DESIGN, TESTING AND SENSITIVITY ANALYSIS OF ELC

A DISSERTATION

Submitted in partial fulfillment of the requirements for the award of the degree

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ALTERNATE HYDRO ENERGY SYSTEMS

By

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CANDIDATE'S DECLARATION

I hereby certify that the work being presented in this dissertation, entitled **"DESIGN, TESTING AND SENSITIVITY ANALYSIS OF ELC "**, in partial fulfillment of the requirement for the award of the degree of Master of Technology in **"Alternate Hydro Energy Systems"**, submitted in **Alternate Hydro Energy Centre, Indian Institute of Technology, Roorkee** is an authentic record of my own work carried out during the period from July 2005 to June 2006 under the supervision of **Shri S.N.Singh,** Senior Scientific Officer, Alternate Hydro Energy Centre, Indian Institute of Technology, Roorkee.

I have not submitted the matter embodied in this dissertation for award of any other degree.

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Date: June 28, 2006
Place: Roorkee

This is certified that the above statement made by the candidate is correct to the best of my knowledge.

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ABSTRACT

This Dissertation presents design, testing and sensitivity analysis of an electronic load controller (ELC) for single-phase synchronous generators suitable for stand-alone micro-hydropower generation with constant input power. The synchronous generator may be used to generate constant frequency if the electrical load is maintained constant at its terminals.

A suitable control scheme has to be developed such that the load on the synchronous generator remains constant despite change in the consumer load. In such applications, water is freely available and, hence, a simple and cheap controller has to be developed, which can operate almost unattended in remote and hilly regions.

In this scheme, the principle of phase angle control of back to back thyristor is used. A thyristor is fired at a specific delay angle relative to the zero voltage crossing of the sine wave (symmetrical for both halves of the sine wave). The thyristor commutates at next zero crossing. Switching occurs a twice the frequency and generates total harmonic distortion (THD) as high as 35 - 40 % in current with added reactive power burden. This scheme can continuously vary the dump power over nearly the entire range from zero to full load as the delay angle varies from 180 degree to 0 degree.

CONTENTS

LIST OF FIGURES

NOMENCLATURE

ELC	Electronic load controller
IGBT	Insulated Gate Bipolar Transistor
IGC	Induction Generator Controller
kW	Kilo Watt
kVA	Kilo Volt Ampere
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
PLC	Programmable Logic controller
AVAR	Automatic Voltage Regulator
IC	Integerated Circuit
PCB	Printed Circuit Board
BJT	Bipolar Junction Transistor
Op-Amp	Operational Amplifier
LED	Light Emitting Diode

INTRODUCTION AND LITERATURE REVIEW

1.1 INTRODUCTION

Micro hydroelectric sets are defined as those with unit ratings of less than 100 kW. They are often situated in remote communities, particularly in developing countries. As they are often isolated from grid networks their technical characteristics are such that they require a governor to maintain the frequency at an acceptable level for the users.

The specification for a rural electricity supply is a lot less rigorous, or rigid. The communities, which install these sets usually, have limited finance and limited skilled labour, if any, to operate and maintain the equipment. Unfortunately, as the kW rating of hydroelectric plant decreases then the cost per kW increases [1]. Hence, for a community to afford a micro hydroelectric generating set the capital cost of the plant must be as low as possible and the plant must be as simple to install, operate and maintain as is possible. The philosophy that must be adopted is that medium efficiency plant, which can be afforded, is of greater value than high-efficiency plant, which cannot be afforded. As a result, communities can reap the benefits of an electricity supply of modest output rather than have no supply at all.

A key item of the plant is the governor. Traditionally, speed governors such as the mechanical-hydraulic type have been installed which adjust the speed of the set by controlling water flow - through the action of a water-regulating device on the turbine. Such devices, e.g., spear valves or guide vanes are highly engineered turbine components and are designed for high-efficiency operation. The modem equivalent is the electro-hydraulic governor which uses electrical or electronic means to sense changes in speed but still controls the water flow. The cost of such a governor is often dearer than the cost of the generator at these ratings. The accepted alternative to the speed governor is the Electronic Load Controller (ELC), which maintains the speed of the set by adjusting an electrical ballast load connected to the generator terminals, maintaining a balance between the total electrical load torque and the hydraulic input torque from the turbine, Fig. 1.1. In this case, the water flow is kept constant and hence the water-regulating device can be dispensed with. Typically the cost of the ELC is about one tenth that of the speed governor and so the economic advantage of the ELC is twofold, as a result of the lower capital cost of the governor and of the turbine.

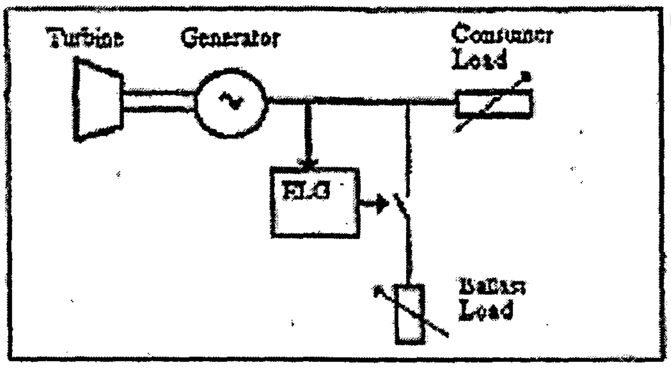

Fig 1.1 The load governing principle

An Electronic Load Controller (ELC) is used for a Micro Hydro Power system fitted with a synchronous generator and powering just some houses or a small, local grid. So it is a stand-alone M.H.P system: It is not connected to the state/national grid. An Induction Generator Controller (IGC) is used for a Micro Hydro Power system fitted with a induction type electrical motor that is turned into a stand-alone generator by fitting capacitors to it. Again, it is a stand-alone system, powering just some houses or a small, local grid.

Together with the dump loads/ballast connected to it, an ELC serves as an automatic, electrical load manager that controls frequency of electricity produced by the generator. It measures frequency and depending on whether this frequency is above or below nominal frequency, diverts more or less power to the dump loads that are connected to it. To a large extend, mechanical power required to drive a generator, is determined by total electrical load connected to it. Mechanical power produced by the turbine is nearly constant so when more power is diverted to dump loads, generator demands more mechanical power than the turbine can deliver, causing turbine and generator to slow down.

With a synchronous generator, electrical frequency is related directly to its mechanical speed, so then frequency will drop also. Inversely, turbine and generator will accelerate and frequency will increase when less power is diverted to dump loads. This way, the ELC controls electrical frequency and, with this, speed of generator and turbine. It prevents the generator from over speeding when total power demand of user load appliances that are switched on, is less than capacity of the system.

With synchronous generators, no special measures are needed to control voltage of the electricity produced [2]. Synchronous generator has inbuilt automatic voltage regulator (AVR) which keeps voltage in check under wide range of operating conditions.

An IGC with dump loads also acts as an electrical load manager. The main difference with an ELC is that it reacts to generator voltage rather than frequency. So in the first place, it keeps generator voltage in check. With an induction generator, speed and voltage are strongly related so by controlling its voltage, also speed and frequency are kept within acceptable limits.

The induction motors used as induction generators, are the standard industrial motor that is used all over the world. It is simple, cheap, widely available, robust and requires little maintenance. Sometimes induction motors are also called `asynchronous' motors. Induction motors as generator are advantageous for smaller systems that are mainly used for lighting.

Especially for small capacity systems, a synchronous generator is more expensive than an induction motor plus capacitors. But with a synchronous generator with ELC, frequency is more accurately controlled and such systems can produce the large starting current required by electrical motors. This makes that synchronous generators become attractive when:

(a). Capacity is rather high.

(b). When it should power electrical motors (e.g. for productive end-uses).

(c). When it should power expensive, sensitive appliances that need a well-regulated electricity supply.

Using dump loads is an energy-inefficient way of regulating as usually, more than half of electricity produced, will be wasted in dump loads. It is like driving a car with a brick on the accelerator causing the motor to continuously run at full throttle, and then regulating its speed by using the brake: Imagine what fuel consumption will be with this driving style.

From efficiency point of view, using a governor that steers a flow control valve on the turbine, would be much better. But then reducing water consumption of the turbine so it only makes sense if water can be stored in a reservoir for future use saves energy. Usually Micro Hydro systems do not have such large reservoirs.

They are 'run of river' systems and any water that is not used right away, gets lost in an overflow. Nowadays only Mini Hydro or full-scale hydro systems have governors as these often have large reservoirs so that water that is saved, can be stored.

Governors are expensive and require careful maintenance, making the M.H.P system more expensive and less reliable. Older Micro Hydro systems often had governors, but that was because building affordable ELC's and IGC's only became possible using modern power electronics.

There are M.H.P systems that run quite satisfactorily without an ELC, IGC or governor. Then a flow control valve on the turbine is adjusted manually. This way of regulating is only feasible if most user loads are connected permanently, so if they cannot be switched off by users. Also, sensitive appliances that might get destroyed by large voltage or frequency variations cannot be used. Which type of system is best for a specific Micro Hydro Power system depends on many factors [3].

Like an ordinary load manger, the ELC / IGC + dump loads can only consume energy and not produce any. This means that it can control frequency and voltage only as long as total power demand from users is less than capacity of the system. When total power demand would be higher than system capacity, there is an overload situation. Then the ELC / IGC can only switch off dump loads completely. It cannot generate any extra power to help coping with a too high demand.

1.2 LITERATURE REVIEW

The Electronic load controller is relatively new concept of governing turbine-generator sets, has met with increasing interest in recent years. Very few technical literatures are available on Electronic load controller.

Wallace, A.R., D.S and Whittington [1] have presented a paper on capital cost of small scale hydro schemes. In this paper it is described as the kW rating of hydroelectric plant decreases then the cost per kW increases.

Nigel P.A. Smith [2] has described a new and simpler control approach to controlling generator on stand alone micro-hydro systems. This paper has explained three techniques for governing the voltage and frequency variations, these were phase-angle control, switched binary-weighted loads and variable mark-space ratio chopping.

Harvey [3] has described non-conventional governing system that could be used to reduce speed during run-away situations.

Jan portegijs [4] has described detailed technical aspects of Electronic load controller. They have developed the Electronic load controller. They have described many technical information and design considerations for building and troubleshooting an ELC.They have focused on phase angle regulation technique with two ballast loads. Control schemes and over/under voltage, over-speed protection features are also emphasized.

SGS Thomson [5] has described about data sheets available on BTA26 and BTA41 triacs.

Fisher [6] has described about the heat sink construction. He has also provided catalogue on heat sinks.

Scharge and Zeeuw [7] have described about thyristors protection. Thyristors can be protected against too high dI/dt by small, saturable noise suppression coils. These should limit current during rise-time and a part of spreading time to several times the latching current.

Foley [8] has described about limitation of voltage. A voltage of 10% above nominal voltage causes life span to be reduced to only 20% of its normal life span.

A.Pittet and B.Oettli [9] have described the functional prototypes and design aspects of Electronic Load Controller (ELC). They have presented plenty of technical details met with interest of development of ELC.

Dr. Douglas Henderson [10] has presented paper in which he has described original research and development of an electronic load controller, which is microprocessor, based and incorporates three-phase balancing.

S.S Murthy, et al. [11] have presented in which he has described the field experoince of a stand alone power generating scheme using electronic load controller.

E.T.Volker et al. [12] have presented in their book about descriptive material intended to assist in the planning for design, development, and operation of small hydroelectric power plant control systems.

Dr. Geetha Varma, et al. [13] have presented their report about field testing of an induction generator load controller for micro hydel station using pump as turbine and induction motor as generator.

Rashid Muhammad [14] has described about different power electronic devices in his book.

Gayakward, R.A. [15] has described about different type of Opamps and their characteristics.

Robert, I.B. [16] has described about electronic devices and their circuitry in hias book.

Woodward, J.L., et al. [17] described about various control systems in his journal.

Louineau, et al. [18] describe about various methods of rural lightening in his publications.

Oreta, et al. [19] have described about micro hydropower initiatives in his publication.

R. Bonert, et al. [20] has proposed an electronic impedance controller to control the voltage and frequency of generator.

WORKING PRINCIPLE OF ELECTRONIC LOAD CONTROLLER

2.1 GENERAL

Phase Angle regulation, Pulse Width Modulation or Binary Loads .ELC / IGC regulates power diverted to dump loads in the same way as ordinary light dimmers: By means of phase angle regulation of phase regulation is shown in Fig 2.1 At some moment during each half period of sine-wave shaped generator voltage, the dump load is switched on and remains switched on for the rest of this half period. The moment, at which the dump load is switched on, is expressed as a phase angle. Right at the beginning of a half period, phase angle is 0° and towards the end, it is 180° (of course at that point, a new half period begins with phase angle = 0° so phase angles between 180 and 360° have no practical meaning).

For phase angle regulation, almost always triacs or thyristors are used as power element. These electronic devices can be switched on by a short trigger pulse on their `gate' connection and then remain conducting for the remainder of that half period. By then, generator voltage drops to zero, current through the dump load and triac or thyristor drops to 0 and they stop conducting or `extinguish' by themselves. Triacs can conduct in both directions, so they can operate during both positive and negative half periods of generator voltage. Thyristors can conduct only in one direction so two thyristors would be needed to steer one load.

A major advantage of phase angle regulation is the fact that those triacs or thyristors can be used. These are the `work horses' of power electronics: They are old-fashioned, cheap, widely available and can stand rough operating conditions. There are thyristor types that can switch thousands of Amperes at voltages well into kiloVolt range and at quite high frequencies. Triac ratings are a bit more modest, but still high enough for this ELC / IGC design and they have the advantage of simpler triggering requirements[5].

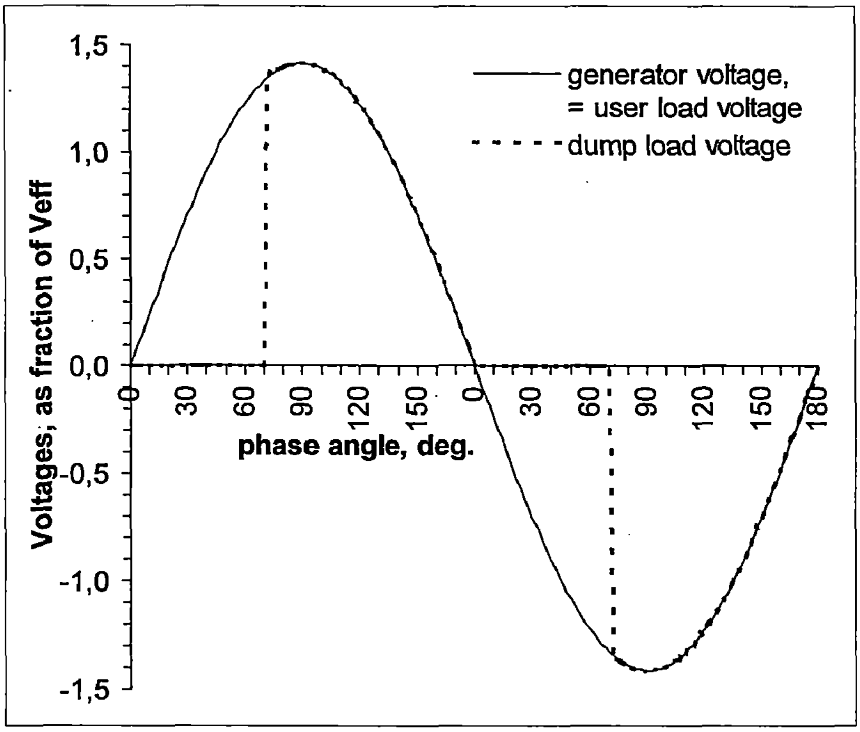

Fig 2.1:Principle of phase angle regulation:A dump load is switched on during only the latter part of each half cycle

A major disadvantage of phase angle regulation is the electronic noise that is created when a triac is triggered while generator voltage is at its highest, so at around 90° trigger angle. Also, a load being switched at a phase angle around 90°, appears as an inductive load to the grid or generator. For use in dimmers in household situation, these effects pose no real problem since the grid is very powerful compared to the load switched by this dimmer. For use in an ELC or IGC, dump load capacity will be even slightly higher than generator capacity and noise is impressive . This makes that for use with a phase angle regulation ELC, the generator must be overrated[3]

ELC / IGC uses 2 or 3 triacs that each steer their own dump loads. Normally, trigger angles for these triacs differ by 90°. Only when trigger angle for one triac reaches its upper limit of 180°, or its lower limit of 0°, trigger angle for the other one(s) can approach this limit as well. So under no conditions, two triacs can be triggered at 90° at the same time and both produce heavy noise. Trigger angles for two triacs can only become nearly the same when they are both close to 0° (so both dump loads are fully switched on), or both close to 180° (both dump loads switched off).

Having 2 or 3 dump loads instead of 1, leads to the following advantages:

(a). Now capacity of each dump load is only 1/2 or 1/3 of that of a single dump load ELC. This makes that the adverse effects of noise are strongly reduced and the generator does not have to be overrated that much[3].Power diverted to dump loads is more proportional to input signal `trigger angle signal'. This makes that over a wider range, PI controller will work optimally.

(b). Since there are 2 or 3 triacs working in parallel, capacity can be quite high even when standard off the shelf triacs are being used.

Another way to regulate power diverted to a dump load is Pulse Width Modulation or Mark-Space regulation. This method stems from D.C. (Decent Current) power regulation. From one voltage, a second voltage is derived by fast switching. The mean value of this second voltage can be regulated by adjusting the duty cycle: The fraction of the time that a dump load is switched on. Usually, this is done by changing the duration of each pulse while time between pulses remains constant. But of course it could also be done by changing time between pulses while pulse width remains constant.

High capacity Pulse Width Modulation systems use thyristors as power elements. With D.C., the main thyristor will not stop conducting automatically at the end of a half period so an extra thyristor circuit is used that produces short, negative pulses that makes the main thyristor extinguish. For M.H.P purposes, this would become too complicated and modern power transistor types are used, e.g. Insulated Gate Bipolar Transistor (IGBT) or MOSFET.These power elements can be steered directly by tiny IC outputs: They conduct as long as voltage at their `gate' or `basis' connection is sufficiently high.

The main advantage of Pulse Width Modulation is that it requires a simple electronic circuit for steering the power transistor. Disadvantages are the relatively high price, poor availability and sensitiveness of those modern power transistors. Also dissipation in such a controller is higher since generator voltage first has to be rectified before it can go to the power transistor itself. Therefore they need a larger heat sink than a phase angle regulated controller with the same capacity.

The third method is by using a set of Binary Loads. This is a series of dump loads in which each subsequent dump load has half the capacity of the former, higher ranking one. With n dump loads, a total of 2^n combinations can be switched on, each of which are represent a different total capacity of dump loads being switched on.
For switching these dump loads, a series of Solid State relay can be used. These contain triacs or thyristors, but produce no electronic noise since they are either triggered just after the beginning of a half period, or remain off completely. Again, steering electronics can be quite simple. Disadvantages are:

(a). Costs of those Solid State relay, which is far higher than the triacs inside them because each of them contains steering electronics.

(b). The number of dump loads and the associated wiring. To achieve smooth regulation, these dump loads should all have exactly the right capacity.

