A MODULAR SWITCHMODE POWER SUPPLY FOR AN INTERLOCKING SYSTEM

by

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Abstract

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A signal is an apparatus that safely provides visual information to the train driver of availability, route and safety of the way ahead and enables him to decide how to control his train. These signal units consist of a number of lights that display the required aspect to the train. The need for safer and more effective train control methods become more important as the number, speed, mass and length of trains increase. By extending the number of aspects to include 'flashing-aspects', i.e. switching some of the aspects on and off at a constant rate, more information can be conveyed to the train driver. A system(s) needs to be introduced into the interlocking in order to produce these aspects. This dissertation explores the implementation of a dc-to-dc switching converter, in a relay interlocking environment, in order to produce an oscillating voltage for these flashing aspects. The reliability of the system is improved by a modular design of power supplies and equal current sharing is implemented by means of current-mode control. The results presented show the system performing satisfactory in the signalling environment and being able to cope with varying loads.

'n Sinjaal is 'n apparaat wat veilig visuele inligting verskaf aangaande die beskikbaarheid, roete en veiligheid van die trein roete en stel ook die trein drywer in staat om te besluit hoe om sy trein te beheer. Hierdie sinjaal eenhede bestaan uit 'n aantal ligte wat die vereiste aspek aan die trein vertoon. Veiliger en meer effektiewe trein-beheer metodes word benodig namate die aantal, spoed, massa en lengte van die treine toeneem. Deur die huidige aspekte uit te brei deur middel van 'flikkerende aspekte' , met ander woorde. aspekte wat aan en af geskakel word teen 'n konstante tempo, kan meer inligting aan die trein drywer oorgedra word. 'n Stelsel(s), wat in die grendeling gekoppel kan word, word benodig om hierdie aspekte te verskaf. Hierdie skripsie bespreek die implimentasie van 'n dc-na-dc skakelmodus omsetter, in 'n relê grendelings omgewing, om 'n wisselende spanning te verskaf vir hierdie flikkerende aspekte. Die betroubaarheid van die stelsel is verbeter deur 'n modulêre ontwerp van kragbronne en stroom-deling is verkry deur middel van stroom-modus beheer. Die resultate toon dat die stelsel aanvaarbaar in 'n sinjallerings omgewing werk en dat die stelsel in staat is om varierende laste te akkommodeer.

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1. INTRODUCTION

Signals are used to convey information to a train driver concerning the route and the safety of the way ahead. Colour light signals are one type of signal used for this purpose. They consist of a pole on which one or more signal aspects (colour lights) are mounted and can be of the single lens or multi-lens type as shown in Figure 1-1.

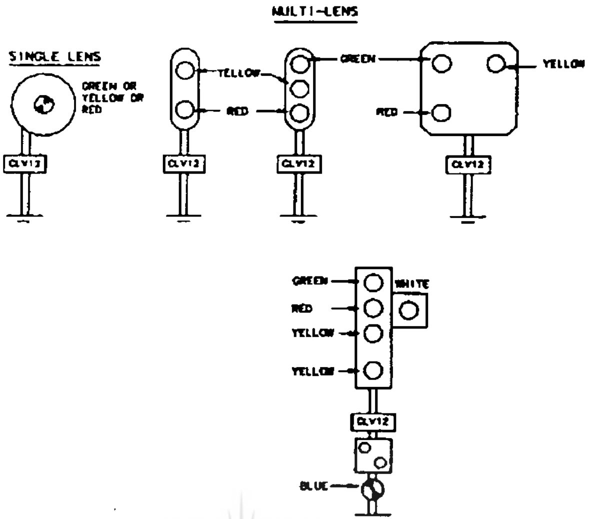

Figure 1-1 : Arrangement of Colour Light Aspects

These aspects are now extended to include 'flashing' aspects e.g. the red stop aspect will be flashed to represent an emergency aspect. This contributes to a more effective and fail safe signalling system (See Appendix A). In order to produce these aspects, a flashing module(s) must be incorporated into the interlocking.

