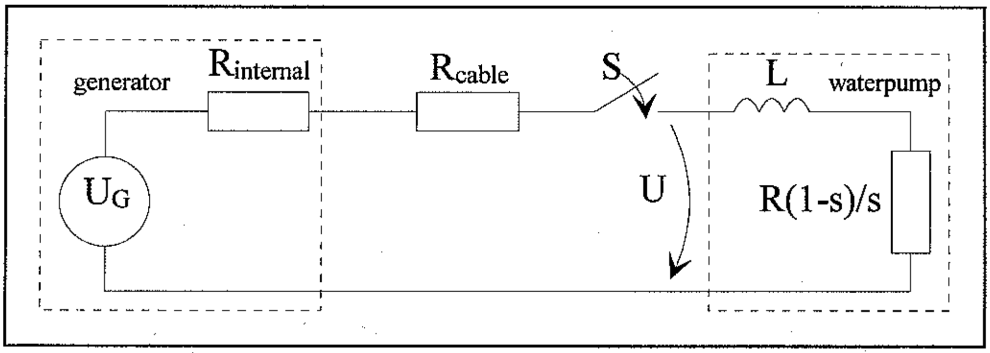
Improvements on the automatic start unit of

the FC 4000 wind turbine

for water pumping application



By

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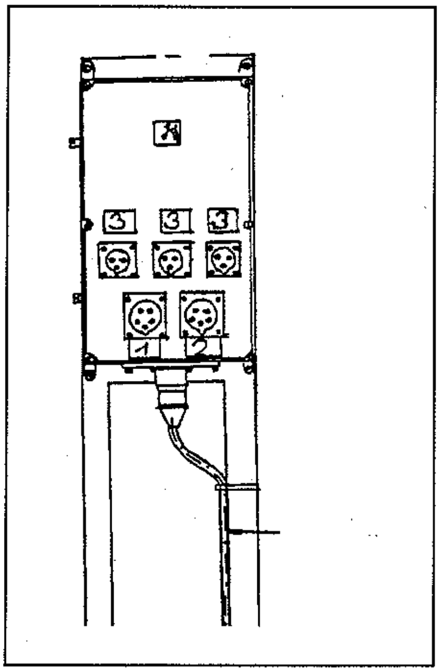
FC-print

Contents

1 Introduction

The FC 4000 is a 1,5 kW wind turbine for multi-purpose applications. It can be used for single phase applications like electric tools or battery charging as well as for 3 phase applications like water pumping, work shop machines grinding machines etc. /1/. It delivers variable voltage and frequency depending on wind- and revolution speed.
Changes became necessary because of the replacement of the 3 x 230 V generator by a 3 x 400 V generator due to matching reasons for the photovoltaic-wind-hybrid power plant which integrates the FC 4000.
The wiring of the sockets for the single phase applications has simply been changed to star connection. To allow unsymmetric operation the star point of the sockets was connected to the generator star point. After changing relay coils and transformer the relay of the control system flickered.



Two reasons for the flickers were found out:

1. Before the change a 3 x 230 V generator was coupled to a 3 x 400 V pump motor in star connection. This is known as a smooth starting help for big motors (star - delta - start), reducing the start current.
2. The working range of the relay coil from 80 - 400 V was far to big.

fig.1: Connection box: The automatic start unit is connected to socket 1, socket 2 is directly coupled to the generator and the 3 sockets above are for single phase applications. The connection can be selected with a hand operated switch (see app 4.5).

2 Water pumping

2.1 Basics

Water pumping is one of the most suitable applications for wind turbines. Generally the centrifugal pump fits better to variable speed windturbines than the piston pump. The power of a centrifugal pump depends in the third power on the revolutions /2/. However if a wind turbine's electric generator is connected to an electric water pump motor the wind turbine is not able to start by itself because it can not provide the necessary start power.
As shown in fig. 2 the wind turbine develops at zero speed zero power while the water pump needs a certain start power P_{start} to overcome the friction and the water pressure. Therefore the water pump works as a brake and avoids a start.