(c). With a low number of dump loads, steps between dump load combinations remain too large and the system cannot regulate smoothly.

2.1.1 Zero crossings and trigger angles

As explained in the previous par., phase angle regulation works by triggering a triac at the right moment during each half period of sine wave shaped generator voltage. For doing this, one should first determine when each half period starts. Here, these moments are called zero crossings, as given in Fig 2.2.
Finding zero crossings would be easy if generator voltage would show a nice, sine-shaped waveform on an oscilloscope. The design has an advanced circuit to find these zero crossings in spite of such noise.

Just like phase angle, trigger angle is expressed as a value between 0 and 180° that corresponds with the moment at which the triac starts conduction, see previous par. The difference between the two is slight: A phase angle refers more to the time a triac is actually conducting and its dump load is switched on (so, from the moment a triac is triggered until the next zero crossing). A trigger angle refers only to the moment a triac is triggered. In this thesis, only trigger angle is used. Once triggered, by itself a triac will remain conducting until the next zero crossing so the right trigger angle will automatically lead to the right phase angle.

Besides this real `trigger angle' (in °), there is also a `trigger angle signal' (in V) in the ELC electronics and often, this is abbreviated to just `trigger angle'. From the context, it usually becomes clear whether this theoretical trigger angle(in °) is meant, or the practical electronic signal in V.

Once zero crossings are found, the right moments to trigger a triac can be found by just waiting for a specific delay time. This delay time can range between nearly 0 to nearly the time that corresponds with one half period. A short delay time means trigger angle is low and the corresponding dump load is switched on at nearly its full capacity. A long delay time means a high trigger angle and the corresponding dump load is switched on at only a fraction of its capacity. The extreme situation is not triggering the triac at all so that it is continuously in blocking state and its dump load is completely switched off. There is no linear relation between trigger angle and power diverted to a single dump load.

For ordinary light dimmers connected to a large grid, one can safely assume that frequency is practically constant at 50 or 60 Hz, so a half period always takes exactly 10 or 8.33 ms (millisecond). Then a specific delay time always results in the same trigger angle. For an ELC or IGC that is meant to regulate frequency, it cannot be assumed that frequency is constant, so the same delay time might result in a slightly different trigger angle depending on frequency at that moment.

There are IC's that can convert a DC input signal right into trigger pulses that correspond with a trigger angle as set by this input signal (e.g. type TCA785 produced by Siemens). So for a two-dump load ELC, in principle two of such chips could replace the sawtooth signal module, FT zone and final comparators. Most likely, these IC's were designed for use in dimmer-like applications, so with a constant frequency grid and little electrical noise. and it is not sure whether they would work fine in an ELC. To integrate such IC's would mean that a lot of testing has to be done all over[4]. The savings in terms of component costs would be limited and these IC's are not widely available.

2.1.2 General features of the design

The detail circuit diagram of electronic load controller is shown in Fig 2.3 and Fig 2.4 shows the protection features of ELC.These circuit diagram's are subdivided into modules that are separated from other modules by dashed lines. Small circles with a name or code printed with it represent measuring points or connections to other modules or the outside. A measuring point can be used for adjusting trimmers and for troubleshooting. With each trimmer, there is a name describing its function. Each Opamp has a number that corresponds with its number on the Printed circuit board (PCB) layout.

Components like resistors and capacitors are not numbered, but are referred to by its value and, if it might be confused with a similar component in the same module, by the other components it is connected to. The easiest way to find a certain component on the PCB is to look up in the circuit diagram which Opamp(s) is/are within that module, and then trace the components from that Opamp on the PCB map. The circuit diagram of ELC on PCB is shown in Fig 2.5 gives a map of print tracks and components on the PCB (Printed Circuit Board). This map is printed as seen from component side. This design is for a two-sided PCB, so with print tracks both on copper side (printed yellow) and on the opposite, component side (printed green). By far the most print tracks are on copper side. When making a two-sided PCB would be too difficult, one could also print copper side only and replace the print tracks on component side by wire bridges. Square islands mean that measuring points will be fitted there. Most of the diamond islands are used to make connections between copper side and component side. Print tracks that carry major signals have some spare diamond islands that can be used for future modifications. On both sides, there is text labeling connections, measuring points, trimmers etc.

The connections diagram of Fig 2.6 shows how the ELC is connected to the other components in the M.H.P system.

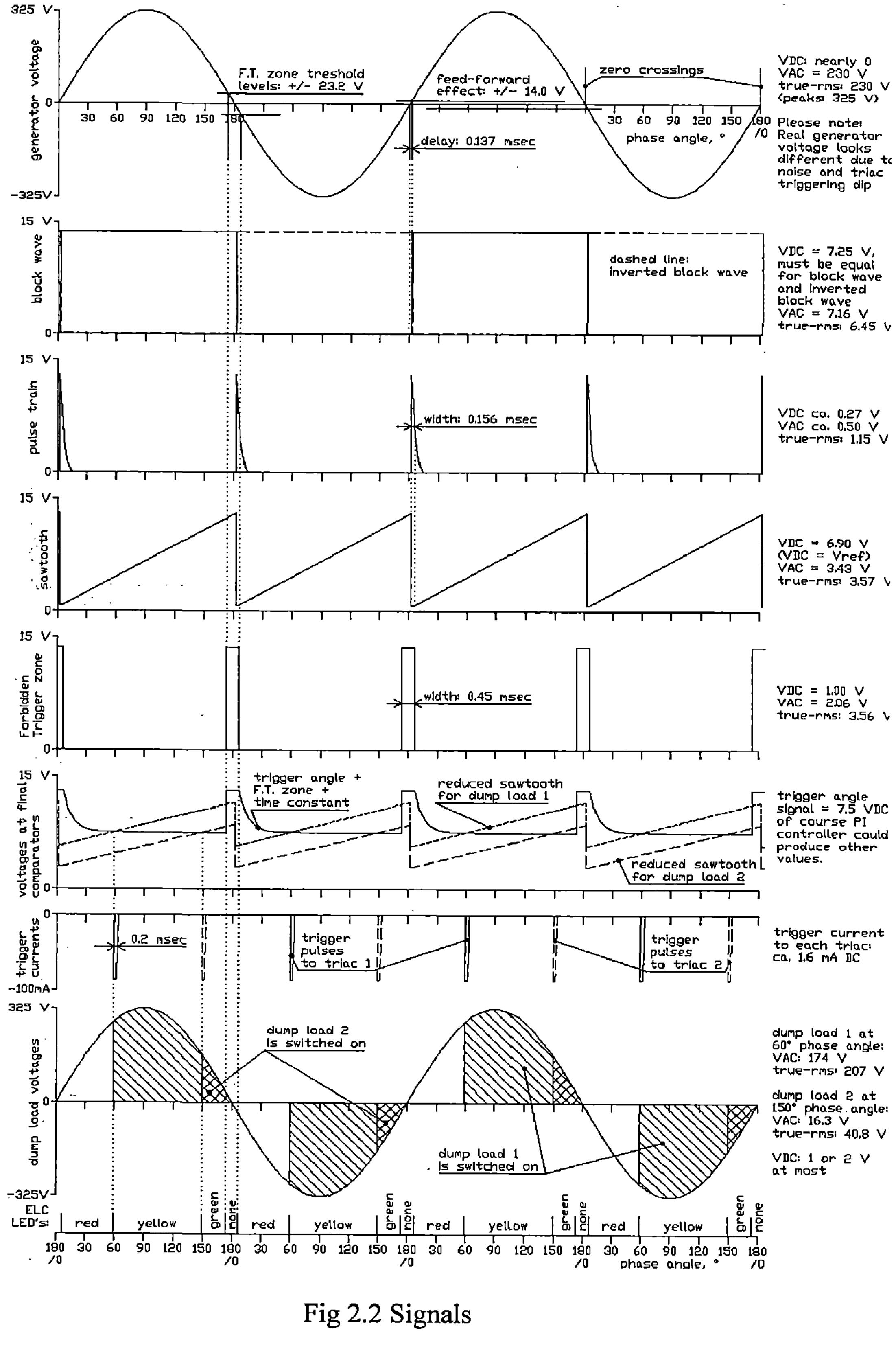

Fig 2.2 Signals

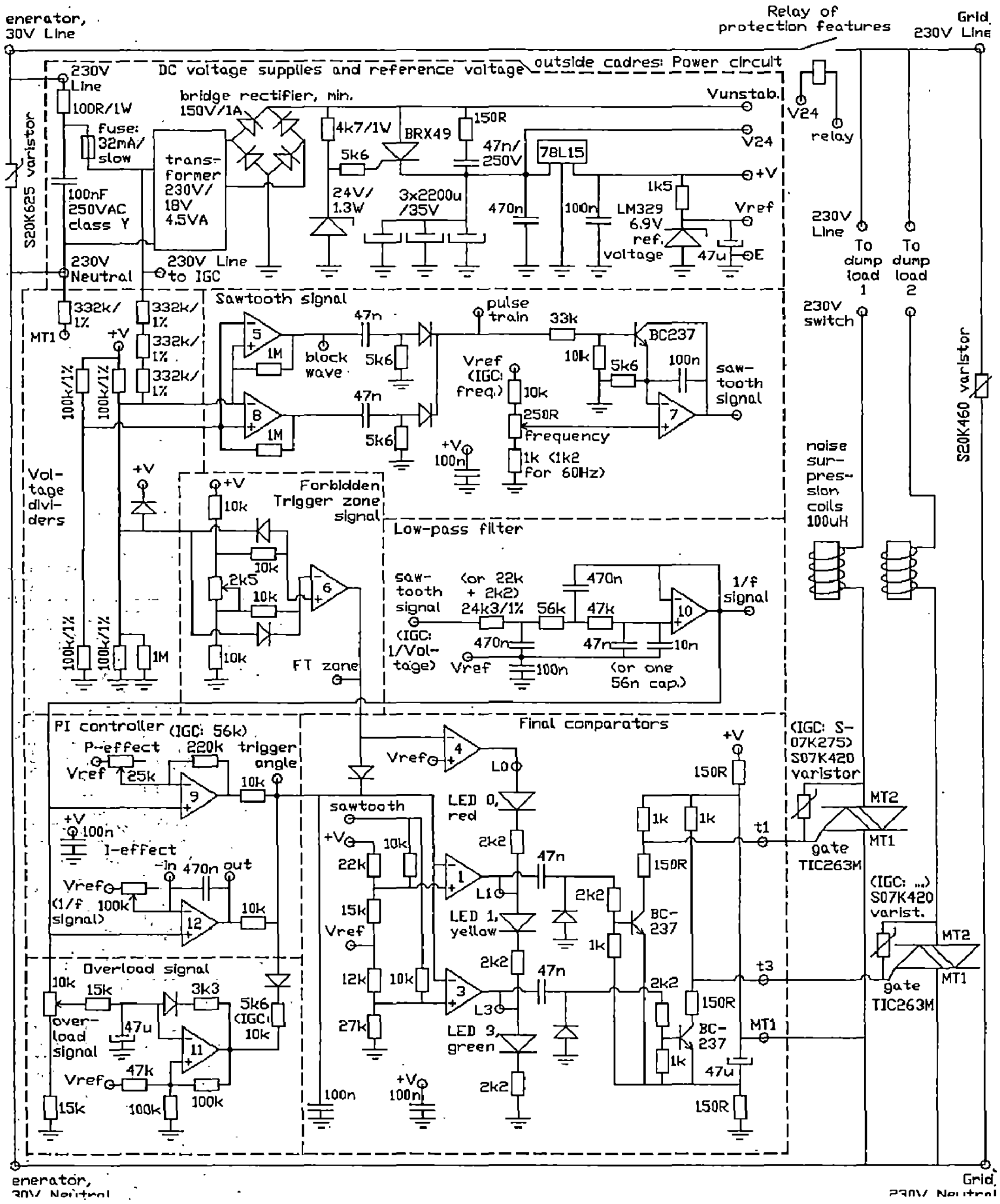

Fig 2.3 Circuit diagram of ELC.

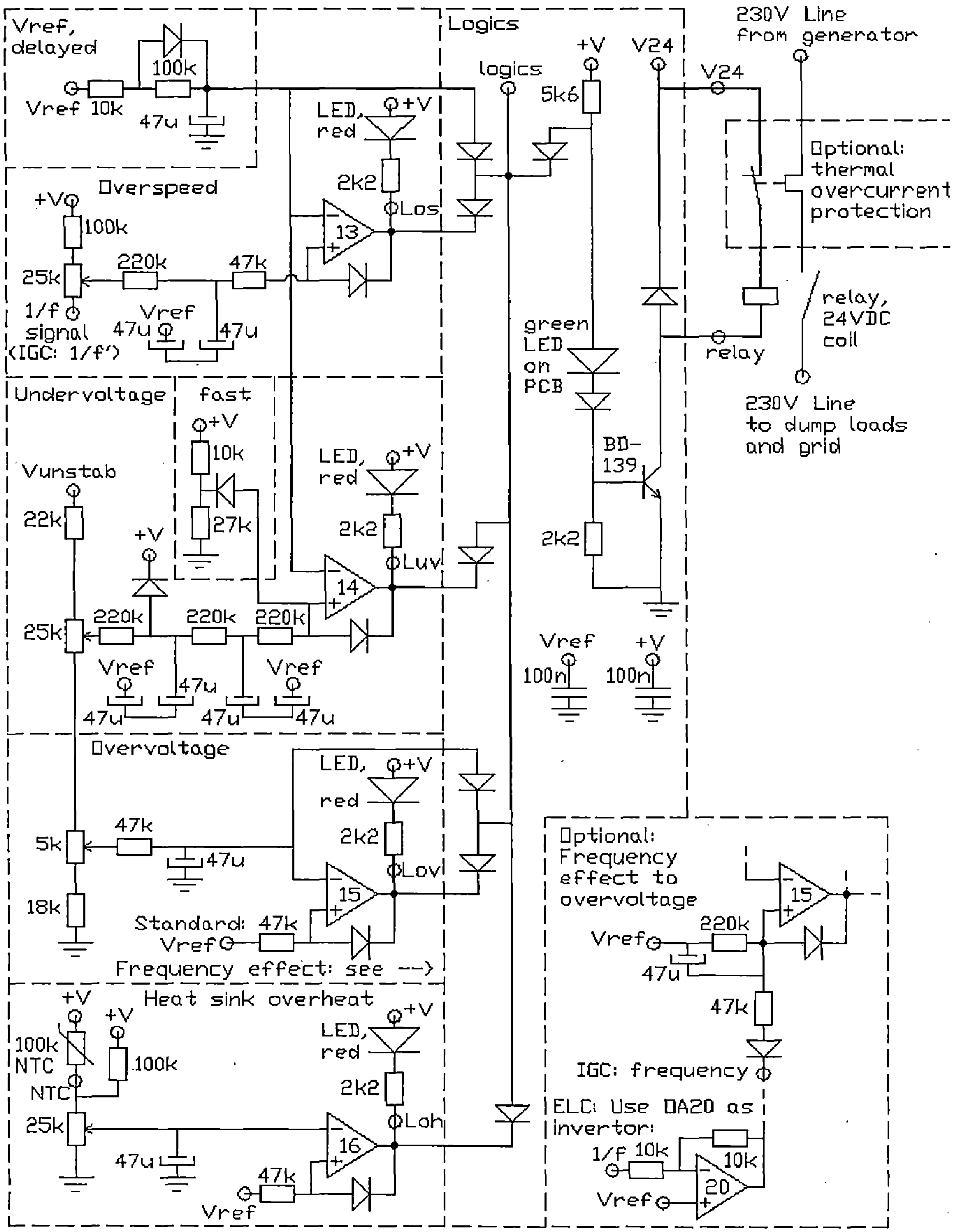

Fig 2.4 Circuit diagram of protection features for ELC .

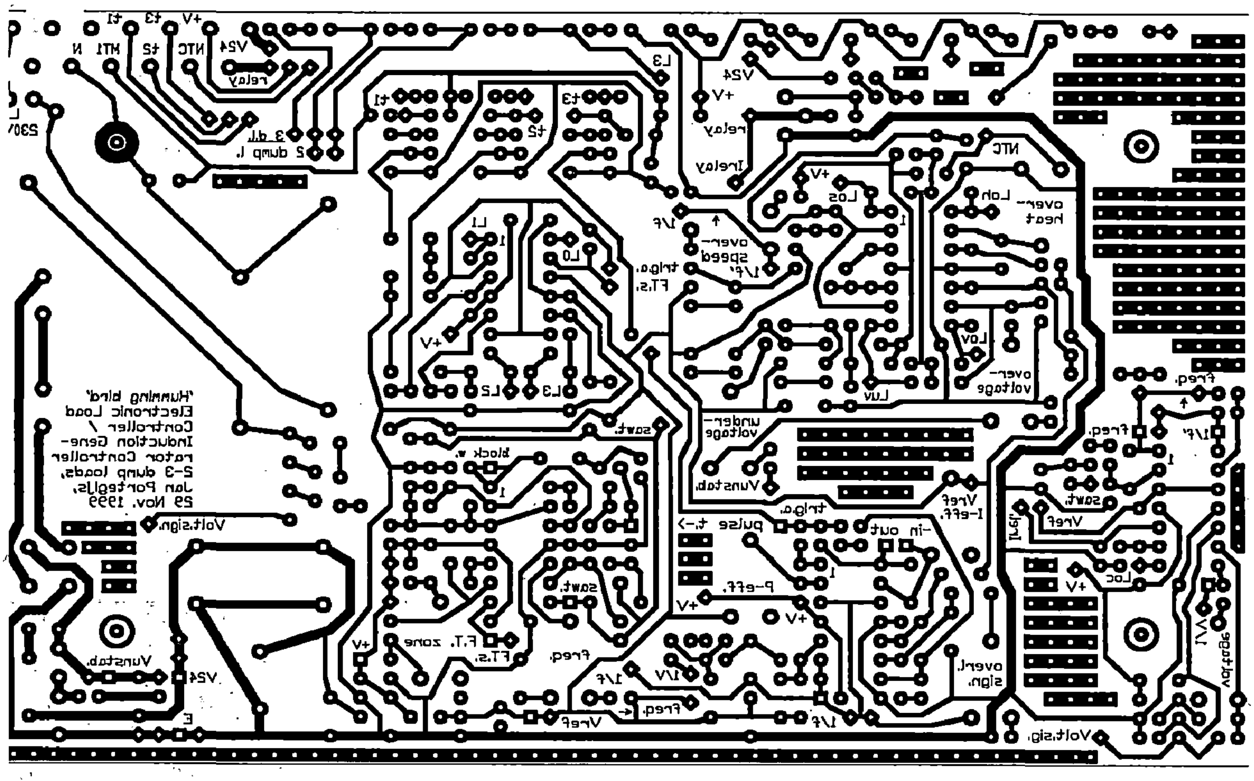

Fig 2.5 Circuit diagram of ELC on PCB.