Dc-to-dc converters are widely used in regulated switch-mode dc power supplies. The input to these converters is an unregulated dc voltage and the switch-mode dc-to-dc converters are used to convert this input into a controlled dc output at a desired voltage level. In this dissertation, dc-to-dc converters will be used to produce a 'flashing' voltage which will then be fed to these signal lamps from the interlocking in order to produce the flashing aspects. Through the use of current-mode control a modular system will be implemented in order increase the reliability of the system. This will also ensure a system which could be adapted for the needs of a specific geographical station layout.

2. SIGNALLING PRINCIPLES

2.1 DEFINITION AND PURPOSE OF SIGNALLING

Signalling is a communication system between the train and the operating center in control of the specific railway section. The purpose of the signalling system is as follows:
- Ensure a safe distance between trains on the same line
- Safeguard the movements of trains at crossings
- Regulate the movements of trains depending on circumstances.

Signalling permits the safe movement of trains at maximum permissible speed and minimum headway. Signalling can also be defined as the methodology of controlling train movements. In the broad sense of the word, signalling is not only the control of station areas but also the shared areas that interconnect the stations.

The speed and density of traffic are therefore factors in determining the necessity and basic elements of a signalling system.

2.2 BASIC REQUIREMENTS FOR A SIGNALLING SYSTEM

An ideal signalling system must comply with the following requirements:
- It must be impossible to display a proceed signal unless the whole section, controlled by the signal, is free of trains and safe for the passage of the train. During the passage through this section, the route must remain locked. In certain cases, normally where points are involved, the train releases the route behind it.
- If any part of the Signalling equipment fails, it must not be possible to wrongly display a proceed signal. In such cases a danger signal must be displayed.
- The signal aspects displayed must not be ambiguous and must always give a clear message early enough for the driver to keep his train under control.
- The system must be very reliable to limit train delays and to ensure maximum safety.

2.3 THE PRINCIPLE OF FAILURE TO SAFETY

Fail safe systems will always fail to a predictable (safe) state. So the failure of train detection equipment whilst occupied by a train, should for example rather indicate that there is a train present rather than indicating the track to be free.

2.4 THE ELEMENTS OF A SIGNALLING SYSTEM

These principles will be discussed briefly here as only a background is required. For a more comprehensive explanation see [1].

2.4.1 POINTS

A set of points is the piece of track equipment that enables trains to move from one track to another. (See Figure 2-1)

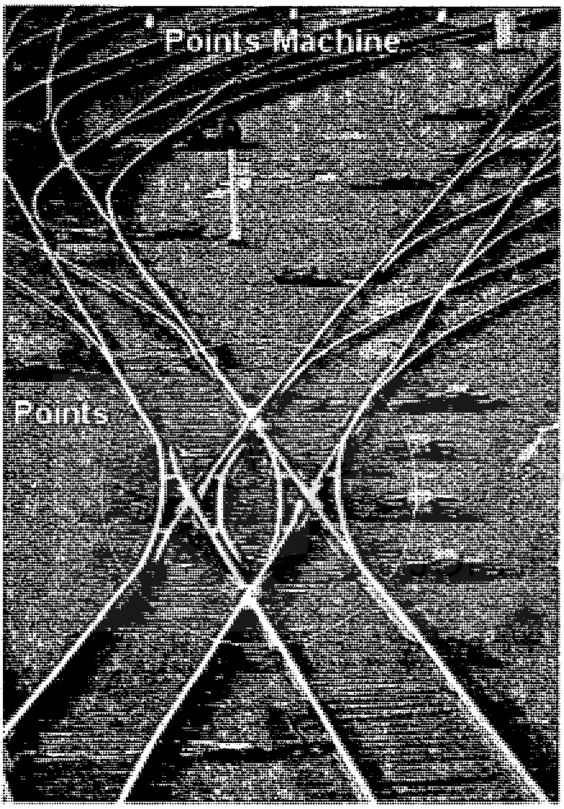

Figure 2-1 : Example of points and points machines

2.4.2 SIGNALS

A signal is an apparatus that safely provides visual information to the train driver of availability, route and safety of the way ahead and enables him to decide how to control his train. A signal can assume various forms and a combination of signals can form a system which displays the safety information. Amongst others the following types of signals are used:

- A wooden staff or Van Schoor token
  When a driver has a token in his possession, he knows that the section up to the next token station is free of trains, or is safe for his departure.

