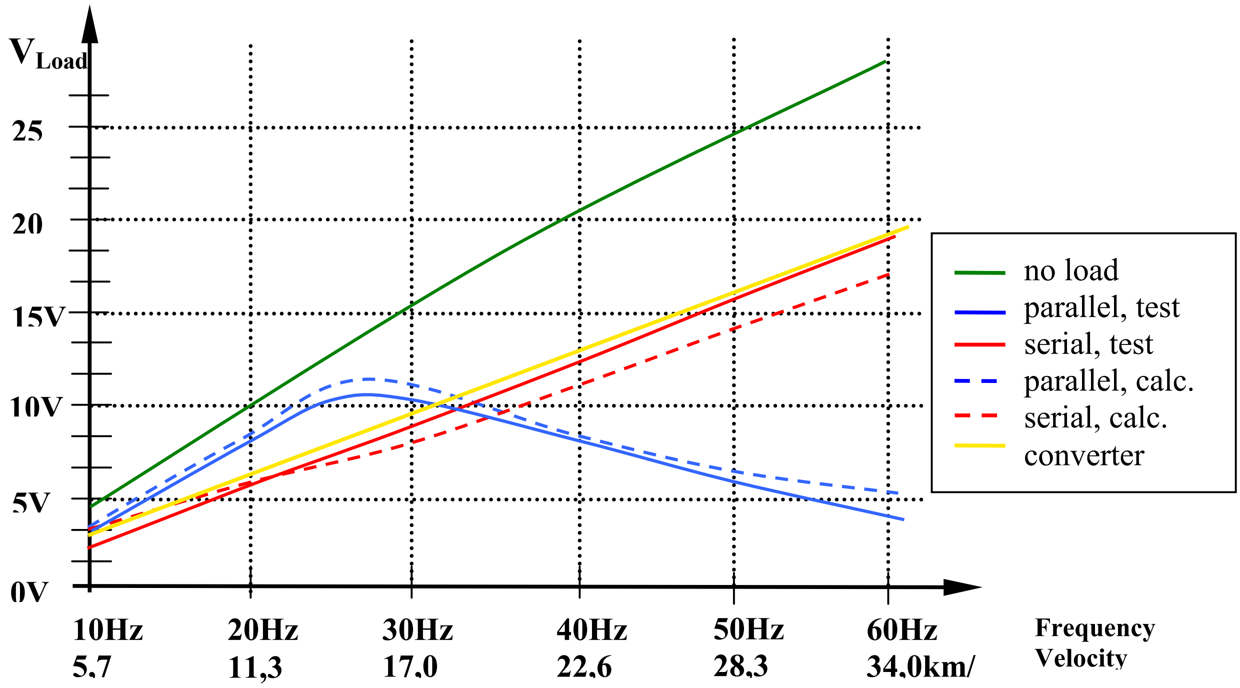

Fig.9: Voltage over optimal R_L versus frequency according to test bed and calculation

Converter architecture

The AC-DC converter consists of two switching converters. A buck converter processes the positive half-wave, and an inverting converter the negative one. Both converters feed the battery. By using this direct conversion a rectifier is no longer necessary. Extra losses of about 10% resulting from the rectifier diodes of a bridge-rectifier are cancelled by the proposed scheme.
A single device micro controller manages the charge control by measuring battery voltage, temperature and the frequency of the alternating input voltage in order to calculate the operating point and the duty cycle for each converter stage.
In general the circuit (fig.10) is a two-port. To the input port an alternating voltage with varying amplitude and frequency is fed. The output port is connected to the battery which can be regarded as a constant voltage source.