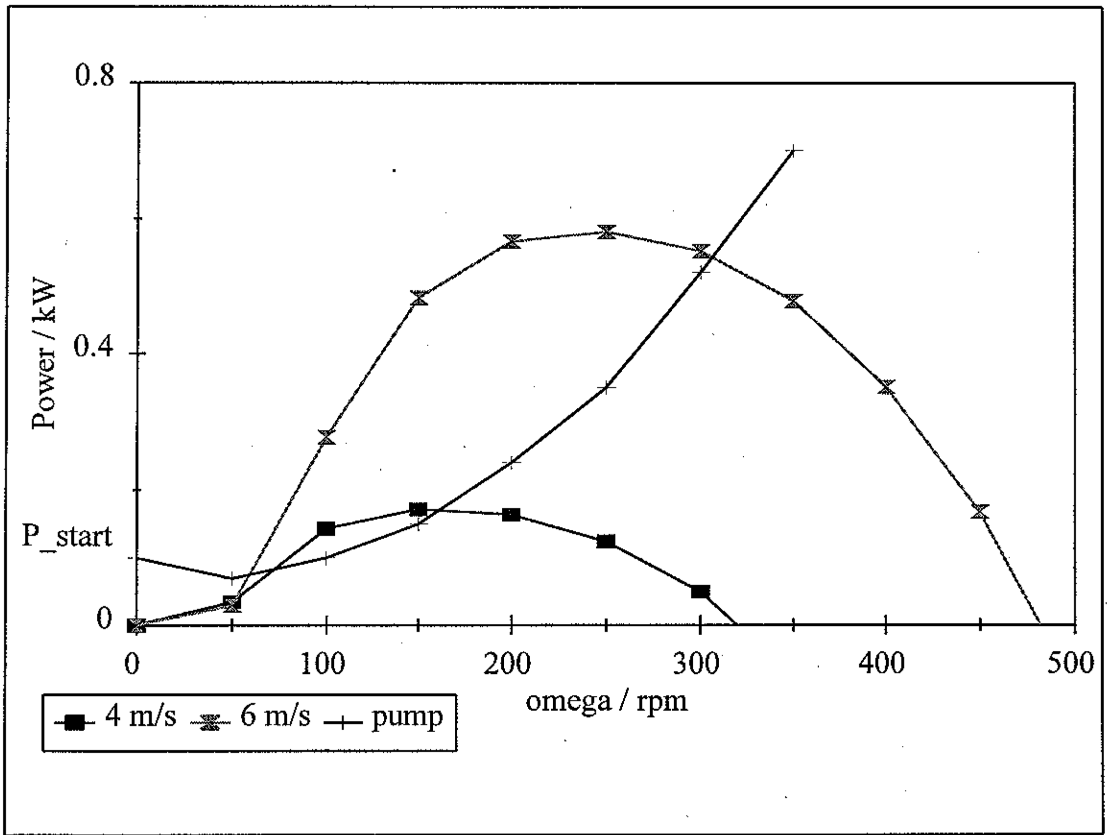


fig.2: Power characteristic of a water pump (the characteristic from 128 to 385 rpm is given by the manufacturer, lower points are assumed) and of the FC 4000 (calculated with Wind Rotor Design 2.0 for a tip angle of 4°)

If e.g. somebody would turn the wind turbine by hand and and increase the rotation speed by $\Delta\omega$ (see fig. 3), $P_{Pump}(\Delta\omega) > P_{wind\ turbine}(\Delta\omega)$.
The power difference is compensated with the deceleration of the wind turbine:
$P_{windturbine} = P_{pump} + dW/dt$

$$P_{Pump}(\Delta\omega) = P_{windturbinet}(\Delta\omega) - \frac{J}{2}\frac{d\omega}{dt}$$

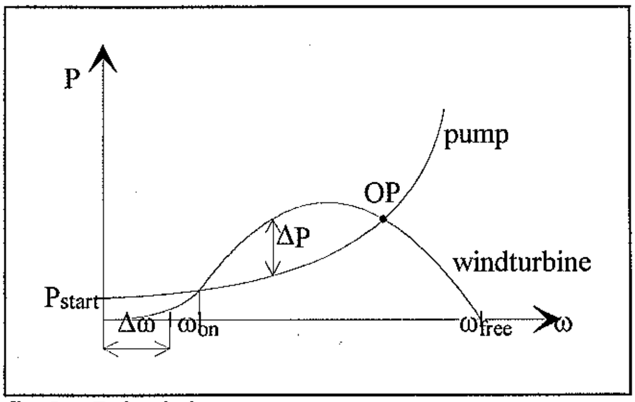


fig.3: Prinziple

Out of this follows that the wind turbine will slow down and stop. Getting started the waterpump must be disconnected. Because of the lack of load the power generated from the blades $P_{windturbine}(\Delta\omega) > 0$ accelerates the rotating mass until the speed ω_{free} is reached and the generated power is equal to the consumed power (which is equal to 0 if the friction is neglect). To get a stable output the load can be connected at a speed of $\omega > \omega_{on}$. From ω_{on} on the waterpump consumes less power than generated. The difference accelerates the wind turbine up to the point of intersection with the pump's curve. The intersection is the stable operating point (op). For deviates from the operating point the following is valid:

$\omega_{op} + \Delta\omega$: $P_{pump}(\omega_{op} + \Delta\omega) > P_{windturbine}(\omega_{op} + \Delta\omega)$ -> The windturbine slows down.

$\omega_{op} - \Delta\omega$: $P_{pump}(\omega_{op} + \Delta\omega) < P_{windturbine}(\omega_{op} + \Delta\omega)$ -> The windturbine speeds up.

In both possible deviates the system returns to the stable operating point (see fig.2).

2.2 Solution

The waterpump is switched on and off automatically by means of a relay as soon as a certain speed is reached /3/. The sensing of the cut in speed can be done by voltage sensing because for permanent magnetized generators (PMG's) the voltage is proportional to the frequency which is proportional to the revolution speed.

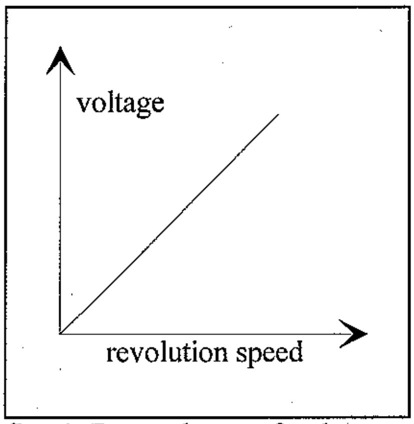


fig. 4: Dependence of voltage and revolutions for PMG's

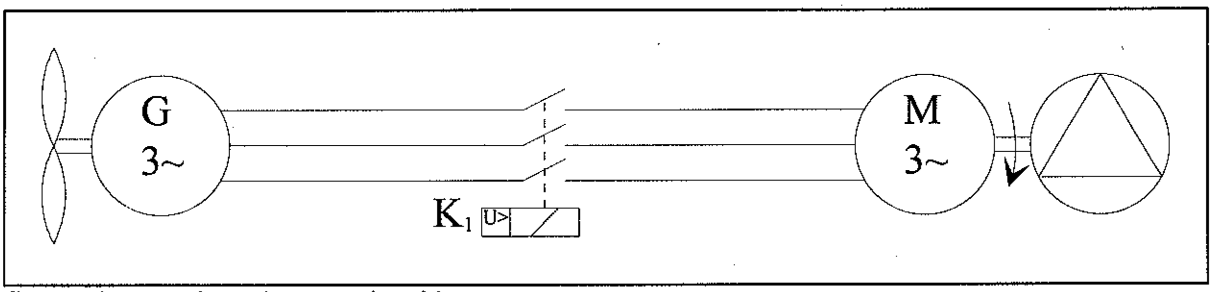


fig. 5: Connections (power circuit)

Closing the switch S (see fig. 5 and 6) the voltage U will drop down as soon as a current flows because of the voltage drop on the internal resistor R_i and the cable resistance. The internal resistance of PMG's is rather high compared with electric excited generators because of the weaker magnetic field in PMG's.