A combination of tokens and paper instructions allows crossings between trains, or trains to follow one another in the section.

- Semaphore (mechanical) signals.
  A semaphore signal consists of a pole or structure with an indicator (arm) attached. The position of the arm relative to the horizontal and the shape of the arm, indicated to the driver what train movements are allowed, and also the state of the section ahead.

- Colour light signals.
  A colour light signal consists of a pole on which one or more signal aspects (colour lights) are mounted, by which the allowable train movements and the state of the section ahead is displayed to the driver. Colour light signals can be of the three aspect or multi aspect type and the various aspects displayed have different meanings:

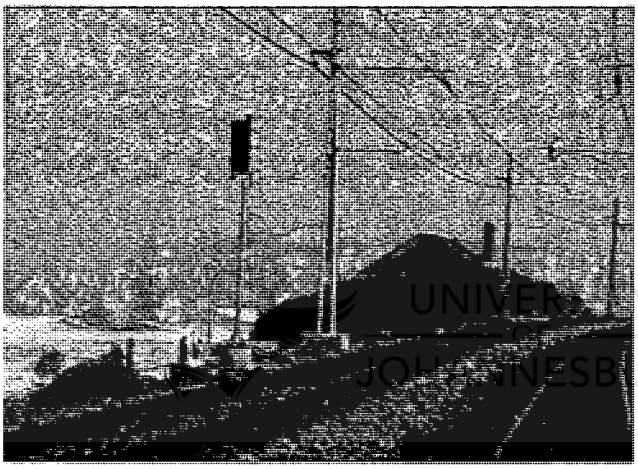

Figure 2-2: Example of a colour light signal

Red light : Danger stop.
Yellow light : Go, but stop at the next signal unless it is showing a proceed aspect.
Green light : go, the next signal is displaying a proceed aspect.
Green light above a yellow light : Proceed at the correct speed for the particular train to deviate over one or more sets of high speed points. The next signal is displaying a proceed aspect.
Yellow light above a yellow light : Proceed at the correct speed for the particular train to deviate over one or more sets of low speed points. The next signal is displaying a proceed aspect.
White light with a single yellow light or with a single green light : Go. But be prepared to stop at the second signal ahead.
White light with two yellow lights or with a green light and a yellow light : Proceed at the correct speed for the particular train to deviate over one or more sets of low speed or high speed points, beyond the next signal. Be ready to stop at the second signal ahead.

Red light above a yellow light : Proceed, the train is authorized to enter a goods siding.

Red light above a blue light : Stop, proceed so that the train can be stopped within sighting distance. Where there are points they are correctly set, but the state of the track circuit is indeterminate and the line is possibly occupied.

No light : Danger - stop.

A typical colour light signal is shown in Figure 2-2.

2.4.3 TRAIN DETECTION

Train detection equipment is track side equipment used to detect a track (or a part of it) occupied by a train in a safe and reliable manner.

The South African Transport Services uses the following types of train detectors for the safe detection of trains.

- Track circuits
  Track circuits are often the most cost effective method of train detection and consequently the most favoured. Figure 2-3 shows the most important parts of a track circuit.