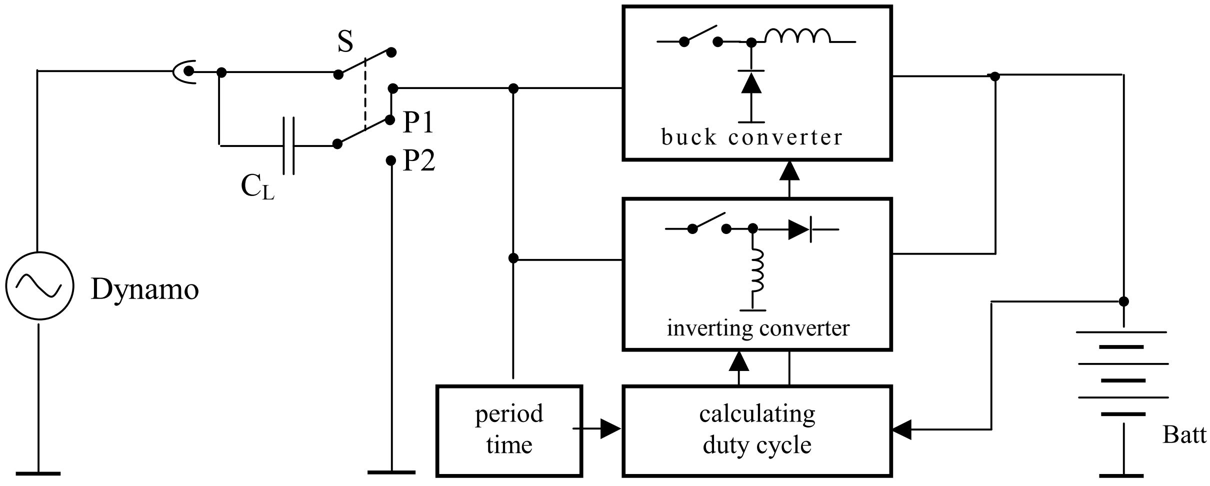

Fig 10: Converter block scheme with dynamo and battery

The phase compensation is realized as follows. For velocities lower than 15 km/h the compensation Capacitor C_L is connected in parallel (S in position 2). For velocities above 15 km/h it is connected in

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series (S in position 1). So with respect to figure 8 the operating point follows the blue graph (parallel) for lower and the red graph (series) for higher velocities.

Converter control

The task of the converter control is to derive the proper duty cycle for each converter. Its input variables are the dynamo frequency, the output voltage a control variable k which is provided by the battery control. Fig. 11 shows the flow chart of the control algorithm.

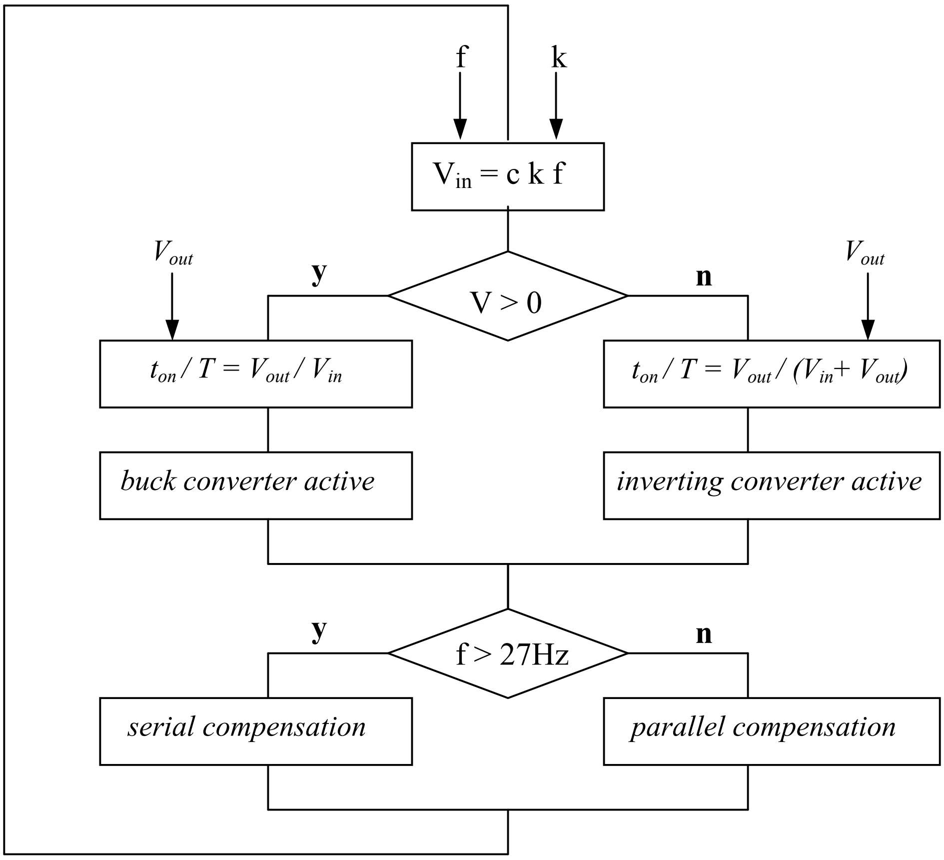


Fig.11: Converter control flow chart

The battery control shall prevent power failure. The battery is permanently watched, and the value of the control variable k is determined by the following strategy:

- the voltage and the temperature of the battery are measured
- the overall current consumption is calculated
- the overall current gain is calculated
- the state of the battery is obtained from voltage, temperature and current
- if the battery is fully charged the input current is adjusted to the current to be delivered. In this case k assumes values from 1 (maximum current) to 2 (no current)
- if the battery is not fully charged the input power is maximized (k = 1),and, if necessary the consumers are turned down.

Fig. 12 shows the measured output power for a load of 12Ω of our solution in comparison with the classical case. For all frequencies the output power is larger than by use of conventional dynamo loads. For frequencies higher than 30 Hz (17 km/h) we obtain an output power gain of about two.

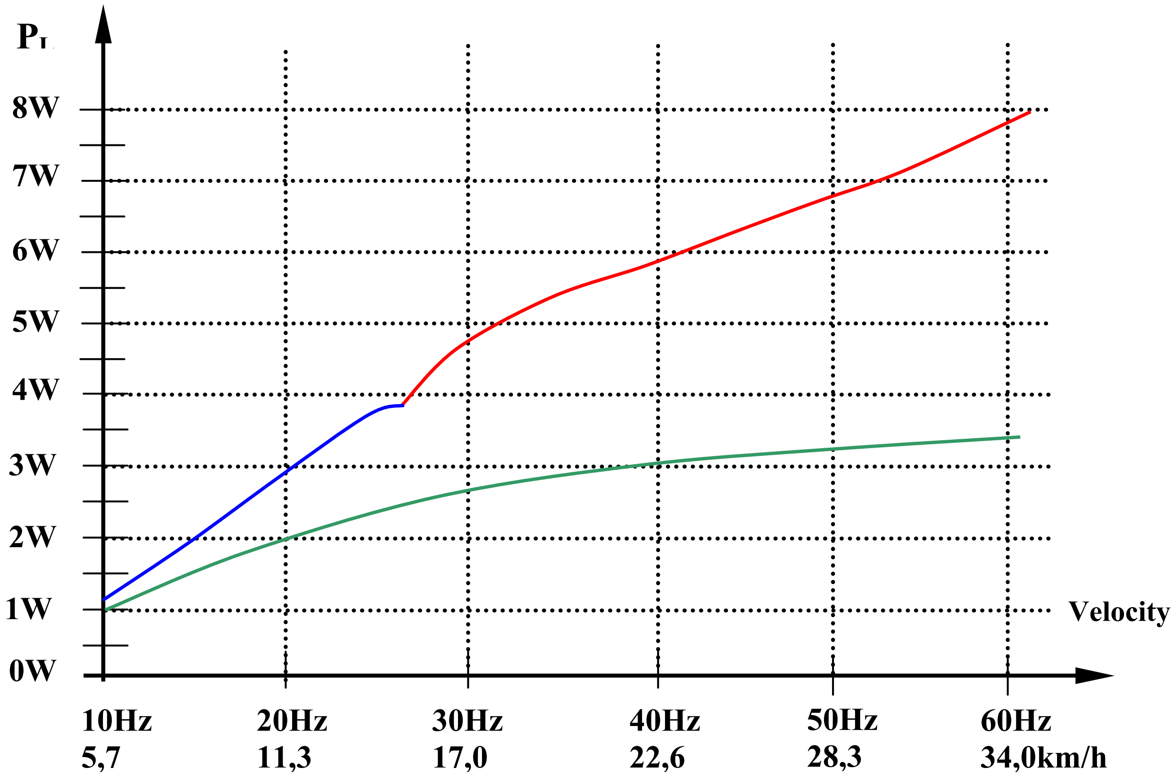
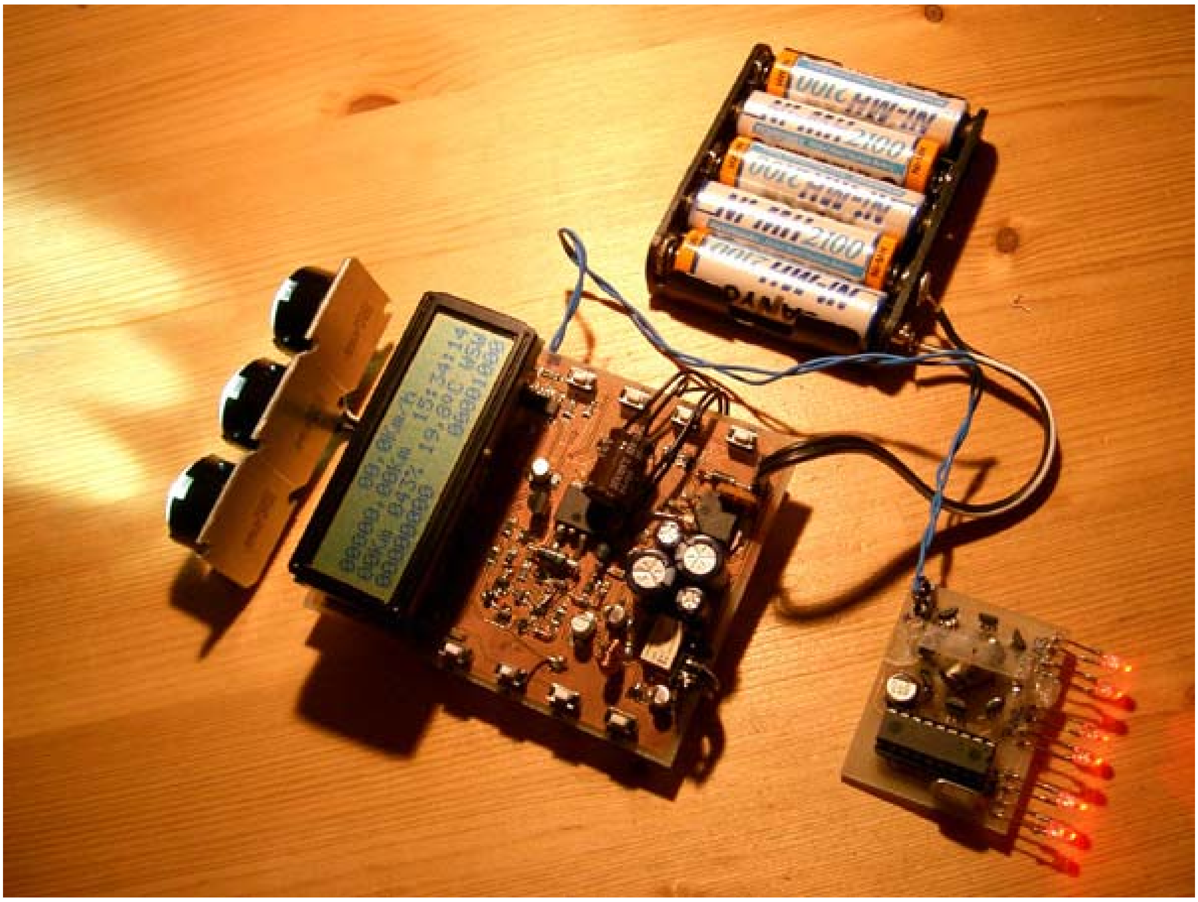


Fig.12: Power versus velocity for conventional case (green) and our proposed solution (blue, red)

Experimental Set-up



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Conclusion

An electronic power management system for bicycles has been developed and analysed. It consists of a combination of two DC-DC-converter structures. A special control scheme provides a load matching including phase compensation for different driving velocities. The electronic power management allows a more effective way of supplying energy from a claw-pole generator. The gain is almost doubled. It is a good basis for building up a more powerful bicycle light and it offers the opportunity to integrate additional functions because of the continuous supply, because of synergetic use of the dynamo as power source and sensor.

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