$U = U_G - \Delta U$; $\Delta U = I * Z$

Following, as soon as the voltage limit exceeds the given limit the relay would switch on the pump, the high start current for induction motors would occur, the voltage decreases below the limit and the relay would switch off very fast. Unloaded, the voltage would rise and the relay switch on... The relay flickers. To avoid this flicker a hysteresis is needed.

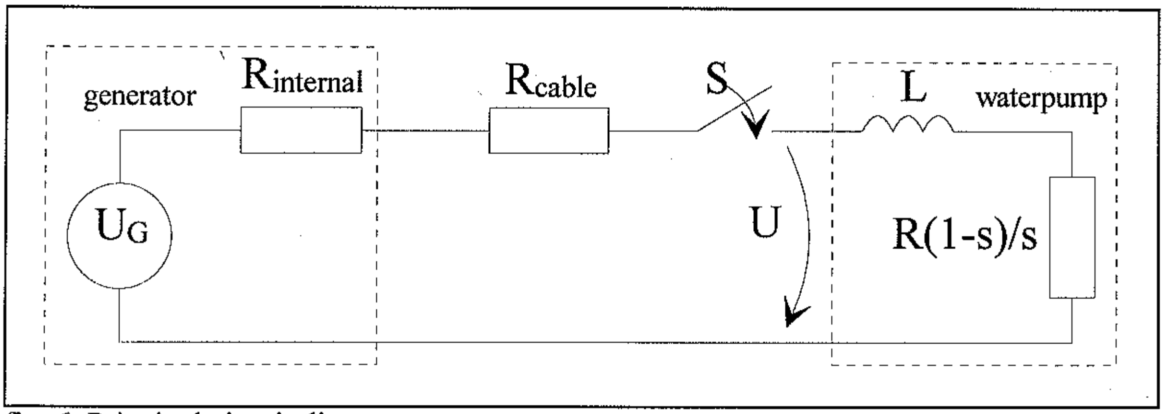


fig. 6: Principal circuit diagram

Measurements on an unloaded 1,5 kW induction motor 3 x 380 V in star connection as well as on a centrifugal diving water pump 1,5 kW, 3 x 380 V have shown, that the voltage drops from the chosen cut in voltage of 140 V down to around 80 V. Therefore the hysteresis must also be roughly 50 %. The start current for electric drives in delta connection is even higher and so the hysteresis has to be.

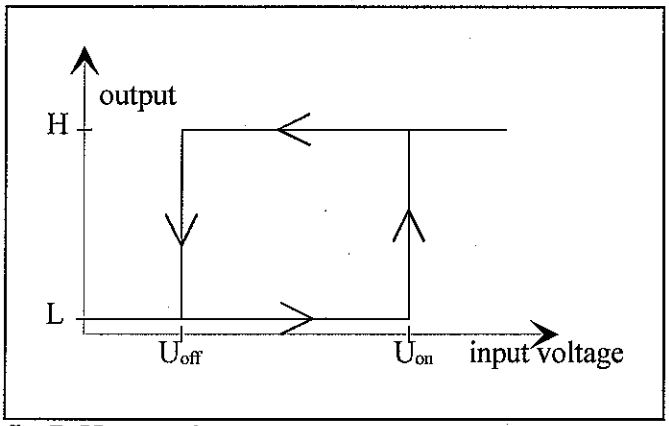


fig.7: Hysteresis

2.3 Realization - circuit design

2.3.1 Sensing unit

Special voltage sensing relays are available with adjustable hysteresis and 24 V DC supply (see app 4.3).
Alternatively it can also be built easily. So one is independent from any supply. The used components are very basic standard components, available all over the world. They could also be taken from scrap radios, computers etc.
Voltage sensing can be done by a comperator which compares the generator voltage with a constant reference voltage. The hysteresis can be realized by a feed back loop which increases the input voltage once the system has switched on. An operational amplifier (OP) with single (unsymmetric) supply was chosen for the realization of the comparator.
The amplification factor of a OP is practically infinite /5/. Out of this follows with
$\Delta U = U_{R2} - U_z$ (see fig. 8) for: $\Delta U > O$: $U_a = U_{supply}$ = High
and for $\Delta U < O$: $U_a = 0$ = Low