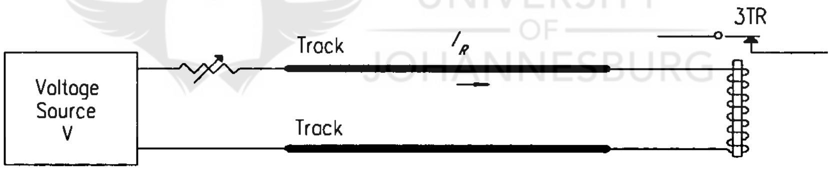

Figure 2-3: Operation of a track circuit without a train wheel present

Block joints insulate the rails of a specific track circuit from the rest of the track. Current I_R flows through both rails to pick up a relay (3TR). The circuit is normally powered and any failures (for example broken rails, discharged batteries, etc.) are immediately detected. When the track circuit is occupied by a train, the wheels and axle form a low resistance parallel path with the relay (See Figure 2-4). This will de-energized the relay, since the largest portion of the current I_w will flow through the axles of the train wheels.

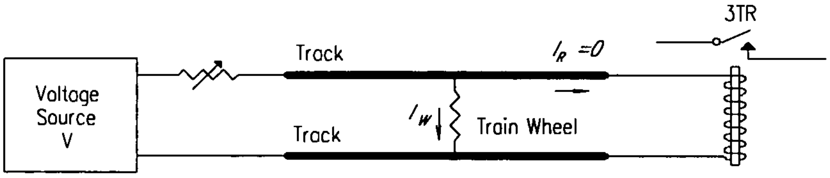

Figure 2-4: Operation of a track circuit with a train wheel present

- Axle counters
  Magnetic rail mounted switches (axle counter heads) are installed at counting points at the two ends of a section. The rail mounted switch is activated by the passing of each wheel of a train. The number of pulses generated corresponds to the number of axles passing the axle counter head. Axles are counted on entering the section and compared with axles leaving the section at the other end. The section is declared unoccupied if the numbers are equal.

- Last vehicle detectors
  The simplest form of a last vehicle detector is a permanent magnet attached to the last vehicle of the train which activates a magnetic switch situated between the rails. In another type last vehicle detector the rail mounted equipment has a transmit coil started with a high frequency and a receiver coil.

- Safety (fouling) bars
  Mechanical signalling uses safety bars, operated by a lever, to determine if a certain track is free of trains. If the track is occupied, the flange of the train wheel will prevent the safety bar from moving and it will not be possible to operate the lever.

2.4.4 INTERLOCKING

Interlocking is the equipment and the manner in which the movements of trains are controlled. The interlocking combines signals, points, track circuits and other equipment, to ensure that no dangerous or conflicting movements can take place.

The main purpose of the interlocking is as follows:
- To ensure that signals can not display a proceed aspect unless all the required sets of points are detected, and locked in the correct position.
- To prevent opposing signals from being operated simultaneously, which may lead to an accident.
- To prevent a set of points from being thrown until the signal has returned to the danger state and the train has moved clear from the relevant set of points.
- To expedite the train movement with maximum safety.
- To increase the capacity of the line.

The interlocking used by the South African Transport Services are divided into three main groups:

- Mechanical interlocking.
  Mechanical interlocking interlocks levers with each other to prevent unsafe train movements (See Figure 2-5)