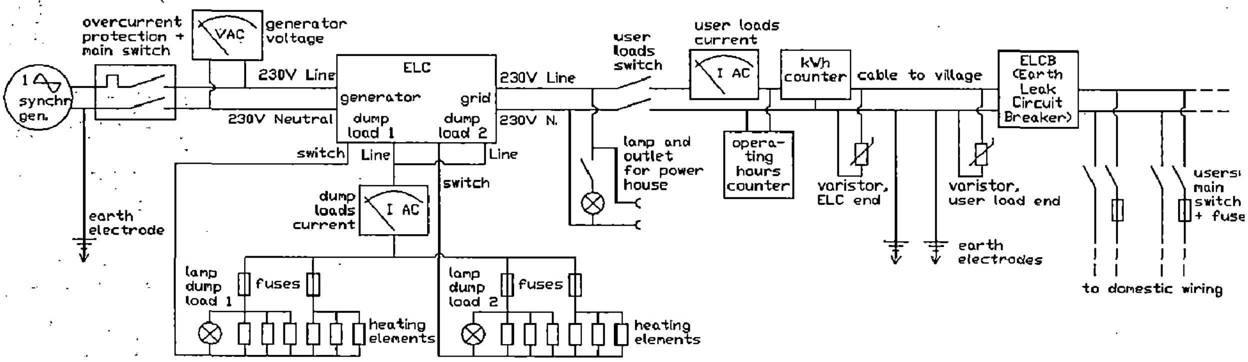

Fig 2.6 Connection diagram of Electronic load controller with synchronous generator, main load and Ballast load.

2.1.3 Modular structure

The complete electronic circuit of the ELC / IGC is so much that it would be too hard to understand, test or repair. To make things easier, it is subdivided into different modules. These modules appear in circuit diagram's as blocks separated by dashed lines and having a name. Each module performs a clearly defined task and has a limited number of named input- and output signals.

Before discussing these modules in detail, one could look at an even simpler model of how an ELC might work: Suppose there are 2 or 3 heavy light dimmers with dump loads connected to them. Then power diverted to dump loads can be increased or decreased by changing setting of the dimmers and in this way, frequency can be controlled. Instead of doing this manually, one could build a controller that does this job automatically. In principle, this controller and the light dimmers steered by it, should serve as an ELC.

Then the different modules can be fitted into this model of a controller and a few light dimmers:

(a). The power circuit and final comparators belong to the light dimmers. Each branch of the power circuit together with the comparator that steers it, works as one light dimmer

(b). The voltage dividers, sawtooth signal and forbidden trigger zone signal provide input signals that are common to all light dimmers. Instead of building these 2 or 3 fold, one of each will do. Sawtooth signal is not only used by the final comparators, but also by 1/frequency signal. So this part also plays a role for the controller.

(c). The low-pass filter and the PI controller itself form the controller. It steers the light dimmers by means of trigger angle signal to final comparators.

(d). DC voltage supplies and reference voltage provide the necessary DC voltages to both light dimmers and controller.

Overload signal and protection features fall outside this simple model. They provide features that become active only outside the normal operating mode of an ELC.

2.1.4 The way trimmers are used

The frequency setting, protection features and overload signal work by comparing a variable input signal with a fixed threshold level. Now it would be logic to design the circuit such that this threshold level can be adjusted by means of a trimmer and compare the input signal with it. However, here trimmers are fitted in the other branch. With those trimmers, an amplification factor in the variable input signal itself can be adjusted. The amplified (or reduced) signal is then compared to a fixed reference signal: Vref. This way, there is less chance that opamps won't function because input signals come too close to either negative voltage supply `E' or positive voltage supply `+V'. Also, troubleshooting is a bit easier since threshold level voltage is always the same.

In general, turning a trimmer to the right (clockwise) means adjusting to a higher value or more stable behavior:

(a). Turning `frequency' trimmer to the right means adjusting towards a higher frequency.

(b). Turning F.T. zone trimmer to the right means adjusting towards wider F.T. pulses and a reduced chance on triggering errors.

(c). Turning P-effect or I-effect trimmer to the right means adjusting towards a lower amplification factor. Then there is less chance on oscillation problems, so a more stable behavior.

(d). Turning protection feature trimmers or overload signal trimmer to the right makes these features react less sensitive. So they will trip or become active only at a higher overvoltage, overspeed, a more severe undervoltage, a higher temperature of the heat sink or a larger drop in frequency.

2.1.5 Opamps

Opamps are used in a number of ways at many places in the circuit. An Opamp (from `Operational Amplifier') is an amplifier with a + input (or non-inverting input), a - input (or inverting input), an output and contacts for a positive and negative voltage supply that powers it. It amplifies the voltage difference between + and - input by a very high amplification factor. The inputs draw or supply virtually no current: They behave as if they have a very high resistance.

Now Opamp circuits can perform a variety of tasks depending on the components around it as given below:

(i). If there are no components that link the output to any of the inputs, it works as a comparator. If voltage at + input is just a tiny bit higher than at - input, the output will go as high as it can: 1.3 V below positive supply voltage. If - input is slightly higher than + input, output will go to the minimum of its range: 0.7 V above negative supply voltage or even lower if current is very low. Opamp 1, 3 and 4 in the final comparators module are used this way. Often, there is a constant reference voltage at one of the inputs that sets a threshold level, and an input signal to the other input, see e.g. the Opamps in protection features.

(ii). If there is a resistor between output and input, a simple feedback loop is created. This makes that output will not swing from one end of its range to the other any more at tiny input voltages. This way, amplifiers with a well-defined amplification factor can be made.

(a). With a resistor R1 and another resistor R2 from this - input to a reference voltage, it works as a non-inverting amplifier. It amplifies voltage difference between + input and reference voltage by a factor R1/R2 + 1. This is the case with Opamp 9 (P-effect) in the PI controller.

(b). With a signal coming in at R1 and reference voltage connected to + input, it becomes an inverting amplifier with an amplification factor of R1/R2.

(iii). If the output is connected straight to - input, it becomes a voltage follower: The output just follows the signal at + input. Now the feedback is extremely strong: Voltage at - input is completely defined by output voltage. A voltage follower is a non-inverting amplifier with an amplification factor of 1. From that point of view, it serves no function but it is necessary if an input signal can not supply enough current for the circuits one wants to drive with it. See Opamp 10 in low-pass filter module for an example.

(iv). If there is a resistor R1 between output and + input, a feed-forward loop is created. Like with an amplifier, there should be another resistor R2 from + input to a voltage signal. This makes output react even more extreme. It does not change from low to high when voltage signal at resistor R2 rises just above the reference voltage at input, but only when it has raised a certain voltage interval above this reference voltage. And to make it swing back to low, voltage signal has to drop a certain voltage interval below reference voltage. This way, a non-inverting Schmidt trigger is created. Of course one could also make an inverting one by interchanging voltage signal and reference voltage. See Opamp 5 and 8 in sawtooth signal module as shown in Fig.2.7

(v). With a capacitor between output and input and a resistor from - input to a reference voltage, a non-inverting integrator is created. Now there is a feedback loop, but it changes in time: The capacitor cannot conduct a feedback current for long because it gets charged-up by it. So after a while, the capacitor is charged to a different voltage and output voltage of the Opamp will have changed also. This Opamp will act as an integrator: A constant voltage difference between + input and reference voltage is integrated into a rising (or falling) output signal with a constant slope. See Opamp 12 (I-effect) in PI controller.

Without other links, the output would soon reach the upper or lower end of its range. But usually, there is another feedback loop that prevents this. With an integrator that is part of a controller, the feedback loop runs via the process that is controlled.

(vi). Opamps can also be used as oscillators or pulse generators and the like, as shown in Fig 2.7 Opamp 11 in overload signal module.

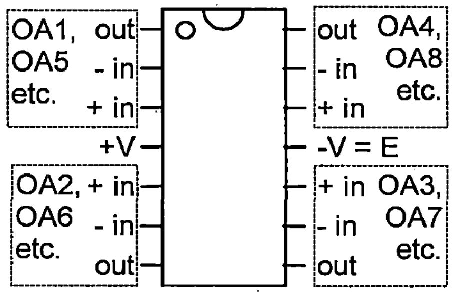

Fig 2.7.connection of LM324 Opamp IC

In this design, the LM324 Opamp is used, some characteristics are as below:

(i). One LM324 chip contains 4 Opamps in a plastic package with two rows of 7 pins at each long side. The pins are numbered starting from the one marked with a little hole and going round towards the left (against the hands of a clock, as seen from component side).

(ii). On the PCB, all LM324 IC's are placed such that pin 1 is at the top left corner. In the circuit diagram's, all Opamps are numbered individually so with 4 Opamps per LM324 IC, the first LM324 contains Opamp 1 - 4, the second one Opamp 5 - 8 etc.

(iii) They are quite robust: They can stand being short-circuited to ground as long as it happens to only one of the 4 Opamps in a package. Maximum supply voltage and input voltages is 32 V. Inputs survive voltages below `E', they just start to conduct as if there were diodes to E.

(iv). They have a wide operating range: It functions with input voltages ranging from 0 to 1.5 V below +V. Outside this `common mode' range, the opamp is not damaged but it will not operate properly.

(v). Depending on current it should supply or sink, output voltage can range from ca. 0.7 V to 1.3 V below +V.

(vi). The rate at which output voltage can rise or drop (= slew rate), is limited to 0.5 V/ µs. So it takes some 6.5 µs for the output to switch from low to high or reverse, as it increase or decrease by 13 V. This helps to make the circuit less sensitive to high frequency noise.

Normally, voltages in an electronic circuit are presented as voltage differences with respect to a ground or zero level. Here, ground level for electronics is `E' (from `Earth') and in the circuit diagram's, the symbol for `ground' is used: Three horizontal lines above one another with the top one longer than the bottom one.

Now if an electrical connection between the electronics circuit and 230 V grid voltage is needed, usually `E' is connected to one of the 230 V lines. In this design however, things were easier with positive print supply voltage `+V' connected to one of the mains voltage lines. Then triacs can be triggered with a negative trigger current by drawing their `gate' connection towards `E'.

When studying the circuit, this has to be borne in mind:

(a). 230 V `N' (Neutral) connection is connected to +V.

(b). Voltage at `E' is some 15 V below this level.

So if 230 V `N' and `L' (Line) wire would be interchanged or 230 V `N' wire would not be grounded properly, the electronics can carry full line voltage.

2.2 DC VOLTAGE SUPPLIES AND REFERENCE VOLTAGE MODULE

This module produces supply voltages that provide power the other modules or serve as a reference voltage. It works in a series of steps, with input of each step being a rather high and variable voltage with a large current capacity, and output being a lower, more stable voltage with lower capacity. See also figure 3.

(i). The 100R resistor (`R') and 100 nF capacitor (`C') form an RC filter with a time constant of 0.01 ms. It acts as a simple low-pass filter that smoothens very sharp voltage spikes from generator voltage somewhat before this is fed to the transformer and voltage dividers module. It works by dissipating power from high frequency noise in the 100 Ω resistor. Even when there is just the usual noise on generator signal, some power is dissipated in this resistor so it should really be a 1 W type. Voltage over the capacitor can rise very high. Preferably, the 100 nF capacitor should be 250V `class Y' capacitor (tested at 3 kV!). If not available, a 250V `class X2' capacitor (tested at 1 kV) might also do. But to be safe, it is better to use two 220 nF 250V `class X2' capacitors in series, giving 110 nF capacitance and a maximum voltage of 2 kV.

(ii). The fuse protects the transformer against too high currents in case of a short-circuit at the secondary side, or generator voltage being too high while frequency has not increased proportionally. The capacitive current drawn by the capacitor should not pass through the fuse because this would partly annihilate the reactive current drawn by the transformer. Then the transformer could still receive a larger current than the fuse allows and the transformer would not be properly protected.

(iii). The transformer reduces generator voltage to a level suitable for powering the electronics. The bridge rectifier converts it to a DC voltage that appears on measuring point `Vunstab'. Apart from serving as input voltage for the next step, this voltage is used as input signal for `overvoltage' and `undervoltage' protection features.

(iv). Together, the 4k7 and 5k6 resistor, 24 V zener diode BRX49 thyristor and 2200 uF elco's form a coarse stabilized voltage supply with `V24' as output voltage. This is a rather unconventional circuit as usually, a standard stabilized voltage supply can be connected straight to the rectifier after a transformer. In this case, secondary voltage of the transformer can become far higher than maximum input voltage for a standard stabilized voltage supply so that they not be used directly. See below for how this circuit works. Besides providing power to the next step, V24 is used to power the coil of the relay.

(v). Together with the 470 nF and 100 nF capacitors, the 78L15 stabilized voltage supply produces a nice, stable voltage '+V' of ca. 15 V that is used to power all electronics.

(vi). The 1k5 resistor, LM329 reference voltage and 47 uF elco capacitor produce an accurate, stable voltage 'Vref' of approximately 6.9 V that is used as reference voltage at many points in the circuit. The LM329 works as a very accurate zener diode so to work well, the 1k5 resistor should always supply more current than is drawn from Vref. The 47 uF electrolytic capacitor serves as a buffer that helps suppress noise. Without this electrolytic capacitor, just touching certain points at the circuit with measuring cables could cause such noise that protection features might trip without reason.

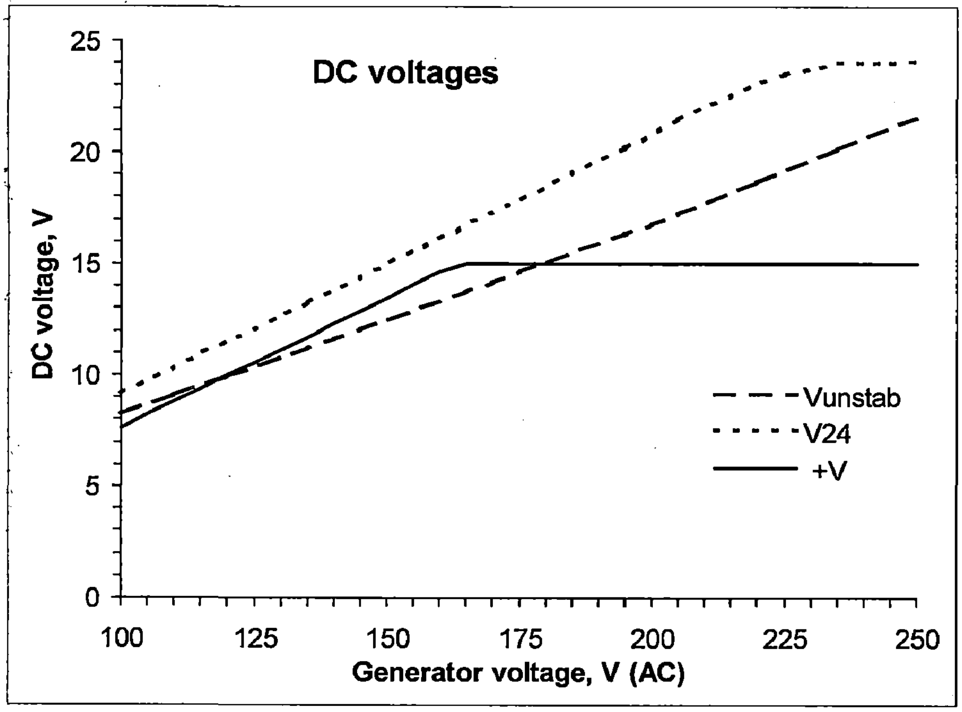

Fig 2.8:DC voltages as a function of generator

Fig 2.8 shows DC voltages as function of generator. To understand how the coarse stabilized voltage supply circuit works, one could imagine that the BRX49 thyristor is replaced by an NPN transistor, with its collector connected to Vunstab, its base via the 5k6 resistor to the zener diode and its emitter to V24. Then as voltage on V24 drops below the 24 V of the zener diode and the base-emitter voltage drop, the transistor will receive base current. This makes the transistor conduct from collector to emitter, the elco's will become charged up and voltage V24 rises again. This way, voltage V24 is regulated. Similarly, the thyristor will start to conduct once it receives gate current. Advantages of using this thyristor over an NPN transistor are as below:

(i). It needs a very low gate current, so the resistors and zener diodes need to carry less current. It has a lower voltage drop, meaning that `V24' can be maintained above minimum level up to a lower generator voltage (see with point 2 and 3 below). This low voltage drop also means that dissipation in the thyristor is minimal. When triggered, the thyristor will remain conducting until it extinguishes by itself during the next zero crossing. So once triggered, it will charge the capacitors with as much current the transformer can supply for the remainder of that half period.

(ii). V24 is not regulated that smoothly: A ripple with ca. 0.09 V AC remains. This has no adverse effects. Voltage on Vunstab looks heavily distorted on an oscilloscope. When the thyristor is triggered at the beginning of that half period, there is no sine-wave like top any more but just a flat line as the transformer is practically short-circuited to the large elco capacitors connected to `V24'. Then the next half period, it might not be triggered at all because V24 is rather high. And some half periods, the thyristor might be triggered near the top and voltage suddenly drops to V24. In principle, distortion of `Vunstab' could be a problem as this is used as input signal to overvoltage and undervoltage protection features. But mean value of `Vunstab' corresponds well with generator voltage. In these protection features, there are RC filters that derive this mean value so this is not a problem either..

Compared to a transistor circuit, the coarse stabilized voltage supply works very efficiently and the thyristor hardly gets warm. So dissipation in the thyristor is low (dissipation is power consumed by a component and converted into heat) But somewhere, excess power must be dissipated, as open circuit voltage of the transformer is quite a bit higher than `V24' output voltage. With this thyristor circuit, this excess power is dissipated inside the transformer: When conducting, the thyristor forms nearly a shortcircuit between Vunstab and V24 and current drawn from the transformer can rise quite high. Consequently, voltage drops over internal resistance of primary and secondary windings are high and dissipation in the transformer is high.

At 230 V generator voltage, the thyristor conducts only some 2/3 of all half periods and in the remaining 1/3, dissipation in the transformer is very low. Still, average dissipation is higher than with a constant current being drawn from the transformer. Dissipation in the transformer rises further when generator voltage is way above normal level. Still the transformer will not overheat because

As current during one half period becomes higher, the thyristor will conduct during a smaller fraction of all half periods.

When generator voltage is that high, the `overvoltage' protection feature should switch off the relay. Then the relay coil draws no power any more and the fraction of half periods that the thyristor will conduct drops even further.

The fuse reacts in the same way as the transformer to high and varying currents. So if, for whatever reason, current through the transformer are such that it might overheat, the fuse will blow first.

When triggered, voltage over the thyristor drops sharply and this means high-frequency noise. To dampen this somewhat, there is an RC filter over the thyristor consisting of a 150R resistor and 47nF/250 V capacitor.

In Fig 2.8, it can be seen that at low generator voltage, V24 is higher than Vunstab. This seems weird since how can current flow from Vunstab to V24 when voltage at V24 is higher. The voltages shown in Fig 2.8 are mean voltages as can be measured with a tester on DC range. Looking with an oscilloscope, it can be seen that when the thyristor is conducting, Vunstab is ca. 1 V higher than V24. In between those periods, Vunstab drops considerably while V24 remains virtually constant. This is why mean value of Vunstab as measured with a tester on DC range, sometimes ends up lower than V24.

Important characteristics of DC voltage supplies module are as given below:

(i). Power consumption: Some 5.4 W when the relay is switched on (measured on 230 V input). All of this is dissipated within the housing so the housing should be large enough to get rid of this by natural cooling. With the relay disconnected, power consumption drops to 2.4 W.