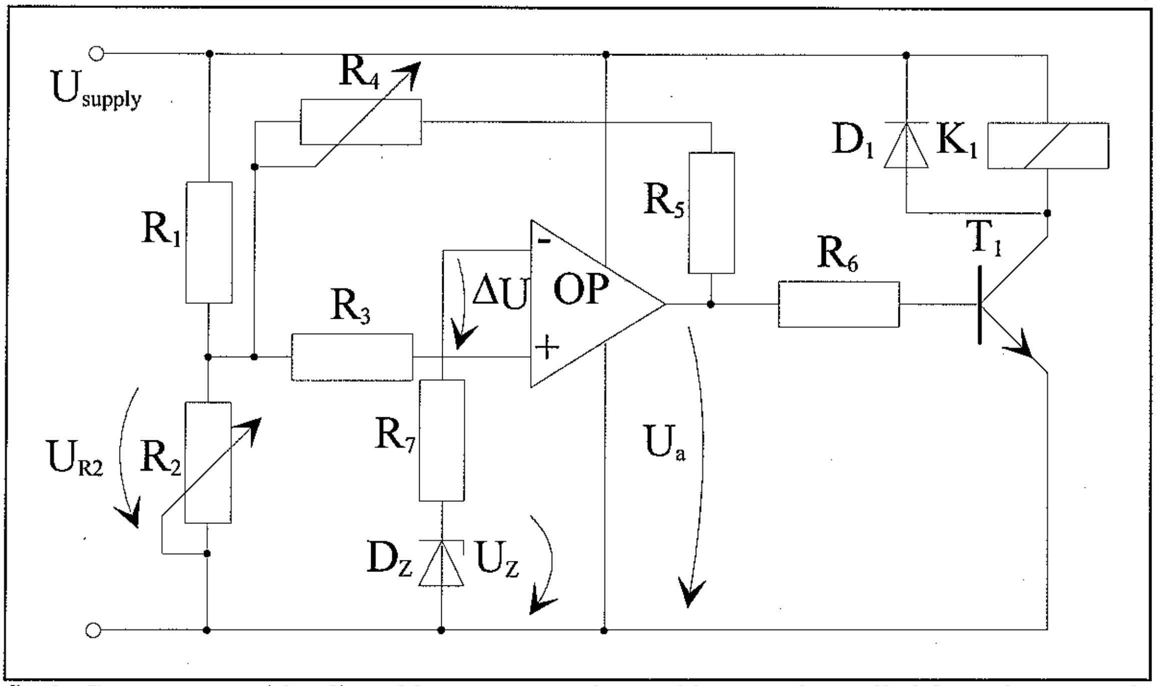


fig.8: Comperator with adjustable response value and hysteresis applied for voltage sensing

For $U_{R2} > U_z$ the OP output is (logic) high. The transistor T_1 provides the necessary current to operate the relay K_1. R_4 and R_5 realize the feedback loop. A part of the output voltage is fed back via R_4 and R_5 back to increase the input level U_{R2}. The hysteresis is adjustable by setting R_4. R_5 sets the maximum of the hysteresis. Without using the resistor R_5 and a too small value of R_4 the feed back is so big that the output remains in the actual state (low or high) independent from the input level.

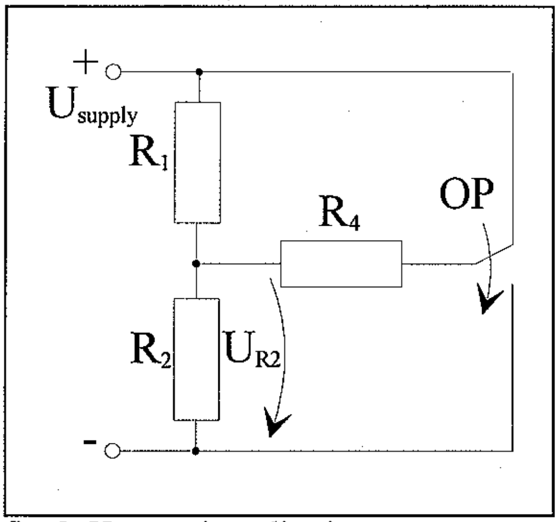


fig. 9: Hysteresis realization

R_2 is adjustable to select the desired cut in speed while R_4 affects the cut off.

2.3.2 Power supply

The sensing unit as well as the relay have to work in a wide voltage range because of the variable speed operation of the windturbine. In /3/ it is mentioned that the desirable cut in speed is at around 140 rpm ≈ 140 V. When unloaded (pump may be disconnected) voltages up to 640 V (at 513 rpm = overspeed; for the nominal speed of 428 rpm the maximum voltage

amount to 563 V) have been measured on the windturbine. For U_N = 400 V these measured values amount to 0,3 - 1,6 U_n. Ordinary relays work usually from 0,8 - 1,1 U_n. Solid state relays have been considered as an alternative but the manufacturer gives a working frequency range of 40 - 60 Hz. Resulting from the lower limit the cut in speed would be much to high. Triacs and optocouplers can be recommended as alternative power units with very low internal consumption.
For availability reasons in developing countries a solution with an ordinary relay was prefered. The realization is based on stabilized power supply at 24 V /5/. Relays are easiely available for 24 V. A relay type Telemechanique LP1 D1801 (18 A, AC3) was used, because it was on hand. This relay works also with 0,5 U_n however the switching time is longer. This will reduce the lifetime. But in this case life time is not so critical because switching takes place at low speed and therefore low power. The relay chosen is suitable for switching off a inductive current up to 18 A and inductive loads. That means it is oversized for this application (max. generator current around 5 A). Therefore it has enough reserves in the switching capability and can be operated slower (with lower voltage).
A nominal 230 V supply input was considered to be the best because of it's universal usability for both 3 x 230 V and 3 x 400 V (phase to phase, phase to ground voltage amounts to 230 V) generators.