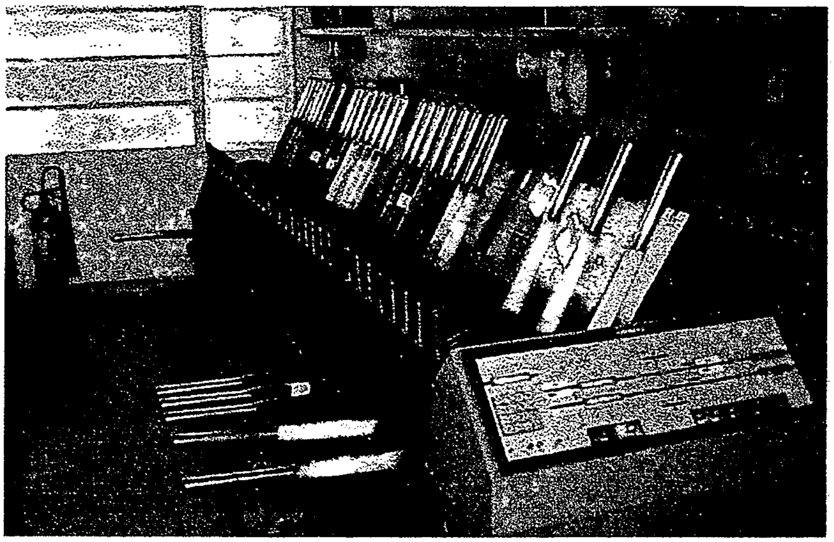

Figure 2-5: Interlocking - Mechanical lever frame

- Relay interlocking.
  Relay interlocking uses special signal relays to achieve the interlocking function. A control panel replaces the mechanical lever frame (See Figure 2-6)

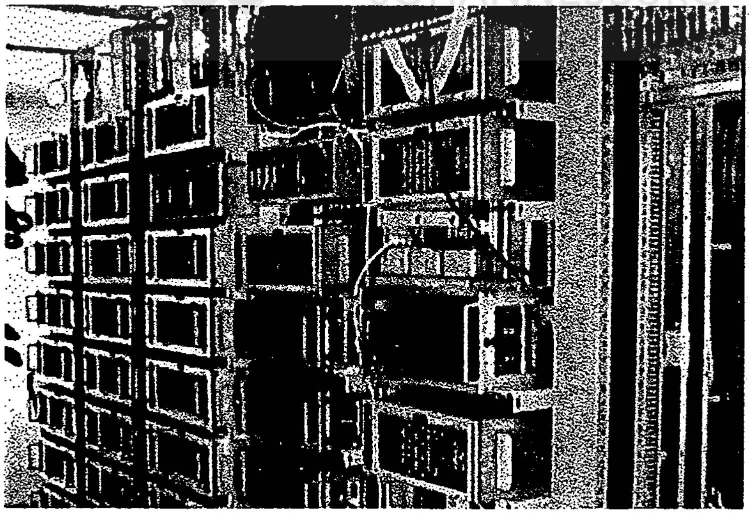

Figure 2-6 : Interlocking - Relay

- Electronic interlocking.
  In contrast to relay interlocking, electronic interlocking uses micro electronic components. When such components are used, provision has to be made to guarantee the safety of the system.

2.4.5 CONTROL

An operator is usually in charge of train movements. It is essential that an interface is provided between the operator and the signalling system, to enable him to control the trains.

This interface can take one of the following forms:

- Different types of mechanical lever frames.
- Different types of push button panels.
- Computer type keyboards.
- Digitizer panels.

The operator of the above will send commands to the interlocking and, if acceptable, they are executed. Indications of the state of the points, signals, track circuits, etc. are displayed on a diagram to give the operator an overall picture of all the train movements under his control. The control system can be refined by the provision of train number displays, train routing or automatic train routing. Figure 2-7 shows a typical control panel.

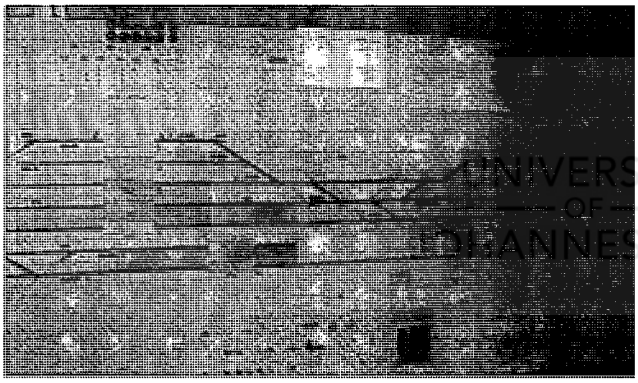

Figure 2-7: Typical push button control panel and indication diagram.

3. INTRODUCING FLASHING ASPECTS

3.1 BACKGROUND

Figure 3-1 indicates the basic components of a relay interlocking feeding a colour light signal. An operator is usually in charge of train movements. Therefore it is essential that an interface be provided between the operator and the signalling system, to enable him to control the trains. Signals, points, track circuits and other equipment are combined by the interlocking to ensure that no dangerous or conflicting signalled train movements can take place.