When switched on, the relay draws some 70 mA from V24. The 78L15 stabilized voltage supply draws some 30 mA, uses ca. 5 mA itself and supplies 25 mA to other electronic circuits. So a total of ca. 100 mA DC is drawn from the transformer. When a higher current is needed, another transformer type must be chosen

(ii). Minimum generator voltage needed to keep the ELC functioning normally: ca. 166 VAC. Then V24 will be 16.7 V and this is just enough to guarantee that +V will be 15 V and stable. So voltage over the relay coil will be some 16.5 V so much lower than its nominal 24V

(iii). Minimum voltage to keep user loads switched on: Ca. 107 VAC. If generator voltage drops below this value for a few seconds, `fast undervoltage' feature will trip Of course `normal undervoltage' feature might trip at a higher voltage already and this might make the relay switch off.

At only 107 V generator voltage, all DC voltages except `Vref' are way below normal already and sawtooth signal becomes heavily distorted. This has no consequences since dump loads should be completely off anyway. `V24' will be only some 10.1 V and with that: Coil voltage for the relay. Once switched on, a 24 V DC relay will remain switched on at this low voltage. This means that the relay is adequately protected by the `fast undervoltage' feature.

(iv). Time the ELC can function without power supply is 1.4 seconds. This allows heavy electrical motors to be started, even if starting current of such motors is so high that generator voltage drops to a very low value. During this time, the relay and electronics are powered from the three 2200 uF capacitors. If those capacitors were not fully charged because voltage was already quite low before it dropped under the 107 V minimum, this time will be less.

(v). Time it takes to charge the large `Elco' capacitors so far that the relay switches on after start-up: 0.3 sec. This value was measured with the PCB being switched onto a 230 V supply. A generator will build up voltage more gradually and then the relay will switch on even faster after voltage has reached 230 VAC

(vi). Maximum generator voltage the ELC can stand indefinitely: 625 V (this value depends on the 625 V varistor in power circuit). This only applies if frequency has increased as well as generator voltage.

Worst voltage spikes the ELC electronics can survive: Probably, DC voltage module can stand a pulse of 2 kV and 1 ms. Such a strong voltage spike can not occur as long as the varistors in power circuit are present and functioning.

2.3 VOLTAGE DIVIDERS

The voltage dividers reduce 230 VAC generator voltage signal into a voltage signal that can serve as input signal to sawtooth signal and FT zone signal modules.

Generator voltage must be measured as the voltage difference between `230 V Line' and `230 V Neutral'. Now voltage on `230 V Neutral' is practically the same as voltage on `+V': Via the power circuit, `23circuitutral' is connected straight to the MT1 terminal of the triacs and in final comparators module, `MT1' is coupled via a 150R resistor to `+V'. Voltage drop over this resistor is negligible, it only serves to make the electronics less sensitive to high frequency noise coming from power circuit.

2.4 SAWTOOTH SIGNAL MODULE

A sawtooth signal is a signal that increases gradually with a constant slope, then drops sharply when it is `reset', after which the cycle is repeated. Here, the resets of sawtooth signal follow shortly after the zero crossings of generator voltage.

Sawtooth signal serves two functions:

(i). Its momentous value tells how much time has elapsed since the last zero crossing. This information is used by final comparators to set trigger moment for this half period.

(ii). Its mean value tells about the frequency at which the generator runs. If frequency is rather low, sawtooth signal rises a bit higher before it is reset by the next zero crossing and its mean value will be slightly higher. If on the other hand frequency is relatively high, mean value of sawtooth signal will be below normal. So its mean value is proportional to the inverse of frequency. This mean value is derived in low-pass filter, after which it is fed to PI controller. Sawtooth signal is derived from generator voltage in 4 steps as shown in Fig 2.2.

2.4.1 **Block wave**

A block wave is a signal that, at any moment, is either `low' or `high'. Duration's of `high' and `low' stages are equal and it switches very fast from high to low or reverse. Actual voltages of `high' and `low' stages depend on characteristics of the electronic component that creates it and its voltage supply. Opamp 5 is connected as a Schmidt trigger. The right-hand voltage divider supplies a reduced, sine-wave-shaped generator voltage signal. This voltage divider has an internal resistance of 45 k and consequently, voltage at + input is influenced also by voltage of its output via the 1 M resistor between output and + input of Opamp 5. This resistor causes a `feed-forward' effect: When output is `low', it influences its input signals in such a direction that it tends to remain `low' longer. This makes block wave less sensitive to noise on generator voltage. Result is a block wave signal with the same frequency as the generator (around 50 or 60 Hz) that switches synchronized with zero crossings of generator voltage. The feed-forward effect however, makes that it does not switch exactly at zero crossings any more but a little later: Block wave signal is somewhat delayed with respect to generator voltage signal at its input.

2.4.2 **Inverted mode**

Opamp 8 works just like Opamp 5, but has its + and - inputs interchanged. This makes that when Opamp 5 is `high', Opamp 8 will be `low' and the reverse, making its output signal the inverse of block wave of Opamp 5. Looking at the combination of Opamp 5 and 8, it can be seen that the effects of the two feed-forward resistors, are added. When Opamp 5 is high, its own feed-forward resistor pulls its + input a bit higher. At the same time, Opamp 8 will be low and pull - input of Opamp 5 little lower.

Both feed-forward resistors are practically equal to the total of 990 k of resistors through which generator voltage signal comes in. This makes that feed-forward effect as calculated back to generator voltage levels, is equal to the full voltage swing that those Opamps can make: Some 14 V (here output voltage range is more than stated because current drawn from it is very low). So after a negative half period in generator voltage, block wave will switch from low to high once generator voltage has risen to +14 V just after a zero crossing from negative to positive. And it will switch back to low when generator voltage has decreased to -14 V after a zero crossing from positive to negative (inverted block wave just reacts opposite). This causes the 0.14 ms time delay between real zero crossings and the switching moments of the blocks. Opamp 5 and 8 make a block wave from a sine-shaped signal and for shortness, they are called `blocks'. So their name has nothing to do with `to block' in the meaning of `to obstruct'.

2.4.3 Pulse Train

Opamp 5 and Opamp 8 both have a 47 nF and a 5k6 resistor wired to their outputs. Over the resistors, there will be a voltage peak right after output of the respective Opamp has switched, which will then dampen out quickly. Both positive and negative peaks are created but only the positive peaks are conducted forward by the diodes. If one branch produces a negative peak (because its Opamp switches from high to low), at the same time the other one will produce a positive one (because then this Opamp must have switched from low to high). So on pulse train measuring point, there is a series of positive pulses with twice generator frequency, so around 100 or 120 Hz and a width of ca. 0.16 ms. These pulses are synchronized with zero crossings but, because block wave itself was slightly delayed, these pulses are also a little delayed with respect to zero crossings.

2.4.4.Sawtooth signal

Together, the 10 k and 1 k (1.2 for 60 Hz) resistor and 250 Ω trimmer form a voltage divider from `Vref' that supply a stable, low voltage to + input of Opamp 7. The 5.6 k resistor and 100 nF capacitor make that Opamp 7 functions as an integrator: It integrates this low, stable voltage at its + input into an output signal that has a constant, positive slope and this forms the gradually increasing part of sawtooth signal. During every pulse of pulse train signal, the BC237 transistor receives current at its base terminal and conducts. This way, the 100 nF capacitor is discharged and, with its – input practically short-circuited to its output, Opamp 7 acts as a voltage follower: Its output just reproduces the low, stable voltage at its + input. As soon as the pulse ends, output starts to rise again. The result is a sawtooth signal of some 100 (or 120 Hz) with the resets synchronized to zero crossings of generator voltage. But again, these resets are slightly delayed with respect to zero crossings of generator voltage.

2.5 FORBIDDEN TRIGGER ZONE MODULE

In principle, sawtooth signal contains all information that is needed to trigger the triacs at the right moments, achieve the desired trigger angles and with that, the right amount of power diverted to the dump loads. In practice, things can go wrong near the ends of the range of possible trigger angles. Forbidden Trigger zone (or F.T. zone) signal creates a safety margin around the danger zone close to the zero crossings: When it is high, final comparators module will not produce a trigger pulse. This way, the following triggering errors can be avoided. Suppose trigger angle should be near 180°, meaning that dump loads should be switched practically off. Now the small delay between actual zero crossings and the resets of the sawtooth signal (see with `inverted block wave' in previous par.), might cause the trigger pulse to come just after the real zero crossing. This would mean that the triac is triggered at the start of the next half period instead of towards the end of the previous one, causing its dump load to be switched on completely. Also if the start of the trigger pulse might be just before the zero crossing, it might continue until a little bit after, with the same effect. Suppose trigger angle should be near 0°, meaning that the dump loads should be switched completely on. Then things could go wrong if the dump loads are slightly inductive, causing current through them to lag a little bit behind voltage over them. This means that the triacs will extinguish shortly after the zero crossing. Now if a trigger pulse would come just before the triac extinguishes, it has no effect: The triac will still block once current drops to 0 and it won't be triggered after this, so the next half period, dump loads are switched fully off.

When FT zone signal is high, the final comparators module will not produce a trigger pulse. If the PI controller produces a trigger angle signal corresponding with nearly 0° trigger angle, the effect is that the trigger pulse is delayed until the F.T. zone signal goes low again, meaning a somewhat higher trigger angle so that the dump load is not switched on completely. If the PI controller produces a trigger angle signal corresponding with just less than 180° trigger angle, there won't be any trigger pulse so the effect is that the dump load is switched off completely. F.T. zone signal is derived from generator voltage, using the signal from the right-hand voltage divider. Around zero crossings, generator voltage is close to 0 and F.T. zone signal will be high. Away from zero crossings, this voltage is large, (either positive or negative) and F.T. zone signal should be low.

2.6 LOW PASS FILTER

Since the slope of sawtooth signal is constant, the maximum value it reaches before being reset, is proportional to the time lapse between zero crossings. This means that peak voltage of sawtooth signal is proportional to the inverse of frequency of generator voltage. Mean value of sawtooth signal is mean value of its maximum (which varies with inverse of frequency) and its minimum (which is constant) so mean value can also be used as a measure of inverse of frequency. Low-pass filter derives this mean value of sawtooth signal and this 1/f signal serves as input to PI controller.

All components of low-pass filter together form a third-order `Butterworth' low-pass filter with a cut-off frequency of 17.3 Hz. Variations in sawtooth signal with a frequency well below this cut-off frequency, can pass the filter without being dampened noticeably. These low-frequency variations contain the information on changes in generator frequency the PI controller should react to. Sawtooth itself has a frequency way above this cut-off frequency so this is dampened very strongly: At 100 Hz (for 50 Hz nominal generator frequency), a nearly sine wave shaped ripple voltage with an amplitude of only 20 mV will come through. At 120 Hz, the filter works even better and an amplitude of only 11 mV will come through.

For this filter, a 24k3/1% resistor and a 56 nF capacitor are needed (ordinary 5 % resistors are not available with a value around 24k so a 1%, metal film type was chosen). Since those parts are not readily available, there is room on the PCB to fit combinations of resistors and capacitors. Instead of the 24k3/1% resistor, a 22k and 2k2 resistor can be fitted in series. The 56 nF capacitor can be replaced by a 47 nF and 10 nF capacitor connected in parallel.

2.7 PI CONTROLLER

In general terms, the PI controller works as follows: It compares actual frequency (an input variable) with desired frequency (a set point, adjusted by means of `frequency' trimmer) and reacts to the difference. If actual frequency is too high, it decreases trigger angle so that more power will be diverted to the dump loads. This will make the generator slow down and frequency will decrease. And the reverse: If actual frequency is too low, trigger angle is increased, power diverted to dump loads decreases and the generator can speed up some more.

The circuit diagram of figure shows some more on how the PI controller works electronically:

(i). There is no `frequency' signal, but an inverse-of-frequency signal: 1/f signal from low-pass filter. This does not matter as long as it makes the controller regulate in the right direction: If frequency is too high (so `1/f' is too low), trigger angle should decrease and the reverse.

(ii). Voltage of `Vref' serves as a `desired 1/frequency' signal. This voltage can not be adjusted so for fine-tuning frequency, one has to manipulate the way the `1/f' signal itself is created, which is done with `frequency' trimmer in sawtooth signal module.

(iii). The PI controller consists of a P-effect (around Opamp 9) and an I-effect (around Opamp 12). Both react independently to changes in `1/f' signal and the two 10 k resistors make that trigger angle signal is the mean value of their output voltages.

The `P' in `P-effect' stands for `Proportional'. Opamp 9 is wired up as a non-inverting amplifier, meaning that its output signal is proportional to its input signal, which is the difference between `1/f' and `Vref'. Its amplification factor can be adjusted with the 25 k trimmer. Setting it to a lower resistance increases the amplification factor and makes P-effect react stronger. So P-effect can be expressed as this amplification factor. With trimmer set to its maximum value of 25 k, amplification of P-effect Opamp, with the trimmer Setting it to a lower resistance increases the amplification factor and makes P-effect react stronger. So P-effect can be expressed as this amplification factor. With trimmer set to its maximum value of 25 k, amplification of P-effect Opamp, with the trimmer in middle position. P-effect reacts instantaneously to changes in `1/f' signal, but it does not regulate in such a way that `1/f' becomes exactly equal to `Vref'. To maintain a trigger angle signal other than its neutral value of `Vref', there must be a difference between 1/f and `Vref' that can be amplified. This means that a P controller (consisting of only P-effect) will not regulate to exactly its set point.

The `I' in `I-effect' stands for `Integrating'. Like Opamp 7, Opamp 12 is wired as an integrator: An input signal is transformed into an output signal that rises or falls with a slope proportional to value of its input signal. The relation between input voltage and slope of output voltage is determined by the 100 k trimmer. Setting it to a lower resistance will make I-effect react faster. So I-effect can be expressed as a conversion factor between an input voltage and a slope of output voltage. With its trimmer set to maximum of 100 k, this conversion factor I-effect is 21 s^{-1} (or `per second'), with trimmer in middle position, I-effect = 42 s^{-1} etc.

Contrary to the integrator of Opamp 7, input signal for I-effect (= difference between 1/f signal and Vref) is not constant. It could be either positive or negative, and either be very small or rather large. Consequently the output of Opamp 12 could go up quite fast, hardly change at all, or go down quite fast. It all depends on whether `1/f' is above, nearly equal to, or below `Vref'.

I-effect continues adjusting its output until there is no difference between Vref and `1/f' left to amplify. By then, I-effect does not change any more, but it might be anywhere between its upper and lower voltage limit. So an I controller (consisting only of I-effect) does regulate to exactly its set point..

As long as the ELC is operating normally, Opamp 12 will not reach the limits of its output voltage range. Suppose 1/f signal is slightly above Vref. Then output of Opamp 12 will rise slowly, trigger angle rises and with that: Power diverted to dump loads decreases. This makes that total load connected to the generator decreases, it will accelerate and frequency rises so 1/f signal drops. So the process that is being controlled by the PI controller (the generator), forms a part of the feed-back loop that prevents I-effect Opamp from reaching the limits of its range To understand how the PI controller works, one has to look how P-effect and I-effect cooperate as explained below:

(i). When 1/f signal changes fast, P-effect is the first to react and make that trigger angle is adjusted to the new situation.

(ii). Once the situation is stable, it is I-effect that does the actual regulation and makes sure that frequency is regulated to exactly its set point.

Via the two 10 k resistors, both P-effect and I-effect have an equal influence on trigger angle signal and this signal is the mean of the two output voltages. Now final comparators have been designed such that, with P-effect having its neutral value equal to `Vref', I-effect on its own can regulate dump loads from being practically switched off to being nearly fully switched on.

Turning P-effect or I-effect trimmer to the left (= anti-clockwise, gives a lower resistance) will make the system react faster to disturbances. This is desirable because generally, this means a better quality of regulation: A given disturbance will cause a smaller change in frequency that will also last less long. However, if P-effect and I-effect are set too fast, PI controller will over-react. Then when user load power changes suddenly, this excites the system and the resulting oscillation will dampen out only slowly. If P-effect or I-effect are adjusted even faster, any initial oscillation will not dampen out, but amplified and the system becomes unstable: It will start to oscillate by itself. Turning these trimmers to the right means PI controller is adjusted less fast and the system becomes more stable. See next par. for background information on this.

The best way to adjust P-effect and I-effect is in the field during installation by using the `recipe' of Ziegler and Nichols. This comes down to adjusting P-effect faster and faster until the system just oscillates and then reducing P-effect to 45 % of that setting. Now I-effect is adjusted faster and faster until it just causes oscillation, and then is reduced to 33 % of this setting. This way, a setting is found that is as fast as possible, while still any oscillations will dampen out quickly.

With a battery-powered oscilloscope with `single' triggering, or a computer connected scope device, the reaction of `1/f signal' to a change in user loads can be recorded. With a properly adjusted controller, it should look like `1/f signal' line.
As P-effect just amplifies 1/f signal, it also amplifies the remaining 100 or 120 Hz ripple voltage that is left over from sawtooth signal by the low-pass filter. If P-effect is set too high, there will be such a large 100 Hz oscillation in trigger angle signal that final comparators can not produce proper trigger moments. At 50 Hz nominal frequency, this noise signal has an amplitude of 20 mV. To be safe, P-effect should never be set higher than 100 (so trimmer should not be set to less than 2.2 k). At 60 Hz, this noise signal has only 11 mV amplitude and P-effect should not be set higher than 170 (so trimmer should not be set to less than 1.3 k). In

practice, such high values for P-effect are not feasible anyway because they would make the system unstable.

2.8 OVERLOAD SIGNAL

In a way, overload signal module is related more to protection features, as it remains inactive as long as the system is operating normally. It is activated only when there is an overload situation, so if user loads draw more power than the system can generate By then, the ELC will have switched off dump loads completely, but still generator frequency might drop further. The overload module is meant to warn users that the system is overloaded and that they should switch off some appliances that draw a lot of power, or at least not switch on any more.

Once frequency drops below a threshold level, overload module will cause the ELC to oscillate in a characteristic way. This makes that all over the grid powered by the M.H.P system, at least frequency, and most likely also voltage, will fluctuate. Most types of electrical appliances will somehow react to this, by a change in pitch of their noise or by a change in brightness of lamps.

2.9 FINAL COMPARATOR

Like Opamp 6, Opamp 1 and 3 are wired up as comparators (in the standard version, Opamp 2 is not used, in the 3 dump load version this Opamp is also a comparator). There is no feedback or feed-forward effect: If + input rises above - input, output will change from low to high. Opamp 1 and 3 receive a reduced sawtooth signal on their + inputs and compare this with trigger angle signal on their - inputs. Once sawtooth signal rises above trigger angle signal, their output changes from low to high and the transistor circuits wired to their outputs, produce trigger pulses for their respective triacs. Sawtooth signal provides information on the time that has passed since the last zero crossing. If trigger angle signal is rather low, sawtooth signal will rise above this level only a short time after a zero crossing, so trigger pulses comes soon after each zero crossing and trigger angle is low. If trigger angle signal is high, either it will take longer, leading to later trigger pulses so to a higher trigger angle. Or the peaks of sawtooth signal will remain below trigger angle signal altogether and triacs are not triggered at all. At this point, also F.T. (Forbidden Trigger) zone signal comes in. When F.T. zone signal is high, it pulls up trigger angle signal via the diode. It will pull up trigger angle so high that sawtooth signal can never rise higher. This makes that while F.T. zone is high, no trigger pulses can be produced so the triacs cannot be triggered near zero crossings. Once F.T. zone signal goes low again, trigger angle decreases only at a limited rate because of the 100 nF capacitor. This way, the circuit is insensitive to very short dips in F.T. zone just after zero crossings that might result from reverse recovery current peaks.