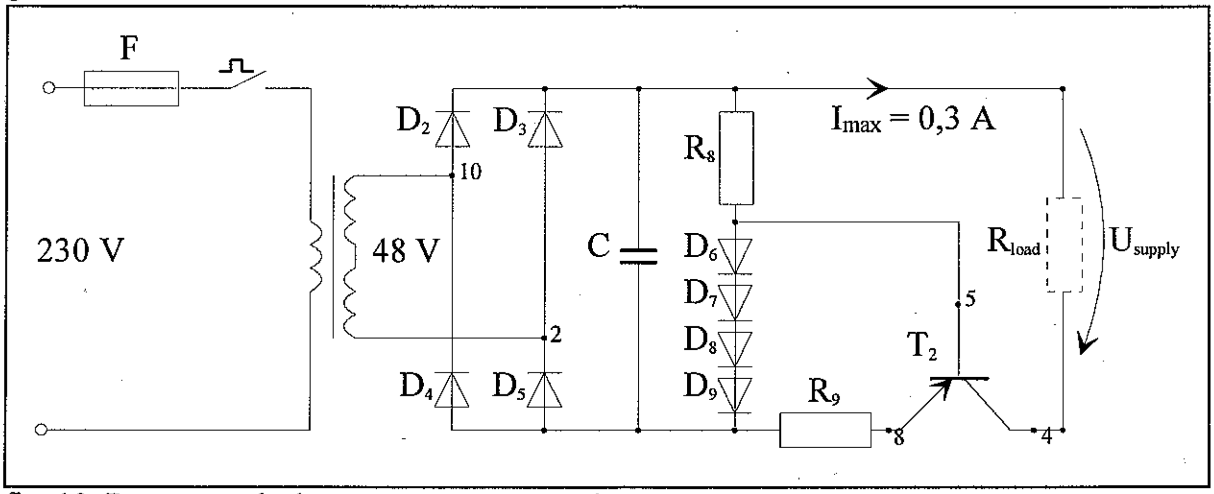


fig. 10: Power supply (constant current source)

The transformer is a 230 V / 2 x 24 V type. The maximum generator voltage (unloaded) is around 310 V. Therefore it is recommended to avoid unloaded operationOne can expect that it will happen sooner of later. Therefore the transformer is protected with a thermoelement and the primary circuit is fused and the secondary circuits are calculated for unloaded operation at nominal speed (428 rpm). However for the insulation of the transformer can not be guaranted. That is why do not put the switch on position 1 if there is no pump connected.
A bridge rectifier delivers DC. The rectifier diodes D_2 - D_5 are stressed by a blocking state voltage (inverse peak voltage) of

$$U_{block} = \sqrt{2} * U_{max,gen} * tr = \sqrt{2} * 310\,V \frac{48V}{230V} = 95\,V$$

The minimum DC voltage for 140 rpm is

$$U_{DC} = 0{,}9 * U_{AC} = 0{,}9 * \frac{140\,V}{\sqrt{3}} * \frac{48}{230} = 15{,}2\,V = 0{,}63\,U_n$$

The current will not exceed 1 A.
A capacitor smoothes the voltage. The capacitor will be charged up to the AC peak value U_{max} = U_{block}. It's value can be estimated so that during the discharging period the voltage does not drop down for more than 10 %. The discharging current is the relay current. The relay current

measured was 0,3 A. The discharging period is between T/2 and T/4 long. For rough calculation it was assumed to $\Delta t = T/3$. The frequency at 140 rpm is 16 Hz.
With f = 1 / T follows:

$$C = \frac{dQ}{dU} = \frac{I * \Delta t}{\Delta U} = \frac{I}{3 * f * \Delta U} = \frac{0{,}33\,As}{3 * 16 * 3\,V} = 2200\,\mu F$$

The capacitor will be charged to the peak value

$$U_{DC,peak} = \sqrt{2} * U_{AC} = \sqrt{2}\,\frac{140\,V}{\sqrt{3}} * \frac{48}{230} = 23{,}8\,V$$

During the discharging period the voltage drops down about 10%.
$U_{DC,min} = 21{,}4$ V
That fits to the lower limit for the relay voltage.
The DC is stabilized by a constant current source. By setting the right current value for the relay it can not burn. Furthermore the voltage has to be constant for a constant current on a defined resistor (relay coil). Instead of D_6 - D_9 a Zener diode could be used. The transistor T2 realizes the constant current source. The current value can be set by varying R_9.
$U_{R9} = I_E * R_9 = U_z - U_{BE}$
Supposing the current would rise the voltage drop on R_9 increases, U_{BE} decreases, the base current drops down and so does the collector current. The current limit was set to 0,3 A which is equal to the measured relay current at 24 V.

$$R_9 = \frac{U_z - U_{BE}}{I_E} = \frac{2{,}8\,V - 0{,}7\,V}{0{,}3\,A} = 7\,\Omega$$

The heat transmission is for R_9:
$P_{R9} = 0{,}3\ A * 7\ \Omega = 2{,}1$ W
The minimal value for R_8 is given by the maximal permissible diode current.

$$R_{8,min} = \frac{U_{max,sec}}{I_{per}} = \frac{95\,V}{1\,A} = 95\,\Omega$$

The maximal value is given by the necessary base current for T_2 which has to deliver 0,3 A collector current for the relay:

$$R_{8,max} = \frac{U_{min}}{I_B} = \frac{U_{min} * \beta}{I_C} = \frac{21{,}4\,V * 75}{0{,}3\,A} = 5{,}3\,k\Omega$$

To operate the transistors T_1 in the saturation range $R_8 = 1$ kΩ was selected.

$$P_{R8} = \frac{(U_{max})^2}{R_8} = \frac{(95\,V)^2}{1\,k\Omega} = 9{,}1\,W$$

The heat transfer capability of T_2 must be:
$P_{trans,max} = U_{CBmax} * I = (U_{max} - U_{relay} - U_{R9}) * I = (95\ V - 24\ V - (7\ \Omega * 0{,}3\ A)) * 0{,}3\ A$
$= 20{,}7$ W
The cooling need is:
$Q = \alpha * A * \Delta T$
with $\alpha = 5{,}82\ W/m^2/K$ for non-moving air, $T_{box} = 50$ °C and $T_{transistor} = 120$ °C. The area of the heat sink comes to:

$$A = \frac{Q}{\alpha * \Delta T} = \frac{20{,}7\,W\,m^2\,K}{5{,}82 * 70\,K\,W} = 0{,}0508\,m^2 = (20\,x\,25\,cm)$$

A disadvantage for this type of stabilisation is that the voltage is only constant as long as the current can flow through the relay. If the relay would be disconnected the voltage would rise without limit and the OP would be destroyed for a voltages above 30 V.
Therefore a solution with a stabilized voltage is a good alternative, see /5/.