The circuit connected to + inputs of Opamp 1 and 3 modifies sawtooth signal in such a way that:

(a). Its amplitude is only some 45 % of that of sawtooth signal itself.

(b). It is either drawn upwards (the one at + input of Opamp 1) or pulled down (the one at + input of Opamp 3).

This has the following consequences.

(i). The reduced sawtooth signals can never rise as high as trigger angle signal when this is pulled up by F.T. zone signal. Since the reduced sawtooth signal to Opamp 3 is always lower than that to Opamp 1, the dump load 2 triac will be triggered later than that of dump load 1. Usually, there is 90° differences between the trigger angles for both dump loads. However, both trigger angles must stay within their range of 0° to 180° so when one trigger angle reaches the end of its range, the other one can approach that end as well. So the two dump loads can never be triggered both at around 90° trigger angle. If dump load 1 is triggered at ca. 90°, dump load 2 will be triggered at nearly 180°, so it will be completely off. If dump load 2 is triggered at

(ii). At nearly 180°, so it will be completely off. If dump load 2 is triggered at about 90°, dump load 1 will be triggered at nearly 0°, so it will be fully on. This effect makes that the adverse effects of switching on a large load, are reduced and the generator does not have to be oversized that much [2]

(iii). As long as power diverted to dump loads is between 1/4 to 3/4 of total dump load capacity, power diverted to dump loads changes practically linearly with trigger angle signal. So if PI controller is adjusted optimally for any point within this range, it will function optimally for this whole range. Outside this range, power diverted to dump loads reacts less strong to a change in trigger angle. So in this range, PI controller will react a bit slower than optimal, making the system even less likely to oscillate.

I-effect on its own can steer trigger angles for both dump loads over nearly their full range. I-effect will do the fine-tuning of generator frequency and P-effect will be `neutral' (so: Output equal to Vref) once frequency is properly fine-tuned. To make that with P-effect being neutral, I-effect can steer trigger angles of both dump loads over their full range, sawtooth signal had to be reduced. With the present circuit, I-effect alone can not steer trigger angle for dump load 1 higher than 138° . It can be seen that in terms of power diverted to dump loads, this matters very little. So for reaching these far ends of trigger angle range, P-effect must help a little and then frequency will deviate slightly from the set value. It would be easy to make that I-effect has a larger influence on trigger angle than P-effect so that I-effect alone can steer trigger angles over their full range. This has not been done since P-effect is important for reacting fast to large, sudden changes in frequency. So reducing the influence of P-effect on trigger angle signal would make the controller react less well to such large, sudden changes.

POWER CIRCUIT OF ELECTRONIC LOAD CONTROLLER

3.1 CAPACITY

The capacity of this circuit determines capacity of the ELC as a whole. The maximum current the triacs can handle determines the kW rating of each dump load. Multiplied by the number of dump loads (2 for the standard version, or 3 for 3 dump load version), this gives the maximum capacity of dump loads that can be connected to the ELC and this is the kW rating of the ELC. This total dump load capacity should be some 5 - 15 % above design power output of the M.H. P station.

Current rating of the relay determines the maximum current that user loads may draw. Normally, one can calculate current I by dividing power P (in W) by nominal voltage V. But user loads could draw a much higher current than this if, Current rating of the relay determines the maximum current that user loads may draw. Normally, one can calculate current I by dividing power P (in W) by nominal voltage V. But user loads could draw a much higher current than this if:

(i). These user loads have a poor power factor [3]

(ii). The system gets overloaded [3].

In this situation, it is better to express capacity of the ELC in terms of kVA = 1000 x maximum current x nominal voltage

Generally, kVA rating of the ELC should be the same as kVA rating of the generator. Then total capacity of dump loads will be only 50 to 70 % of kVA rating of the generator [3].

Of course the internal wiring and connectors, must be rated according to the currents that can be expected. For the standard design described in this manual, components for power circuit make up about half of total component costs. So if only a low capacity ELC is needed, it might make sense to economize on these components by choosing lower capacity ones. This design could be seen as a general purpose design. It has a moderately high capacity of 7 kW (10 kW for the 3 dump load version) while it still uses reasonably priced components.

3.2 RELAY

The relay serves to connect the grid and dump load circuits to the generator when its coil is powered by the `logics' module of the protection features. If one of these protection features gives an `unsafe' signal, current to the relay coil is interrupted and the relay will switch off. This way, user loads, dump loads and triacs are protected against too high or too low voltage, and too high a frequency. If there is no DC voltage supply, the relay cannot be switched on. After the generator is started and produces normal output voltage, it takes ca. 0.2 s before the large capacitors in DC voltages module are charged up high enough for the relay to switch on.

One has to choose a relay type based on specifications as listed below:

(i). Coil rated at 24 V DC with a coil resistance of, preferably, 350 Ω or more. When a 24 V transformer is used, DC voltages module can supply enough current for a relay with a resistance as low as 200 Ω. Then the time the ELC can function without power supply, drops to less than 1 s. Also, a 24 V transformer will overheat more easily when generator voltage becomes too high, so this is only possible if `overvoltage' protection feature is set to 250 V. With a small type relay that draws much less current, (500 Ω or more), one of the three 2200 μF capacitors in DC voltages module can be left out.

(ii). Current rating equal or above current rating of the generator (= kVA rating times 1000 and divided by 230 V. If the relay contains 2 or 3 parallel sets of contacts, these can be connected in parallel. Then current rating of the parallel sets will be double or triple the rating of a single contact [2]. Ideally, current rating for the relay should be as high as short-circuit current of the generator since when the generator would be short-circuited, `undervoltage' feature will make the relay switch off. This would mean that, depending on generator characteristics, current rating of the relay should be several times rated current of the generator. Considering that it will not happen too often that the relay has to switch off such a high current, it seems acceptable to choose a relay type with a current rating at least as high as rated current of the generator. Even a relay with a slightly lower current rating, might still function well in practice [2].

(iii). Voltage rating at least 230 V AC, but preferably higher.

(iv). A `switch-on' or `switch-over' type. With a `switch-over' type, those contacts that are connected to the middle contacts when the coil is not powered are left open. `Switch-on' means that contacts are not connected when the coil is not powered, so this is equivalent to `normally off' types.

(v). Sometimes, separate current ratings are given for largely resistive loads ('AC1' rating), and for inductive loads ('AC3' rating), with the latter one being lower. Probably it is safe to use the higher, AC1 rating [2].

(vi). Sometimes, separate ratings are given for peak currents and for lasting currents. Then generator current rating should be equal or lower than the lasting current rating.

(vii). Preferably a maximum operating temperature of 65° C or more.

Relay with a 24 V DC coil do function at lower voltages already. This Potter & Brumsfield relay switched on when voltage rises above 15.3 V, and switched off when voltage dropped below 4.4 V. Probably most other 24 V DC relay will show similar values. This means that before the relay would switch off due to a too low coil voltage, `fast undervoltage' feature is activated and makes it switch off permanently.

3.3 TRIACS

The power element used for switching dump loads, is the TIC263M triac produced by Texas Instruments. It is rated 25 A and 600 V. If this type is not available, smaller 600 V types requiring 50 or 75 mA trigger current, could also be used, e.g. TIC246M (16 A), TIC236M (12 A), TIC226M (8 A), TIC206M (3 A), or similar types from other manufacturers. If no 600 V types are available and a generator with AVR will be used, also 500 V types (type code ends with `..E') or 400 V types (type code ends with `..D') could be used. The TIC263 and some triac types can not be triggered by a positive trigger current when main current is negative (then the data sheet will mention something like `trigger current is not specified for quadrant IV'). There is no problem using such types since final comparators provide a negative trigger current anyway.

Although the TIC263M triac it is rated at 25 A, it can do so only when cooled very well and this is difficult to achieve in practice: For 25 A, case temperature must be kept at or below 70 °C. It has a casing that is connected to its MT2 terminal so it must be mounted on the heat sink in such a way that it is insulated electrically and this insulation layer forms an extra barrier for efficient cooling. In effect, maximum current for the triacs is limited to 16 A by heat sink construction, see next par.

There are more attractive triac types with respect to cooling requirements but their electrical characteristics are less favorable. Instead of triacs, also pairs of thyristors can be used and with these, capacities of hundreds of kW are very well possible. Fitting 25 A triacs in an ELC that will be used at only 1 or 2 kW might seem like overdoing things. But heavily overrated triacs have following advantages:

(i). It makes that a triac might survive a short circuit in the dump loads. The TIC263M has a very high peak current: It can stand 175 A for 20 ms. When generator is rather small, its short-circuit current will be way below this 175 A. By the time overcurrent protection switches off the ELC, the triac might still be undamaged.

(ii). It has a larger case, so better heat conductivity and lower cooling requirements.

3.4. HEAT SINK

A heat sink is a large piece of aluminum with fins that increase its surface area so that it cooled efficiently by surrounding air. It serves more or less like the radiator of a car engine. It prevents the motor from being destroyed by overheating. In this case, cooling capacity of the heat sink determines the maximum allowable dissipation for triacs and with that Maximum current for triacs and maximum capacity of dump loads connected to it.

In general, calculating maximum allowable dissipation comes down to calculating `thermal resistances'. Power is dissipated in the junction of a transistor or triac and the resulting heat is conducted in a number of steps to ambient air. Now if thermal resistance is known for each step, the dissipation at which the junction just reaches its maximum allowable temperature, can be calculated.

With this ELC, preferably the housing should be completely sealed and small. This makes a heat sink inside the housing impossible, as this would require a larger housing and cooling slots. Having the heat sink at the outside of the housing, poses extra demands to heat sink construction.

3.4.1 Electrical safety:

The triacs should be well insulated electrically from the heat sink so that it can never carry a dangerous voltage. There is safety at stake here and this insulation should comply with national electricity standards. The Dutch standard prescribes that insulation between any metal part that can be touched and voltage carrying parts, should stand a voltage of 2120 V peak value, while those outside parts should still be grounded. Air gaps between voltage carrying parts and any outside parts should be 3 mm at least (for appliances with non-grounded metal parts, double insulation is prescribed, with a minimum voltage of 4240 V peak value and 6 mm air gaps).

3.4.2 Safety with respect to burning:

Heat sink temperature should still be safe with respect to burning when touched. In capacity calculations for central heating radiators, a temperature difference of 60 °C between radiator temperature and ambient temperature is used. Assuming a room temperature of 20 °C, a radiator temperature of up to 80 °C apparently is considered safe. With a central heating system, even higher temperatures are possible as the maximum temperature at which the boiler switches itself off, is normally set to just above 100 °C. For the moment, maximum temperature is set at 80 °C. At this temperature, still the heat sink can not be touched for more than a second or so. But if one would withdraw one's hand when it begins to hurt, the skin will not be burned.

3.4.3 Sealing: The heat sink should be fitted onto the housing in such a way that the housing remains waterproof.

3.5 NOISE SUPPRESSION COIL

The noise suppression coils serve 4 purposes:

(i). To eliminate radio frequency noise, which would be annoying to users listening to a radio. Also it might disturb proper functioning of other electronic appliances.

(ii). To protect the triacs. After being triggered, the rate at which main current increases, should stay below the maximum dI/dt value specified for the TIC263M triac: 200 A/µs. To achieve this, a self-induction of just 3 µH would be enough to protect them[3]

(iii). The noise suppression coils also play a role in protecting the triacs in case of a lightning strike on an overhead cable.

(iv). To avoid interference problems within the ELC. Without noise suppression coils, any wire from the power circuit running parallel to a signal wire on the PCB, would induce short, sharp voltage spikes in this signal wire. This induced noise might cause the electronics to malfunction.

3.6 WIRING AND CONNECTORS

Proper wiring of the power circuit is important because of the following:

(i). Loose connections might be hard to find, as a wire might just connect when the housing is opened.

(ii). If a wire comes loose after e.g. the housing is opened up a few times, it might touch an electronic component and somewhere in the circuit, one or more components might be destroyed, producing unpredictable errors.

(iii). Bad connections or too thin wiring might cause excessive heat production. Too high a temperature inside, will reduce life span of Electrolytic capacitors.

(iv). A power cable that runs close along a signal wire on the PCB, will induce noise and cause interference problems. With carefully fixed power cables, such problems can be avoided.

3.7 HOUSING

A good quality housing is vital for good reliability of the ELC. If water, dirt or insects come in and reach the PCB, there might be tiny leakage currents that can make characteristics of the ELC drift. Such leakage currents could have even larger influences on protection features since these work with very small currents themselves. So by the time ELC electronics start to behave funny and users notice there is something wrong, probably protection features will not work either and user appliances might get damaged if the ELC fails.

Minimum inner dimensions with respect to fitting all components in are: Length x width x height = 160 x 110 x 85 mm if a connector rail is used. If connector blocks are used, minimum height can be reduced to 70 mm. How much bigger the outer dimensions should be, depends mainly on inward protrusions (e.g. in corners where the top is fixed to the housing etc.) With respect to length x width, the PCB (160 x 100 mm) should fit in and on one side, wires to the triacs should pass the PCB (so a width of 110 mm is not necessary all along the PCB length). However, a housing that is just big enough to accommodate all components, is not recommended: Then components would be placed so close together that it is difficult to fit power wires neatly and it would look messy, making testing and troubleshooting more difficult.

OTHER ELECTRICAL EQUIPMENT OF THE M.H.P STATION AND PROTECTION FEATURES

4.1 GENERATOR AND OVER CURRENT PROTECTION

The generator is an expensive and critical component of the M.H.P station. So it is important to get data on the electrical and mechanical characteristics of the generator type that is going to be used. Ideally, a few catalogues from different suppliers should be available when choosing a generator type so that the most suitable type can be selected. If this is not possible, at least the manual, maintenance requirements and technical data of the generator that was chosen, should be delivered with the generator [3].

Many different versions of generators exist [2]. Some basic demands are as below:

(i). It should be the right type: With an ELC, a synchronous generator must be used (an induction generator can be used if the IGC version is built).

(ii). If it is a synchronous generator, it should be single phase. For a 3-phase generator driving a 3-phase system, a 3-phase ELC is needed.

(iii). It should be able to stand run-away speed of the turbine. With a crossflow type turbine and optimal transmission ratio, this means that the generator should stand 170 % of its nominal speed.

(iv). The bearings should be able to stand forces exerted by the transmission.

To reach an acceptable life span, kVA rating of the generator should be high enough to allow for the expected power factor of user load and the extra load caused by switching of dump loads. Generator current could become dangerously high for a number of reasons and many options exist to protect it against this.

4.2 DUMP LOADS AND DUMP LOAD LAMPS

Dump load capacity be 5 to 15 % above kW rating of the system. Since this ELC design has 2 (or 3) dump loads, the extra load to the generator caused by a phase angle regulated dump loads, is much less. This makes that it is not that important to keep dump load capacity as low as feasible and it won't be a problem if total dump load capacity ends up 20 or 30 % higher than kW rating of the system. When the ELC will be used close to the maximum rating of the triacs, capacity of each dump load should not be higher than necessary.

Ideally, each dump load should consist of a series of heating elements connected in parallel. Then the ELC will remain functioning even when one or two elements burn out. This also allows for fine-tuning capacity of dump loads later by installing some more elements or disconnecting one or two.

For small systems, it will be cheaper to have each dump load consist of one heating element with the right capacity. Then fine tuning of dump load capacity is difficult and probably, total dump load capacity will be somewhat more than 115 % of system capacity.

For optimal controlling action, the 2 (or 3) dump loads should have roughly the same capacity. Then for the whole range of trigger angles, there is a linear relation between trigger angle signal and power diverted to dump loads so PI controller can be adjusted optimally for this whole range. If the number of heating elements required for the desired total dump load capacity can not be divided equally over 2 (or 3) dump loads, it is better to choose dump load 1 smaller as this will reduce the load to the generator slightly. Then PI controller should be adjusted with dump load 2 (= the largest one) being triggered around 90°.For dump loads, many kinds of air heaters, cookers or water heaters can be used. If water heaters are used, they should be installed in a tank that gets a continuous supply of water from the penstock pipe or another source.

Dump loads should be placed such that the heat (from air heaters) or damp air (from water heaters) can not affect other components. This means that they should have adequate ventilation and must be installed well away from the generator, the ELC and sensitive components like indicators, counters, overcurrent protection and fuses.

Only dump loads with a resistive character are recommended. With special precautions, the ELC can handle dump loads with a slightly inductive character like the transformer of a battery charger, 'universal' type electrical motors etc. Under no circumstances, capacitors should be connected in parallel to a dump load. These would cause strong peak currents are dangerous to the triacs, the generator and the capacitors themselves. There is no sense in fitting capacitors there either, as they would create extra noise rather than reduce noise.

The brightness of dump load lamps show clearly how much power is diverted to each dump load. Even quite fast oscillations can be seen from flickering of these lamps. These dump load lamps might seem superfluous since the LED's on the ELC already indicate trigger angles for the dump loads. But they offer a number of advantages as below:

(i). For troubleshooting, it is important to have information from both the LED's and dump load lamps to distinguish between triggering errors and oscillation problems.

(ii). Brightness of dump load lamps corresponds more closely to power being diverted to dump loads than the dump load LED's because of following:

(a). Brightness of dump load lamps corresponds more closely to '% on' for the dump loads than to trigger angle.

(b). Dump load lamps also react to changes in generator voltage. This is relevant when the AVR of the generator oscillates in conjunction with the PI controller.

If the ELC is installed not too far away from the houses of users, the dump load lamps can be installed outdoors in such a place that they can be seen easily by users. Then they show whether the system still has spare capacity to switch on more user loads. This information could help preventing overload situations.

4.3 OPTIONAL COMPONENTS

4.3.1 Earth electrodes

For adequate lighting protection on outdoor cables, it is necessary to have the 230 V Neutral wire grounded at regular distances.

4.3.2 Earth Leakage Circuit Breaker (ELCB):

This is an expensive device that disconnects user loads when it detects a leakage current to earth. The ELCB's prescribed for domestic wiring in Dutch electricity standard, react to leakage currents as small as 30 mA and provide adequate protection against accidentally touching a live wire. It will also trip when appliances with poor insulation are connected and this can be a nuisance when there are many poorly insulated appliances around. It is only effective when 230 V Neutral wire is grounded only at the generator end of the ELCB and not grounded at any point after it. So if the outdoor cable has to be grounded for lightning protection, each house or cluster of houses will need its own ELCB.

4.3.3 User load switch

This might be necessary if `undervoltage' feature trips when the turbine is started up with user loads connected. It also serves as an `emergency stop' switch that might be life-saving in case someone holds a live wire and can not let go of it as the current through the body makes muscles cramp. This is especially important if the turbine can not be shut down fast and easily.

4.3.4 Varistor at ELC end

This varistor protects the ELC against voltage spikes and worse. Alternatively, a surge arrestor or spark plug could be used.

4.3.5 Voltage indicators

This shows clearly what happens when a large load is switched on or when there is an overload situation. If there is no voltage on the grid, it is handy to know whether the problem is in the ELC or in the generator. It should have a range of 0 to 250 or 300 V. With a compound type generator, the voltage indicator should be able to survive 600 V.

Instead of the indicator, also a small capacity filament lamp can be fitted. Then with a compound type generator, two lamps should be connected in series as one lamp would blow in run-away situations

4.3.6 Current indicators

These are needed only for troubleshooting. During a normal overload situation, either overcurrent protection or undervoltage feature will trip and these indicators are not really needed. If overspeed feature has tripped because one or more heating elements in the dump loads are destroyed or their fuses blown, the dump load current indicator will show that this current is too low. If a user load with a very poor power factor is connected, user load current indicator will show that this current is too high.

For measuring currents to both (or all 3) dump loads, one indicator will do. One end of all dump loads is connected to the `230 V Line' wire inside the ELC . So these wires can go jointly to the current indicator, and split up only after it. Make sure that the right wires are connected to one another, as any other combination would lead to either a short-circuit of the generator via a triac, or a short-circuit of one dump load to the other.

When using a current transformer, things are even simpler: Just have both wires pass through one current transformer and its reading will correspond to the sum of both currents (or to the difference: In case one wire was put through the transformer in opposite direction).

4.3.7 kWh counter and operation hours counter

From a technical point of view, these are not important. But they form a proof of how effective and reliable the system works. This can be motivating for operators and users, and important to the agency who has installed the system.

4.3.8 Overcurrent protection for triacs

Fuses to protect triacs and dump loads are not always necessary.

4.3.9 Main switch and fuse

For safety reasons, each house normally has a main switch with fuse. But this is not necessary in all cases as follows:

a. If the wiring inside the house is just a few meters of cables, a switch, a lamp and a wall socket, there is little sense in fitting a separate main switch to disconnect this small amount of wiring in case of danger. The lamp and any appliances connected to the wall socket, could just as well be disconnected by the lamp switch and pulling the plug from the wall socket.

b. If capacity of the generator is rather low (say less than 10 kVA) and cables inside a house have a normal cross-section of 1.5 mm^2 or more, a fuse is not needed to protect indoor wiring against short-circuit. If there would be a short-circuit in this part, either the generator overcurrent protection or `undervoltage' feature will trip.

4.3.10 Varistor at user load end

These could protect user appliances against voltage spikes due to indirect lightning strikes on cables. For instance, varistor type SIOV-S14K275, with a clamping voltage of 350 V could be used.

This type has a much lower voltage rating than the one at the ELC end. If overvoltage feature would be adjusted too high, it could be destroyed by overvoltage caused by the generator. But these varistors have a better chance to survive this as each one has to conduct only a part of generator current. Also, due to cable resistance, voltage at user load end will remain lower.

Fitting varistors with a voltage rating as high as the one near the ELC (clamping voltage of 560 V or more) makes little sense: Then any tiny varistor in a sensitive appliance will have blown long before these large varistors come to their help

4.3.11 Cable to village

Usually, there will be a cable from the M.H.P installation to a village, where it might branch out to connect all houses of users. Normally, this cable must be sized based on maximum allowable voltage drop (so not based on maximum power dissipation like the power wires inside the ELC). This usually means that the outdoor cable must be much heavier than wiring inside the ELC. When the long cable to the village works at a high voltage and thus a low current, cable losses are reduced strongly and a thinner cable will do, but then transformers are needed.

There are limits to the voltage drop over this cable : Appliances have an upper and lower voltage limit between which they will function normally and reach an acceptable life span. Now if generator voltage is adjusted to just below maximum voltage, then total voltage drop over all cables should be such that voltage at the appliance is still above minimum voltage. Ideally, total voltage drop from generator to an appliance should be no more than 6 %. A voltage drop up to 10 % can still be allowable if there are no user appliances that are very sensitive to undervoltage. If the ELC is installed near user loads, an even larger voltage drop can be allowable.

4.4 WHERE TO INSTALL THESE COMPONENTS

There are a number of components that are normally installed inside a housing. Inside the housing of the ELC itself, there is no space to install any more components. Also, it would become less reliable if holes are drilled through it to fit e.g. an indicator or if the housing is opened regularly by operators.

So it is best to have one large housing just below the ELC for those components that do not have a proper housing of their own. Often this means that all cables to the ELC will pass through this extra housing. Then for the cables going to the ELC, short lengths of cable with round cross-section can be used that fit properly in the watertight cable lead-throughs of the ELC housing. The extra housing for the other components does not need to be watertight and for cables going to other components, a cheaper type of cable can be used.

Then a general advice on electric wiring, Mind safety aspects. Users might not be familiar with the dangers of 230 V electricity. Sooner or later, children will become curious and might touch everything they can reach. Especially in an area where there has been no electricity before, users should be informed well about the dangers.

People who are interested, can be explained which jobs they can do and trained how they can do these jobs safely. This will be construction and servicing of house wiring. Explain that if the ELC itself fails, chances are slight that they can find and repair an error if they are not trained technicians. If they would try, they might very well cause more problems than solve any. The best way to discourage this, is by keeping an ELC as spare and promising to install it immediately when the old one fails.

4.5 ELC NEAR USER LOADS

Normally, an ELC is installed in a power house that also contains the generator and turbine. This power house is located at a site that is favorable with respect to length of canal needed, penstock length, protection against floods etc. Often, the power house is not located near houses of users and a long cable is needed to connect those houses to the system. This standard configuration is convenient with respect to operating the system.

But there might be reasons to install the ELC at the other end of this long cable towards houses of users:

(i). With the ELC at user load end, the long cable from generator to ELC will carry a nearly constant current and consequently, there will be a nearly constant voltage drop over this cable. Then it becomes possible to compensate for this voltage drop by adjusting generator voltage higher. It could be set even higher than the 240 V upper limit for user appliances. So then a somewhat higher voltage drop in this cable would still be acceptable and a somewhat thinner and cheaper cable could be used.

(ii). Overvoltage and undervoltage feature will react more closely to voltage as experienced by user loads. So they will protect these more accurately.

(iii). There is a better chance that users can see the dump load lamps more easily. This can help prevent overload situations.

(iv). There is a higher chance that power diverted to dump loads, could still be of use, e.g. for outdoor lighting.

(v). With this option, it is possible to use a high-voltage generator (e.g. 400 V 'Line to Neutral'), have the long cable to the village carry this high voltage and connect the ELC just after the step-down transformer. This way, ELC design does not have to be adapted for such a high voltage, while still only one transformer is needed.

Disadvantages are as follows:

(i). Operating the system becomes slightly more difficult, as the person starting up the turbine can not see how the ELC reacts. This can be avoided by listening carefully to the sound, and with that, speed of the generator.

(a). If speed does not increase above normal speed while the turbine is fully on, the ELC must be working properly and its relay must have switched on.

(b). If generator speed increases to run-away speed, a protection feature must have tripped and the turbine must be shut down again.

Also, it would help if the operator can see the dump load lamps from the turbine site.

(ii). Now, lightning could hit this cable between generator and ELC. So both ends of this cable must be protected against lightning with e.g. large capacity varistors. Also the 230 V Neutral wire must be grounded at regular intervals, but that would have been necessary anyway.

(iii). No houses can be connected along this cable. The fact that they would receive a somewhat higher voltage is not such a problem. More serious is that they are not protected by the protection features.

(iv). An extra shed or small building might be needed for installing the ELC and dump loads properly.

4.6 PROTECTION

The protection features are meant mainly to protect user appliances against conditions that might destroy certain types of appliances:

4.6.1 Overspeed

Against too high a frequency. This is dangerous for motor driven appliances, especially if the driven machinery requires much more power when driven too fast, e.g. fans or centrifugal pumps. It can occur if the ELC or dump loads fail and the turbine speeds up to run-away speed.

4.6.2 Overvoltage

Against too high generator voltage. This is dangerous for many types of appliances. Normally, this can only happen with a compound type generator when the ELC or dump loads fail. So then it is linked with overspeed. It might also happen with a generator with AVR if the AVR fails.

4.6.3 Undervoltage

Against too low voltage. Then electrical motors might be unable to start and might overheat. There are protection features that are meant to protect the ELC itself.

4.6.3.1 Fast under voltage

This protects the relay against `rattling' when generator voltage nearly collapses because a very large load is switched on. It works by switching off the relay permanently before supply voltages drop to such a low level that it might switch off because voltage over the relay coil becomes insufficient. Having the relay switch off due to lack of power for its coil is dangerous because it would switch on again right away because once this heavy load is disconnected, generator voltage rises to a normal value. The end result would be that the relay would rattle (switch on and off at a very fast rate), and would not survive for long.

This feature is built into the normal undervoltage feature. Its threshold voltage is lower, but also its time constant is lower. So it can act fast, but will only trip if voltage drops rapidly to a very low value.

4.6.3.2 ELC overheat

This protects the ELC against overheating of the heat sink to which the triacs are fitted. When installed properly, the ELC should never overheat. But this could still happen if:

(i). System capacity is higher than ELC rating.

(ii). Ambient temperature rises higher than expected. This could happen if a dump load is fitted below the ELC.

(iii). Cooling effect of the heat sink is impaired, for instance because somebody hung a T-shirt over it.

However, the protection features do not protect against all possible hazards:

(a). User loads are not protected against voltage spikes or (indirect) lightning strikes.

(b). If the relay switches off, only the 230 V Line wire is interrupted. This will interrupt power supply to all connected loads, but it does not guarantee that the grid can be touched safely: 230 V Neutral wire will still carry a voltage if:

The generator has a filter. This will make it carry only half of generator voltage, but it can supply only a very small current of around 1 mA. The 230 V Line wire is grounded at the generator. Now 230 V Neutral wire can carry normal output voltage and full generator current. Of course this situation should be avoided. If one of the generator wires is grounded, then this wire should be connected to the 230 V Neutral wire of the ELC.

(c). Protection features offer little protection to the generator, so in most cases, there must be a separate over current protection device to protect the generator [3]. Sometimes, under voltage feature can be used for this because too high a current usually means that the system is overloaded and that voltage will be exceptionally low. The generator should be able to stand being driven at overspeed for hours [3]

(d). Recommended threshold settings and time constants should be treated with caution. I cannot guarantee that with these settings, user appliances are protected adequately while unnecessary tripping of protection features is reduced to a minimum.

4.7 COMMON CHARACTERISTICS OF PROTECTION FEATURES AND LOGICS MODULE

The way protection features work, is based on the following principles:

(i). When the turbine is started and speed becomes high enough for the generator to produce its rated voltage, power supply to the ELC electronics comes up. Then all 4 features automatically go to `safe' state and the relay switches on in about 0.3 seconds. This is the only way to reset all features to `safe' state, as there is no button to reset them once they have tripped, see at point 3.

(ii). If input signal to a protection feature is such that this feature is triggered and goes to `unsafe' state, the following things happen:

(a). It makes the relay switch off, so that user loads and dump loads are disconnected from the generator.

(b). The right, red `protection feature' LED lights up, showing which feature made the relay switch off. There is just one LED for normal `undervoltage' and `fast under voltage', so from that LED, one can not see which made the relay switch off.

(c). It remains in `unsafe' state for as long as there is power supply (so for as long as the generator remains running and switched on), even if its input signal goes back to a normal, `safe' values.

(d). It influences other protection features in such a way that these can not trip any more. So only the LED of the feature that actually made the relay switch off, will light up. This way, a confusing situation with 2 or 3 LED's lighting up, is avoided. Suppose the relay switched off because of under voltage, then the fact that there is no load to the generator any more, will make it overspeed and, if the generator is a compound type, also voltage will be way too high.

(a). Overheat' feature is not influenced by one of other 3 features going to `unsafe' state, as this seemed superfluous.

(b). If more than one features have tripped, the cause might be a lightning strike on an overhead cable. This will produce such heavy interference's that two or more features might go `unsafe'.

(iii). To reset protection features, one has to shut down the turbine and wait at least 10 seconds. If it was `under voltage' feature that made the relay trip, it takes at least

15 seconds before the system can be started up again. If one tries too early, `under voltage' feature will trip again within 1 or 2 seconds after starting up.

4.8 Vref, DELAYED

This module produces a delayed reference voltage to the - inputs of opamp 13 and 14, making these go to `safe' state when power comes up. There are conflicting demands as to how much this signal should be delayed:

(i). As long as Vref, delayed has not approached its normal value, `overspeed' and `undervoltage' feature can not make the relay switch off. So to make these features work within a second after start-up, the capacitor should be charged relatively fast.

(ii). For the `fast undervoltage' feature to work properly even when Vref itself is already decreasing because print voltages are collapsing, the capacitor should be discharged much slower.

4.9 OVERSPEED

The diode over the 100 k resistor makes that the capacitor can be charged rather fast. For discharging, the diode is in blocking direction so the capacitor can discharge itself only via the 100 k and 10 k resistor in series. Threshold voltage for this feature can be set from nominal speed as set by `frequency' trimmer up to 1.5 times this frequency. Time constant is 5.2 seconds. It is possible that this feature trips in case of short-circuit or heavy overload, as then generator speed might increase rapidly [3].

4.10 UNDERVOLTAGE

Threshold voltage can be set from ca. 105 to 215 V AC. For this feature, there are two time constants in series of 5.2 s each. With a single time constant, output voltage would react immediately to a change in input voltage by decreasing or increasing towards this new input voltage. So with one time constant, this feature would still react rather fast to voltage dropping to way below the threshold level. Two time constants in series give an averaging effect in which the values of input voltage before a sudden change, count more strongly. So if generator voltage would drop to way below threshold level for a second or two and then return to normal, undervoltage feature will still not trip. This makes it possible to use heavy electrical motors that draw such a high starting current that generator voltage practically collapses for a few seconds.

4.11 FAST UNDERVOLTAGE

This feature is integrated in the normal undervoltage feature. It consists of the 10 k - 27 k voltage divider from '+V' and the diode from + input. It has no trimmer and no time constant by itself. When '+V' drops below 8.5 V, + input will be drawn below 6.9 V and opamp 14 will go 'low' irrespective of the voltage of the capacitors that form the time constants for normal undervoltage.

If '+V' drops to 8.5 V, then 'V24' will be a bit higher at 10.1 V. This voltage is too low to make a 24 V relay switch on, but it is more than enough to keep it switched on once it has switched on. So before the relay might switch off due to lack of voltage supply, this feature will trip and make sure the relay stays switched off until the system is restarted.

Without this feature, the relay could start to 'rattle' if a very heavy load would be connected. This might make that generator voltage drops so low that 'V24' from DC voltages module decreases below the minimum value the relay coil needs to keep the relay switched on. Then once the relay has disconnected all user loads, 'V24' would return to normal and the relay would switch on again within a second. This way, the relay would switch on and off a large load at a very fast rate, and it would not survive for long.

Even though this feature has no time constant, it won't trip immediately when generator voltage drops below this value: The large capacitors in DC voltages module have a buffer capacity enough to keep the ELC functioning for about 1.4 second after generator voltage has dropped below this value. This 1.4 second period is only reached if these capacitors were charged to their normal value, so when generator voltage was normal just before it dropped below 107 V AC.

Please mind that fast undervoltage might trip when the turbine is started up very slowly while a user load is already connected. This could happen when the turbine is fitted with a flow control valve or a gate valve that is opened slowly. If the relay switches on already while the turbine is producing only a fraction of its normal power, these user loads will make the turbine slow down considerably and voltage might fall below the threshold level. Then it will trip within a second, as the large elco capacitors in DC voltages module were not fully charged yet when the relay switched on. To avoid this, either disconnect all user loads during starting-up, or have the turbine start up faster.

4.12 OVER VOLTAGE

Over voltage reacts to voltage as measured in ELC. If cables to user loads are long and thin, voltage drops in the cable could be rather large. Then over voltage feature might trip while voltage at user loads could still be well below the threshold level. To account for the voltage drop in a long cable, the ELC could be installed near the user loads rather than near the generator.

This threshold voltage and time constant are open to discussion. They are a compromise between conflicting demands:

(i). When adjusted insensitive, some user loads could get destroyed due to over voltage.

(ii). When adjusted rather sensitive, it might trip too frequently.

For more information over voltage reacts to voltage as measured in ELC. If cables to user loads are long and thin, voltage drops in the cable could be rather large. Then over voltage feature might trip while voltage at user loads could still be well below the threshold level. To account for the voltage drop in a long cable, the ELC could be installed near the user loads rather than near the generator.

DESIGN, FABRICATION AND TESTING OF ELC

5.1 PRACTICAL ASPECTS OF DESIGN

The PCB design is described as below

(i). Start with blank PCB material that has a photosensitive layer on top of its copper layer, which in turn is covered by black foil that shields this layer from light.

(ii). Design for the copper pattern should be on either tracing paper (kind of paper used for technical drawings) or on transparent like the ones used on overhead projectors.

(iii). The black foil is removed, the transparent original is placed right on top of the photosensitive layer and this is exposed to U.V. light. On those places where the original is transparent, the photosensitive layer is exposed to U.V. light, while the black areas where print tracks should come, the photosensitive layer remains as it is.

(iv). The PCB is developed: Remains of the photosensitive layer are washed away on those areas that were exposed to U.V. light.

(v). The PCB is etched: Copper is etched away from those areas where it is not covered by the (developed) photosensitive layer.

Making double-sided PCB comes down to printing on both sides of the PCB and making sure the two patterns are well-aligned.

Check whether the PCB is printed correctly:

(a). No interruptions in print tracks. No spotted surface because even unexposed areas were etched away slightly.

(b). No short-circuits by hair-like lines or stains of copper that were not etched away properly.

(c). No part of the circuit should have ended outside of the PCB material.

(d). With a double-sided PCB: The two sides should be aligned properly. A hole drilled from copper side may not end up so close to a print track on component side that there is a chance on short-circuit.

5.2 FITTING COMPONENTS ON THE PCB

The description about fitting of various component of ELC is given as below (i). A good quality of soldering reduces the chance on errors:

(a). The copper layer on the PCB should be clean, No remains of the light-sensitive layers, no oxidation etc.

(b). Use fine solder with a resin core.

(c). A soldering iron with a fine, silver tip works best. Copper tips get deformed as copper gradually dissolves in the solder. The soldering iron should not be too hot as then resin evaporates too fast and the solder freezes in pointed cones instead of flowing out properly. A soldering iron that is too hot, can be regulated with an ordinary light dimmer. Or its capacity can be reduced by half by fitting a 400 V, 1 A diode (e.g. type 1N4004) in series, for instance included in its plug

(d). Have a proper stand for the soldering iron and place it such that the cable won't get entangled.

(e). Have the PCB fixed in some kind of clamp or put a weight on it so that it does not wobble with the lightest touch.

(f). A neat work place at the right height and proper light makes it easier to work precisely and notice when soldering joints are faulty.