2.4 Results

The circuit was build in a PCL-relay house and works well. The transistor T2 was mounted on a cooling sheet metal. All the components were placed in the connection box.
The performance is well. Under low wind regimes without stable operating point (see fig. 2) the wind turbine speeds up for a few minutes, cut in, slow down some minutes, cut off... so that even low wind regimes without stable operating point can be used for water pumping.

2.5 Improvements: Matching generator - waterpump

Under good wind conditions (around 10 m/s) one can expect significant more water pumped than under less wind conditions. But it does not. Comparabel to the measurements taken in /2/ it was observed that the voltage breaks suddenly down at high frequeny while the generator accelerate until the airbrakes works. It could be because at higher speed the pump motor takes a higher current which leads to a higher internal voltage drop in the generator and finally the power decreases.
Fig. 10 shows that the generator power exceeds the water pump input power a little bit for the working range shown. The matching is very well done in this range. The reason for the only slowly rising output at high wind regimes must be searched for somewhere else. There were no data form the manufacturer on hand for the range above 400 rpm. It could be worth to examine this range by further measurements because the power drops at a speed above 400 rpm.
One could also focus on the reactive power balance /4/. A reactive power compensation must be controlled by the voltage, frequency or load. Otherwise the open circuit voltage would rise even more (640 V have been measured, for speed reduction down to 428 rpm (nominal) it is still 563 V !).
Possibly better matching could be reached by the application of an optimum power controlled AC - DC - AC converter. However the expenditure is high. The efficiency of inverters is usually up to 93 %.

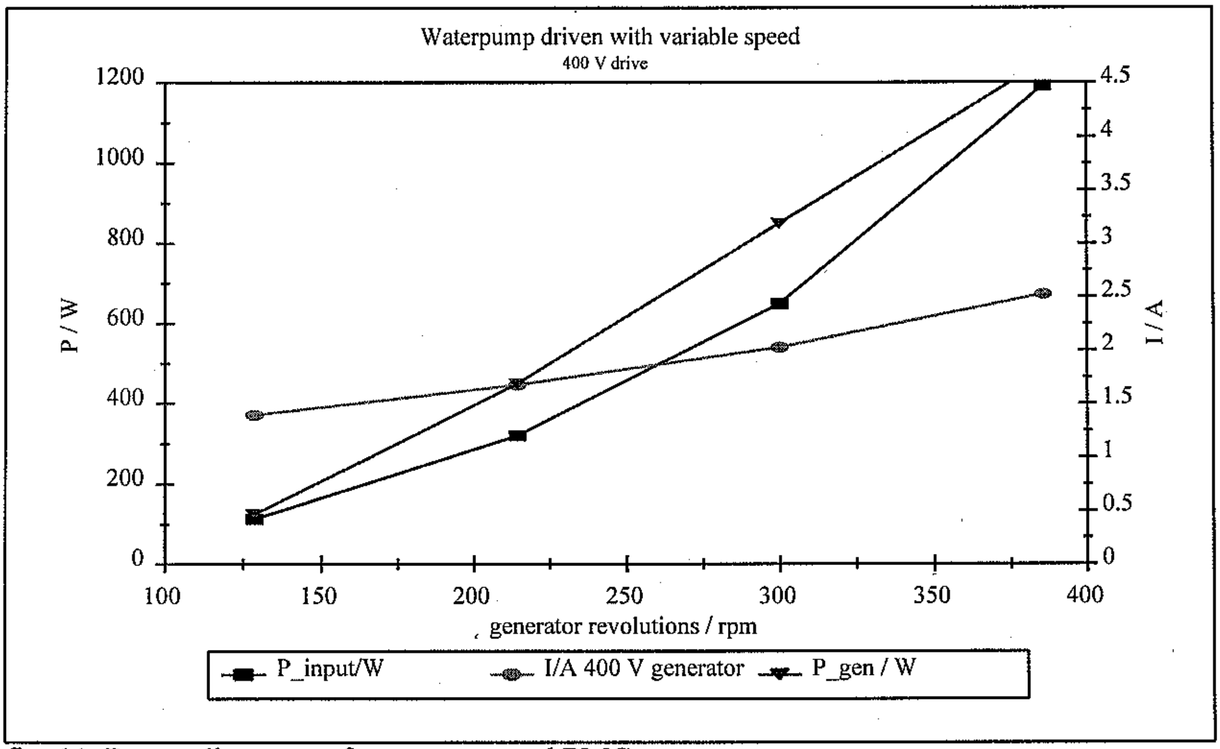


fig. 11: Power diagrams of waterpump and PMG

3 References

/1/ Yde,L., Jagadeesh,J., Rasmussen,P.: FC 4000 - A stand alone windturbine with multiple applications for developing countries, FC-print

/2/ Grisko,J.: Wind pump system FC 4000 Measurement on a modell, FC-print, 1993

/3/ Yde,L., Gylding,C., Schugmann,M.: Manual on FC 4000 Wind Motor, FC-print, 1993