(g). Take care not to fit wrong parts or parts with wrong polarity. Getting them out is a lot more work and all the heating and tinkering increases chances on lousy connections. Components can be un-soldered by Pulling with a hook from copper wire and touching connections one after the other with the soldering iron. Once the component itself is out, its holes usually are blocked with solder. This can be removed by heating from copper side, and then blowing from component side. There are little hand-held vacuum pumps that can suck up melted solder.There is a kind of stranded wire that sucks up melted solder.

The first method works well for components with only 2 or 3 leads. For unsoldering an LM324 chip or the transformer, the second or third method will be needed.

(h). Mind that some components can be destroyed by overheating when soldering takes too long,Tiny diodes, LED's. To be safe, solder one lead of a heat-sensitive component and allow it to cool down before soldering the other lead.

(ii). Keep the work place clean. Watch out for specks of solder and tiny strands of copper wire that could end up under a component and cause an invisible short-circuit that is very difficult to find.

(iii). Have a series of components at hand. It can be handy to sort components first before fitting them.

(iv). Have the PCB at hand. Always have the PCB in the same position in front of you, so that you can find your way around easily.

(v). First solder the pins that connect copper- and component side islands (mind that some points should not be connected, see with 2- and 3 dump load version . Apply plastic spray to component side to protect this side against corrosion.

(vi). Start with the lowest, lightest parts and the ones that do not fit in easily as they have a lot of pins. So first the IC connector for the LM324 chips, trimmers, connector, measuring points, transistors etc. then the bulk of resistors and tiny capacitors, and then the large Elco's and transformer. The LED's should be mounted last as they must be fitted on copper side on such long leads that they reach the top cover when the PCB is fitted inside the housing.

(vii). Fit components in batches: Place a series of components with their leads through the proper holes, then solder them, and cut off all excess leads. If in doubt whether the right components were fitted, check them right away. Do not fit too many components in one go because it will be difficult to solder them with all those excess leads sticking through. If two or more PCB's are needed, place the same component on all PCB's, then the next etc. and then solder them all.

(viii). Make sure you know the color code for resistors or have a guide at hand. Resistors should be fitted upright, so with one lead bent nearly 180°. Once resistors are fitted, it is a bit difficult to see their color code and things are easier if for all resistors, the color code starts at the top. So always bend the lead at the end where the color code starts.

If resistors are so close together that their bare leads might touch one another, fit them in such a way that chances on short-circuit are minimal: Either the bare lead of one resistor should be near to the insulated housing of the other. Or bare leads that might touch one another, should both be connected via a PCB print track anyway.

(ix). Safety

Some resistors have long, bent-over leads that will carry a dangerous voltage when testing with only the PCB connected to mains voltage. To make sure that all parts at component side are safe to touch during this type of tests, these leads should be isolated by shoving a piece of isolation hose stripped from a cable, over them. These resistors are:

(a). The 100R / 1W resistor in DC voltages module.

(b). The first 332k resistor from the series of 3 (the one connected to the fuse).

(c). The 332k resistor between 230V Neutral and MT1.

(x). Mind polarity of polarity-sensitive components:

(a). LM324 chips: Pin 1 is often marked with a tiny hole, the side towards pin 1 and 14 is also marked with a notch.

(b). Transistors, thyristor, LM329 stabilized voltage supply, rectifier: Their outline is printed.

(c). Diodes: Cathode (the end the arrow in their symbol points towards) is marked with a black band.

(d). LED's also have their cathode marked, either by a flattened side on the LED itself, by a tiny protrusion on cathode lead just under the LED, by cathode lead being slightly shorter and often by a combination of the two.

(e). Polarity of diodes and LED's can be checked with a tester on `continuity' range indicated by a `diode' symbol.

(f). Elctrolyticcapacitors: Negative lead (the larger side with its sides standing up in their symbol) is marked with a black stripe, often with `-' printed in it. The PCB is designed such that all electrolytic capacitor should be fitted upright, so with their positive leads towards the top of the PCB.

(xi). Check the whole PCB for accidental short-circuits. On copper side, spilled solder might cause short-circuits. Watch out for short-circuits via text printed in copper. When in doubt, check with a tester or cut through possible short-circuits with a knife. On component side, bent components could cause short-circuits. If both sides were poorly aligned during printing, the lead of a component might touch a print track on component side.

(xii). When in doubt, check the whole PCB for wrong components being placed or with wrong polarity.

(xiii). After fitting all components Check component side of the PCB for any leads that might touch and create a short-circuit.

Check copper side for droplets or tiny threads of solder that could cause a short-circuit.

5.3 TESTING

5.3.1 PCB connected to mains voltage

Different components of the ELC can be tested in different ways. Of course the most realistic test is by installing it in the M.H.P system and letting it run. If it does not work by then, there is a problem.

The PCB with all electronics can be tested very well by connecting it to a power outlet of the grid. Then only some components near the transformer can carry dangerously high voltages and most of the PCB can be touched safely.

(i). Check whether the 332 k resistors in voltage dividers module, are really 332 k and there is no short-circuit there. If wrong resistors are fitted there, the PCB might not be safe to touch.

(ii). Put a few layers of electrical tape on copper side of the `high voltage' area on the PCB. Cut off very pointed excess leads first so that these will not penetrate the electrical tape. The connections to the following parts should be covered:

(a). 230V Line and 230V Neutral pins of the connector.

(b). Primary windings of the transformer

(c). Fuse and the 100 R resistor + 100nF capacitor that make up the filter.

The 332 k resistors in voltage dividers module (of the series of 3, only the one at the fuse-end can carry a dangerous voltageThese resistors have metal parts sticking out at the component side. To insulate these, they should have a piece of insulation (stripped from a cable) over their long, bent lead.

iii. Solder an ordinary 230 V cable with plug to 230V Line and 230V Neutral pins on the female connectorconnector. Insulate these soldering joints with electrical tape. It can be handy to have a switch in this cable, but then it should be a double one that disconnects both leads.

(iv). Put the plug in a 230 V outlet. Then check with a voltage seeker whether voltage on `E' or `+V' (or any other measuring point on the PCB) is quite low as compared to 230 V. If not, put the plug upside down in the outlet so that 230 V Line and 230 V Neutral wires are reversed.Making sure that print voltages are nearly 0 is not only important for safety, but also for measuring with an oscilloscope. Then chassis of the instrument is connected to `earth' of a probe and it will pick up less noise when it carries less current.

(v). For extra safety, one could measure how much current could flow from any print voltage to earth: Measure AC current between `+V' and `earth' connection of an outlet or any other grounded point (do NOT try to measure current between 230 V Line or 230 V Neutral and an `earth' connection). Start on 10 A range and when this gives a minimal reading, measure it on mA range also. This current should be no more than 0.23 mA when the plug is connected right, or 0.70 mA when the plug is connected reversed. If it is higher or the measurement caused a short-circuit, disconnect the plug. Check the 332 k resistors in voltage dividers module and look for short-circuits in high-voltage area of the PCB. Only currents of 25 mA ore more can be harmful to humans. This way of testing is safe not because the circuit can not carry a noticeable voltage, but because the current it can supply, is limited to less than a mA.

(vi). Make it a habit to test whether print voltages carry 230 V with a voltage seeker every time the plug has been disconnected and reconnected.

5.3.2 Complete ELC connected to mains voltage

The complete ELC can be tested for building errors by connecting it to mains voltage and connecting dump loads to it. Since the ELC cannot influence grid frequency, there is no need to connect real, high capacity dump loads to it.

With too small dump loads, the ELC is not tested up to its design capacity. In principle, this setup could be used to check whether triacs might overheat when running with dump loads of planned capacity. In most cases however, a fuse in the grid will blow well before planned capacity of 2 times 16 A is reached. Filament lamps connected as dump load lamps show beautifully how power diverted to a dump loads gradually increases or decreases. Triacs will not work when their dump loads draw too little current [3] and to avoid trigger problems caused by this, use lamps of at least 50 W or fit them in parallel to form a higher capacity dump load. An extra lamp fitted to the `grid' connections on the ELC, will show when the relay has switched on user loads.

This way of testing is more dangerous than with only the PCB connected to the grid. Now many parts of the power system carry dangerous voltages and also print voltages could be connected directly to the `live' wire of the grid. So: Test whether print voltages carry 230 V AC with a voltage seeker and reverse the plug when they do.

With a grid-powered oscilloscope that is grounded via its power supply, it is not possible any more to use `E' on the PCB as reference for scope signals. Either disconnect `earth' wire of the power supply of the scope (with the risk of putting it under voltage when earth of a probe is connected accidentally to a dangerous voltage) or use `+V' as reference.

With this way of testing, the parts of final comparators that produce trigger pulses, are tested.

5.3.3 ELC connected to a generator set

It is important to have an oscilloscope at hand as now, reaction of the ELC to noise signals must be tested and any hidden faults must be detected and solved.

The electrical circuit could be like in a real M.H.P system, but it is not necessary to install fuses and an overcurrent protection. Ideally, the generator set should have the same type of generator as the one installed in the M.H.P system. To make that the governor of a gasoline generator set does not interfere, this governor should be adjusted to a frequency that is ca. 10 % higher than nominal frequency. Of course now real dump loads are needed, with a total capacity that is higher than generator capacity. Only then, the ELC can control frequency and it will end up at the value set with `frequency' trimmer.

In this set-up, the generator motor will run at full capacity, with the associated noise, fuel consumption and wear of the machine. With a gasoline engine, power output can be reduced by pulling the throttle towards a lower speed. This can be done even with the bar from the governor to the throttle still attached. Because the engine and the machine frame are vibrating so much, a light but strong type of wire must be used, e.g. nylon fishing thread. This way, there is no risk of overloading the generator set and less heavy dump loads are needed.

5.3.4 ELC installed in M.H.P station

(i). Starting up

At the site, the ELC can be connected, all wiring checked, water supply to the turbine installed and then the system is ready for action. The normal start-up procedure is described. For a first test it is better to let it run at low capacity first:

(a). If there is a gate valve in the pipe towards the turbine, this can be used to reduce both flow and head available to the turbine. It can be opened just enough to let the generator reach its nominal speed and produce a voltage. This way, both generator current and run-away speed are limited. Reducing the flow before the inlet of the pipe has the same effect, as then the pipe will become only partially filled with water.

(b). If there is a flow control valve on the turbine, this can be used to reduce the flow. Now generator current will be limited, but it could still reach normal run-away speed when a protection feature trips.

(ii). Basic ELC functions

The first test is whether the ELC works when the turbine is started:

(a). The relay should switch on.

(b). The dump load LED's should light up as well as dump load lamps.

(c). From the sound, it becomes clear whether the ELC maintains frequency at a fixed value.

(iii). Generator current

It is important to test whether the generator produces approximately its design current soon after starting. Suppose actual generator current would be much higher than design current, then the generator might overheat while one is busy with testing other things.

Measure actual generator current using a current transformer, or disconnect all user loads and estimate power consumed by each dump load by measuring voltage over it . When generator current is close to design current during this test, it could still end up much higher under other conditions.

(iv). Power output

If a kWh counter is available, it can be connected temporarily between the generator and ELC. Check its indicator plate for a number that defines how many revolutions of its wheel add up to one kWh. Then use a watch or stopwatch to time how long it takes for the wheel to make a given number of revolutions and calculate actual electrical power output from this.

If a kWh counter is not available, one has calculate electrical power from measured currents and voltages. Ideally, only resistive user loads should be connected so that no power factor calculations are needed. Power going to dump loads that are partially on, can only be calculated reliably if its current and voltage are measured using a `true-RMS' tester.

If actual power output is lower than design power output, this might be disappointing but generally, there is no technical problem. If actual power output would be higher, there is a risk of overloading the generator:

(a). When the turbine has a flow control valve, this valve can be adjusted such that the generator just produces its design power output. Mark this position clearly so that after testing, either the flow control valve can be locked in this position, or a guard mounted that prevents it from being adjusted any higher.

(b). If there is no control valve, Turbine power output must be reduced in another way, e.g. by reducing net head (by partially closing an ordinary valve just before the turbine, or by placing the turbine a bit higher up), or by choosing a lower transmission ratio or spoiling turbine efficiency in another way. Calculations on generator size should be done all over to see whether this generator can handle such a high power output. Then possibly, setting for overcurrent protection or undervoltage feature must be changed as well.

(v). Dump load capacity

Ideally, dump load capacity should be between 105 and 115 % of system capacity, but a somewhat higher capacity is still acceptable. Measure voltage over dump load 2 with no user loads connected.

Dump load capacity is O.K. (so: between 105 and 115 % of system capacity) when voltage over dump load 2 is between 69 and 84 % of generator voltage when measured with an `average responding' tester. When using a `true-RMS' tester, voltage over dump load 2 should be between 86 and 95 % of generator voltage.

5.4 ELC FEATURES

Some features need to be tested more extensively because the M.H. system will react differently than the generator set used in the previous test:

(i). PI controller

It must be adjusted again, as proper adjustment depends on total moment of inertia of generator and turbine, and capacity of dump loads.

(ii). Starting with user loads connected

If the turbine is started slowly, `undervoltage' feature might trip right after the relay has switched on because user loads make the generator slow down.

(iii). Can the generator stand runaway speed

When a protection feature trips and the relay switches off dump loads and user loads, generator speed will go to ca. 170 % of nominal speed and this might destroy the generator.With a compound type generator, its voltage will go up to about twice nominal voltage. ELC electronics are designed to stand this, but it is worthwhile to check this in practice.

(iv). Inductive appliances

When the generator has an AVR and the ELC has no `frequency effect' to its overvoltage feature: Check whether inductive appliances might be damaged by the combination of too low speed with a normal voltage. This can be done by measuring current through a fluorescent lamp or CFL (Compact Fluorescent Lamps, with an ordinary screw fitting) with magnetic ballast. If the lamp is O.K., then likely other inductive appliances like transformers and motors will be safe as well.

Wait a few minutes until the lamp has warmed up and current through it has stabilized. Then gradually create an overload situation by switching on more user loads so that frequency drops . Continue this test until generator voltage has dropped to say 170 V AC. If current through the lamp does not increase above 110 % of its value for normal voltage and current, there is no problem at all. If it has increased more than 25 %, life span might be reduced seriously. In principle, each fluorescent lamp could be protected by fitting a fuse that just allows their normal current. But probably it is better to protect all inductive appliances by fitting 'frequency effect' to overvoltage feature. Or to advise users only to buy electronic CFL's (these can be recognized by their small weight and small dimensions of the part where the ballast must be, as compared to CFL's with magnetic ballast). These electronic CFL's have the added advantage that their power factor is practically 1, so much better than for ordinary fluorescent lamps or CFL's with magnetic ballast. Of course this test could have been done with the generator set if that has the same type of generator.

(v). Overspeed/overvoltage

Test what happens when the system gradually gets into a run-away situation. Reduce dump load capacity by disconnectin the turbine with the flow control valve or a gate valve partially open and gradually increase turbine power by opening the valve further. If turbine power can not be regulated, have a number of user loads connected when starting, and gradually disconnect more and more of them. Now either overspeed or overvoltage feature should trip. Measure frequency and voltage and write down the values just before it tripped. The feature that did not trip, can not tested easily so one has to rely on the adjustment that was made before.

(vi). Overload signal/undervoltage

Test what happens when the system gradually becomes overloaded. If there are not enough appliances around to create a real overload situation:

(a). Some of the heating elements that are used as dump loads, can be connected as user loads.

(b). A large, makeshift heating element can be made from an appropriate length of heating element wire wound spirally and fitted on nails on a wooden board (make sure nobody touches this).

(c). Turbine power can be reduced by gradually shutting down its valve. This leads to a less realistic test as now the generator will run at a reduced capacity and its voltage will drop less.

Gradually switch on some more, small capacity user loads to worsen the overload. Now first overload signal should become active: Demonstrate its signal and explain its function to users. Eventually, undervoltage feature will trip. Again measure frequency and voltage and make notes on frequency and voltage at which this happens. It could be that the overcurrent protection trips before overvoltage feature does, as generator current will increase during an overload situation. This does not necessarily mean that either of them is adjusted wrong.

(vii). Power test

Have the system run for at least 2 hours at design power output with no user loads connected so that all power will go to the dump loads. Check regularly whether the generator, the ELC heat sink or any part of the wiring gets too hot. The generator will be more heavily loaded if user loads with a poor power factor are connected and/or if the system is slightly overloaded. So repeat this test under such conditions.

If a tester with `frequency' range is available, frequency can be checked and, if necessary, readjusted.

(viii). Generator voltage

Ideally, voltage at user load connections should always stay between 200 and 240 V (standards might differ a bit between countries). To allow for voltage drops over cables, generator voltage should be close to the upper limit, but never surpass it. Mind that an AVR might be disturbed by triac triggering dip so that generator voltage can vary slightly with trigger angle. And a compound type has no accurately regulated voltage by itself. So generator voltage should be measured a few times with different user loads.

If generator voltage is a bit too low or a bit too high, maybe the AVR or compounding mechanism can be readjusted, see the generator manual for this. If a compound type generator has no adjustment possibilities, generator voltage can still be increased somewhat by adjusting the ELC to a slightly higher frequency than nominal frequency. Adjusting it to a lower voltage by setting the ELC to a lower frequency is not recommended.

5.5 INSTALLATION

The ELC itself should be installed such that it is protected against too high temperatures and well-ventilated

(i). Find a cool spot on a wall in the shade. It should be so high that it is out of reach for at least small children, but also not just below the roof where hot air will accumulate. Make sure there is adequate ventilation. A power house that can be locked, would be best but the ELC can be installed in just a shed.

(ii). Keep dump loads well away from the ELC so that heat from dump loads will not lead to an increased ambient temperature around the ELC. Preferably, the dump loads should be in another room, with plenty of ventilation.

(iii). Mount the ELC on a wall, so that heat sink is placed with its bottom plate and fins vertically.

(iv). Mount it with thick washers between its bottom and the wall, so that there is at least a 10 mm air gap between the wall and bottom of the housing. Then the bottom area will serve as cooling surface for heat dissipated inside the ELC housing.

RESULTS AND CONCLUSION

6.1 RESULTS

In this scheme, the principle of phase angle control of back-to-back thyristor is made use of. A thyristor is fired at a specific delay angle relative to the zero voltage crossing of the sine wave (symmetrical for both halves of the sine wave). The thyristor commutates at next zero crossing. Switching occurs a twice the frequency and generates total harmonic distortion (THD) as high as 35 - 40 % in current with added reactive power burden. This scheme can continuously vary the dump power over nearly the entire range from zero to full load as the delay angle varies from 180 degree to 0 degree. Data taken during testing is given in table 6.1

Table 6.1 Testing data of main load and ballast load

Sl no	Generator voltage (V)	Load voltage (V)	Load current (A)	Power of main load (kW)	Power factor	Voltage in dump load (V)	Current in dump load (A)	Power of ballast load (kW)
1	235	234	10.68	2.5	1	230	0	0
2	235	232	8.6	2.0	1	227	2.20	0.5
3	235	230	6.521	1.5	1	225	4.44	1.0
4	235	229	4.36	1.0	1	220	6.81	1.5
5	235	226	2.21	0.5	1	215	9.30	2.0
6	235	228	4.38	1.0	1	226	6.63	1.5
7	235	229	6.55	1.5	1	229	4.36	1.0
8	235	231	8.65	2.0	1	230	2.17	0.5
9	235	233	10.72	2.5	1	232	0	0

6.1.1 Sensitivity analysis

Sensitivity of an instrument is the ratio of the magnitude of the output signal or response to the magnitude of input signal or the quantity being measured. Its units count per division, millimeter per microampere etc depending upon the input and output. The table showing load transferred from ballast to main load & vice versa and the time required is given in Table 6.2

Table 6.2: Load transfer and time

Serial No.	Main load (Watt)	Ballast load (Watt)	Total load transferred from main load to ballast load &vice versa in watt	Time taken to transfer load in millisecond
1	2500	0	0	
2	2000	500	500	21.50
3	1500	1000	1000	22.00
4	1000	1500	1500	22.40
5	500	2000	2000	23.20
6	1000	1500	500	21.00
7	1500	1000	1000	22.20
8	2000	500	1500	22.80
9	2500	0	2000	23.40

6.1.1.1 Calculation work for sensitivity

Sensitivity=Power transferred (Watts)/Time taken in transfer process (ms)
Sensitivity is calculated as under:

First reading 0 W/ms

Second reading 500/21.50=23.25W/ms

Third reading 1000/22.00=45.45W/ms

Fourth reading 1500/22.40=66.96 W/ms

Fifth reading 2000/23.20=86.20W/ms

Sixth reading 500/21.00=23.80W/ms

Seventh reading 1000/22.20=45.04W/ms

Eight reading 1500/22.80=65.79W/ms

Ninth reading 2000/23.40=85.47W/ms

Average sensitivity=0+23.25+45.45+66.96+86.20+23.80+45.04+65.79+85.47/9

=49.10 W/ms

6.2 CONCLUSION

A prototype ELC has been designed and assembled which has undergone successful testing on turbine on the specially designed test rig in the hydraulics laboratory of IIT Roorkee. Single-phase versions of the ELC were designed and tested for 50Hz operation, and the electrical output of the test generators ranged from 1 kW to 7 kW. Considerable research was undertaken into the technical and economic parameters associated with the overall design requirements of an ELC in order to improve on as many of the features associated with ELC design as would be possible. This included study into the extent of the harmonics generated by phase angle control, the phase shift effect caused by integral cycle control, the choice of induction or synchronous type generators, the choice of analogue or digital electronics, the choice of microcomputer and the need for three phase balancing to avoid unbalanced loading of three phase generators. The outcome of this research pointed to a particular design specification, which is now summarised. The ELC was designed for applications in electrical generating systems which are isolated from grid networks and which are fed by three phases, synchronous ac. generators. In its most basic form, the ELC has only two control variables, which need to be set as the unit is first commissioned. Prior knowledge of the ratio of the turbine runaway speed to nominal speed would permit the pre-setting of one of these variables. The unit is connected only to any two lines at the terminals of the generator. Its internal transformer feeds both the integral power supply circuit and the frequency sensing circuit. The power supply switches on once sufficient voltage is induced on the generator terminals as the generator runs up from standstill. The ELC automatically takes control of the speed of the set from that point until the generator is shutdown. In the event that the generator terminal voltage is not available the governor would not operate and so the set must have mechanical over speed protection fitted.

6.3 SCOPE FOR FUTURE WORK

6.3.1 A three-phase version

M.H.P systems with a capacity of more than 7 kW are likely to be build as 3 phase systems. Advantages of a 3-phase system are

(i). For such large capacities, the generator will be a bit smaller and cheaper.
(ii). Cables could be a bit thinner and thus: cheaper.

6.3.2 A cheaper version

There is a trend towards `pico-hydro' M.H.P systems with a capacity of less than 5 kW and mainly lighting as end use. For such pico hydro systems, a simpler ELC would do:

(i). The over voltage, under voltage and overheat protection feature and overload signal could be left out. Then over speed feature will protect user loads against run-away situations. With only one protection feature left, there is no need for LED's indicating which feature made the relay switch off. The trimmer for `over speed' could be replaced by fixed resistors. Then a much simpler PCB design with only 3 LM324 chips and 3 trimmers would remain.

(ii). Maybe even over speed feature could be left out and then no relay would be needed either.

(iii). Dump load LED's could be left out. Once working properly, the LED's indicating trigger angle give the same information as the dump load lamps. Anyway, users will notice that the system is overloaded when their lights go dim.

(iv). Component costs could be reduced further by choosing a smaller heat sink, relay, connector materials and housing.

Such a stripped ELC design would be cheaper and require less time to build. But it would not be easier to troubleshoot, as the ELC part works just the same as the standard design. So I think it only makes sense to develop such a design if there is a market for many of such small capacity ELC's.

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APPENDIX-1: VARIOUS PHOTOGRAPHS OF ELC AND ITS EXPERIMENTAL SET UP

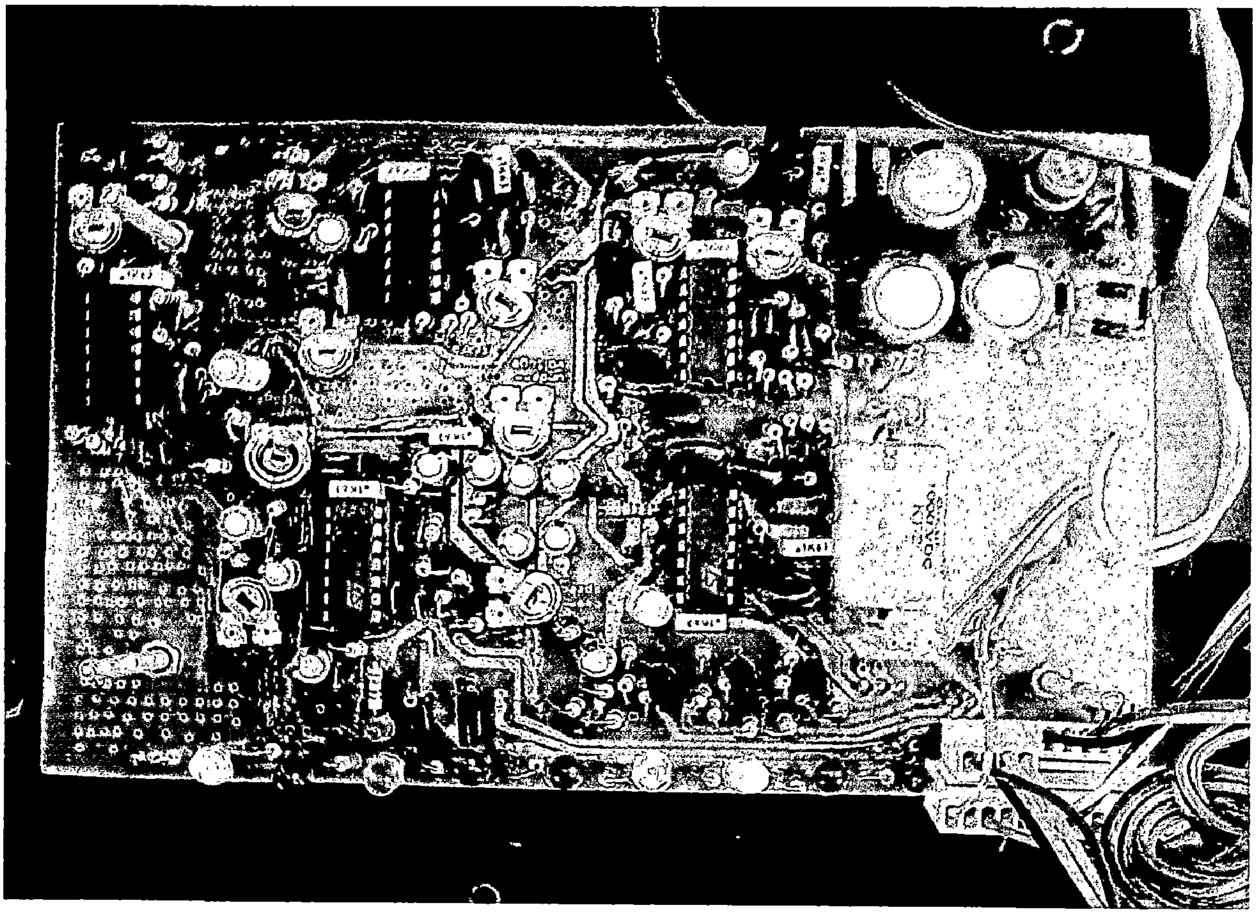

Fig 1 Circuit diagram of ELC on PCB

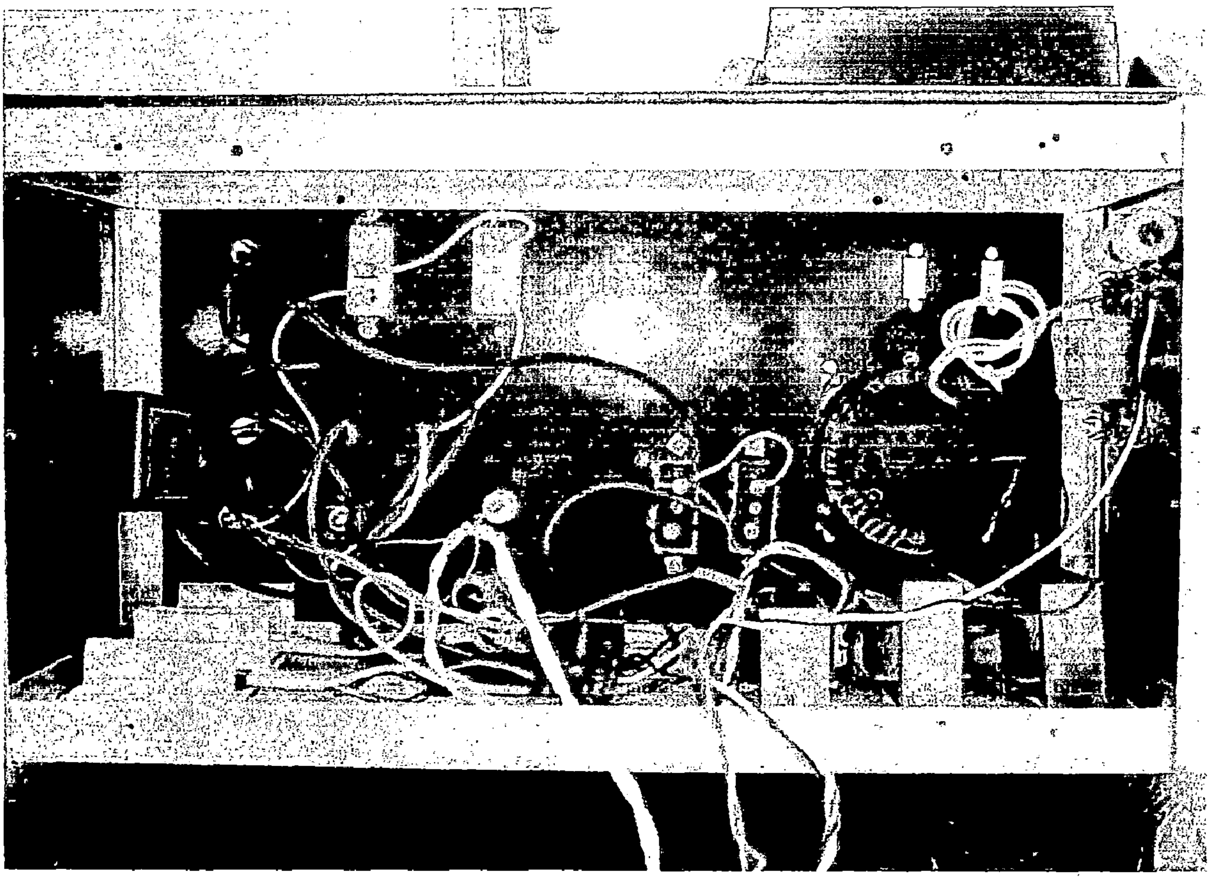

Fig 2 Power circuit of ELC

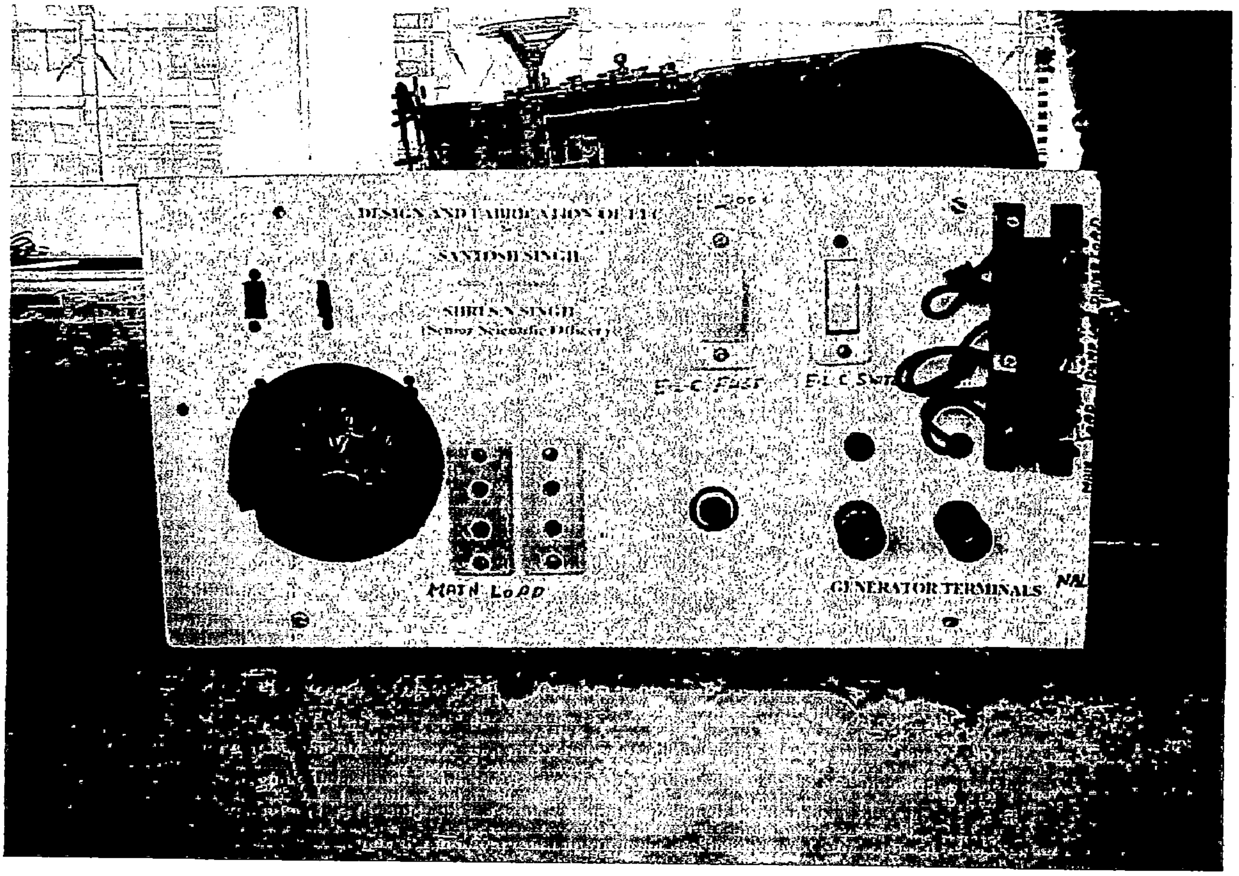

Fig 3 Developed ELC

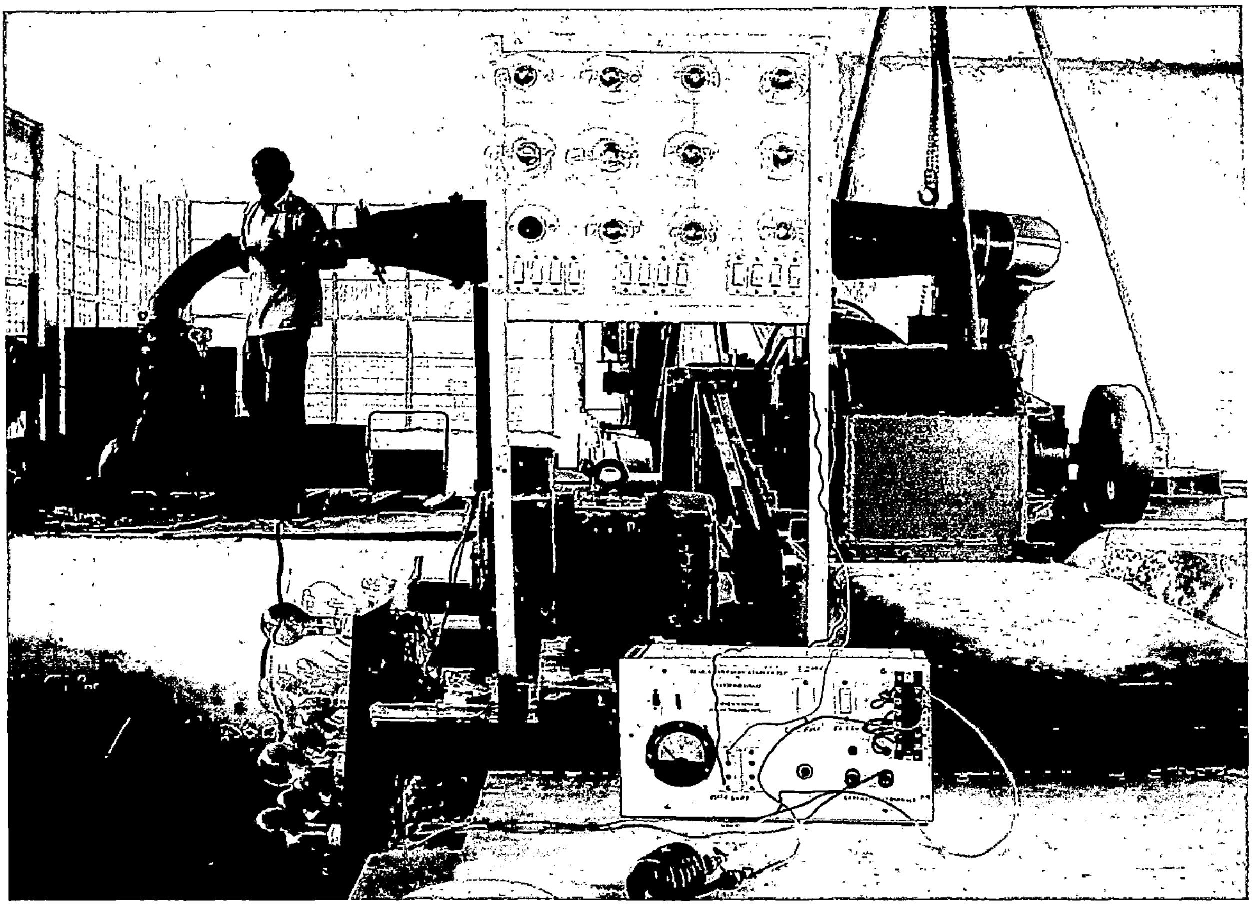

Fig 4 Experimental Set up

APPENDIX-2: GENERATOR RATING

Phase	single
Rating in kVA	3
Power output in kW	3
Current in Ampere	12
Speed in RPM	1500