/4/ Grundfoss: Dykpumpe Grundfos SP2A-27 (user manual), 1991

/5/ Köthe,H.K.: Stromversorgung mit Solarzellen. Poing, 1994

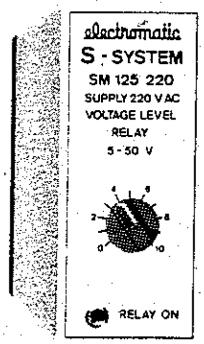
4 Appendix

4.1 Components

element	value / name	remark
R1	100 kΩ	
R2	50 kΩ	potentiometer
R3	10 kΩ	
R4	100 kΩ	potentiometer
R5	12 kΩ	
R6	1 kΩ	
R7	50 kΩ	
R8	1 kΩ	10 W
R9	6,8 Ω	2 W
D1	1N4007	
D2..D5	με WO-005	
Dz	BZX 6V2	
D6..D9	1N4007	
C	1000 μF	
T1	BD 135	npn, $\beta = 75$
T2	2N3055	npn, 120 W
K1	Telemechanique LP1 1801	
F	melting fuse 0,2 A	
OP	LM 124/A	single supply 3 - 30 V

4.2 Abbreviations

A	area
C	Capacity
H	logic high
I	current
J	inertia moment
L	logic low
P	power
Q	heat
R	resistance
s	slip
T	temperature
t	time
tr	transmission ratio
U	voltage
W	energy
Z	Impedance
α	heat transmission factor
β	current amplifying factor
ω	$\omega = 2 * \pi * f$



SM 125 = 11-pin circular plug

SM 125

- AC/DC voltage metering relay.
- Measuring range 0.1-500 VAC (peak) or VDC, divided into 5 ranges.
- Knob-adjustable set point.
- Latching at set level possible.
- 10 A SPDT output relay.
- LED-indication: relay on.
- AC or DC power supply.

SPECIFICATIONS

See common technical data

Hysteresis
Approx. 10%. The hysteresis can be extended to 75% by connecting a resistor between pins 8–9. Resistor limits are 1 MΩ and 15 KΩ. The hysteresis increases by decreasing resistance.

Measuring range

Ranges	Internal resistance	Max. voltage (peak)	YYYY
0.1 – 4 VAC/DC	8 KΩ	50 VAC	4 V
2 – 20 VAC/DC	50 KΩ	100 VAC	20 V
5 – 50 VAC/DC	100 KΩ	200 VAC	50 V
20 – 200 VAC/DC	450 KΩ	350 VAC	200 V
50 – 500 VAC/DC	1 MΩ	500 VAC	500 V

By AC voltages the SM 125 measures the PEAK VALUE - and the above AC ranges are VAC PEAK.

Latching
The relay latches at set level when pins 8–9 are interconnected.

Ordering key
11-pin circular plug
SM 125 XXXYYYY = 10 A SPDT

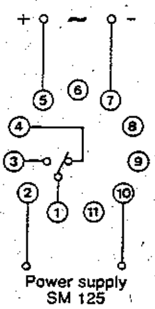
XXX = power supply
024 = 20– 28 VAC
115 = 95–135 VAC
230 = 195–265 VAC
724 = 20– 28 VDC

YYYY: See measuring ranges.

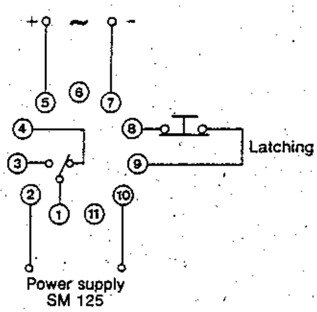
Accessories
Bases.
Hold down spring.
Mounting rack.
Base covers.
Front mounting bezel.

WIRING DIAGRAMS

Example 1



Example 2



Note:
At DC supply:
Do not connect pin 7 with pin 10, as these pins are internally connected via a resistor of 3.9 KΩ.

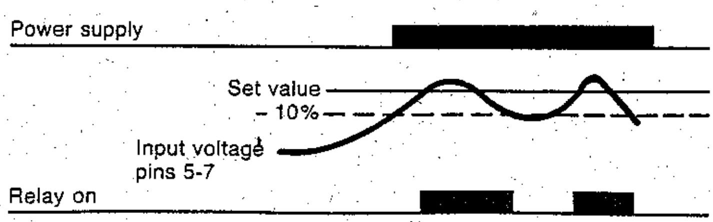
MODE OF OPERATION

Example 1
AC/DC voltage metering.
The relay operates when the voltage (peak voltage by AC) reaches the set value.
The relay releases when the voltage drops at least 10% below the set value (see hysteresis) or by interrupting the power supply.

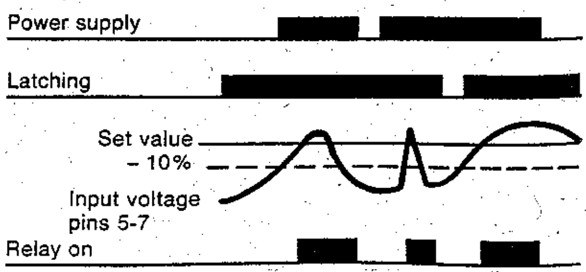
Example 2
AC/DC voltage metering.
Latching.
The relay operates when the voltage (peak voltage by AC) reaches the set value and then latches in operating position. The relay releases by removing the latch, i. e. by opening the contact between pins 8-9, provided that the voltage has dropped at least 10% below the set value (see hysteresis), or by interrupting the power supply.

OPERATION DIAGRAM

Example 1



Example 2



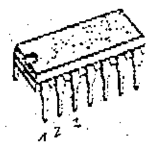
4.4 Operational amplifier

SGS-THOMSON
MICROELECTRONICS

LM124/A - LM224/A LM324/A - LM2902

LOW POWER QUAD OPERATIONAL AMPLIFIERS

- LARGE VOLTAGE GAIN : 100dB
- VERY LOW SUPPLY CURRENT/AMPLI : 375μA
- LOW INPUT BIAS CURRENT : 20nA
- LOW INPUT OFFSET VOLTAGE : 2mV
- LOW INPUT OFFSET CURRENT : 2nA
- WIDE POWER SUPPLY RANGE :
  SINGLE SUPPLY : +3V TO +30V
  DUAL SUPPLIES : ±1.5V TO ±15V



N
DIP14
(Plastic Package)
J
CERDIP14
(Cerdip Package)

D
SO14
(Plastic Micropackage)

DESCRIPTION

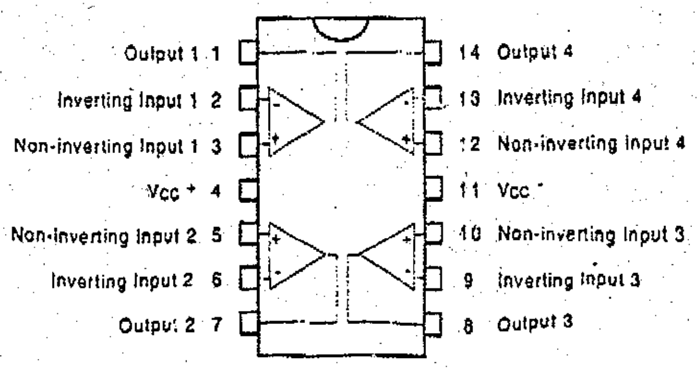
These circuits consist of four independent, high gain, internally frequency compensated operational amplifiers which were designed specifically for automotive and industrial control systems. They operate from a single power supply over a wide range of voltages. Operation from split power supplies is also possible and the low power supply current drain is independent of the magnitude of the power supply voltage.

ORDER CODES

Part Number	Temperature Range	Package N	J	D
LM124/A	− 55°C, +125°C	•	•	•
LM224/A	−40°C, +105°C	•	•	•
LM324/A	0°C, +70°C	•	•	•
LM2902	−40°C, +105°C	•	•	•

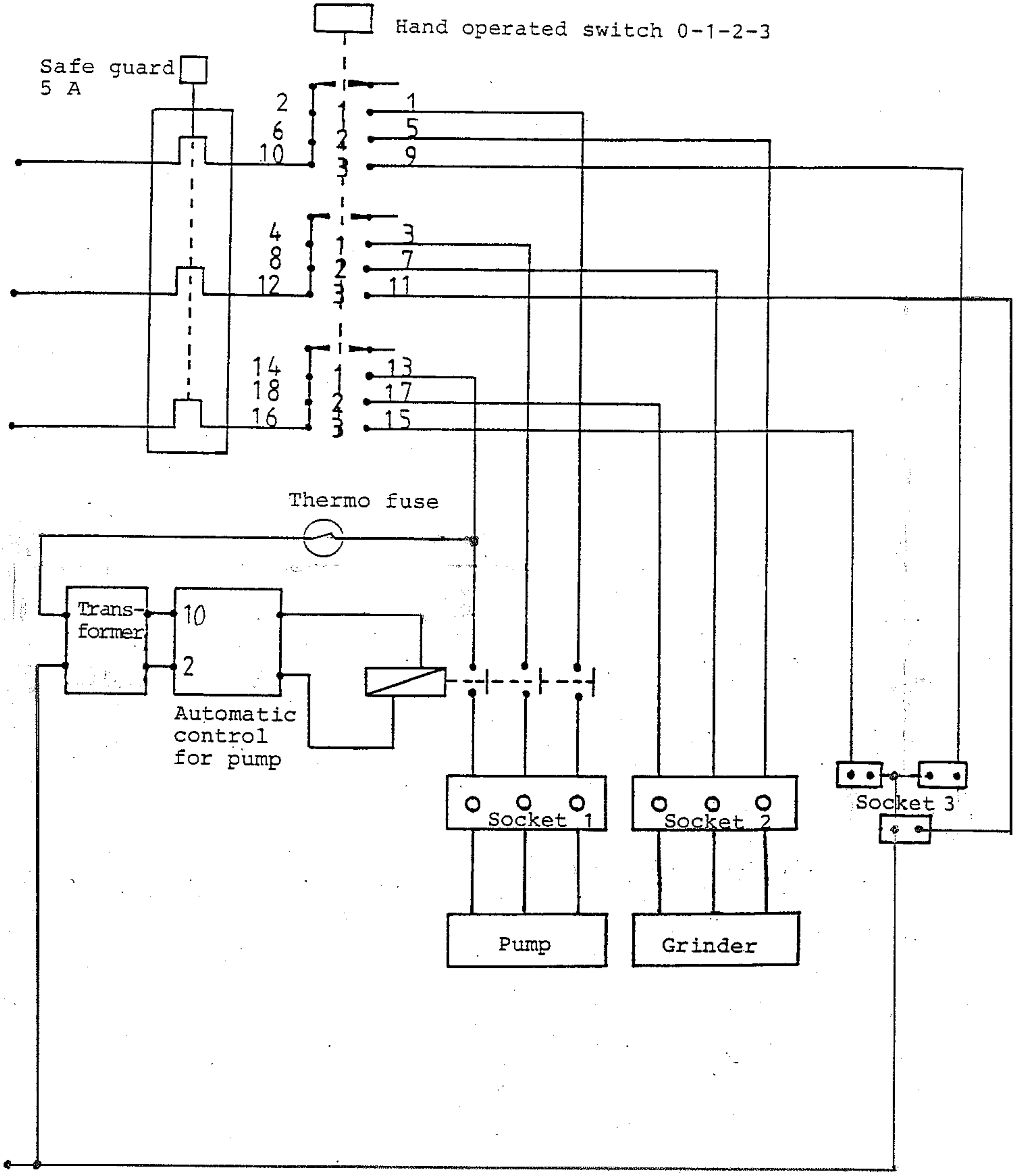
Examples : LM124J, LM224N

CONNECTIONS (top view)



124-01.EPS

4.5 Connection box



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Energi

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