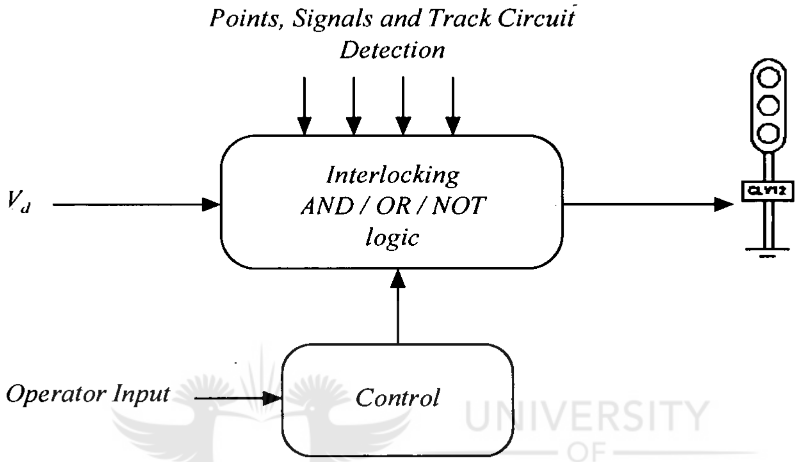

Figure 3-1 : Block diagram of the basic components of an interlocking feeding a signal aspect

The operator will request a signal aspect via the control device. A 55-cell battery bank (110V) supplies the voltage V_d to the signal lamps (as shown in Figure 3-2). The interlocking will complete a circuit feeding current, I_O to the signal unit if it detects that it is safe to do so. [1] This detection is obtained through the interconnection of relay contacts. It ensure the safety and correctness of the signal aspect and also assist in the prevention of false feeds to the equipment due to short circuits. A variable resistor R_1, mounted in an apparatus case next to the rail, limits the current I_O. As long as current flows to the lamp, a current relay, *CR*, will prove that the lamp is in a working condition (see appendix C).

The lamps used for the colour aspects are rated at 50V, 25W. In its normal working condition, the lamp can be modeled by a 100Ω resistor (see appendix B). If a minimal voltage drop is assumed in the interlocking stage and the transmission line, the external resistor (R_1) must be set to 120Ω to ensure a current of 500mA to the lamp. No isolation is used between the source and the load because this increases the cost and decreases the safety of the interlocking. Instead, both the positive and negative supply rails are ‘cut’, reducing the possibility of errors in the interlocking due to short circuits.

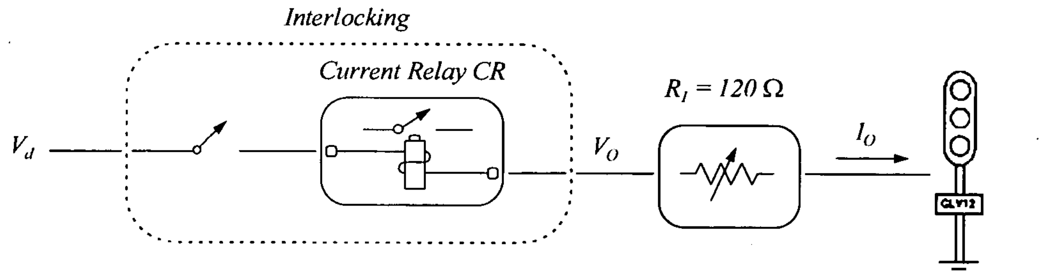

Figure 3-2 : Interlocking feeding a signal lamp

To produce flashing aspects, an unit(s) needs to be placed within the interlocking to switch the voltage to the lamps ‘on’ and ‘off’. The input to this unit is the 110V direct current, V_d, fed from the battery bank. In order to flash the aspect, this supply must be switched ‘on’ (100% current to the lamp) and ‘off’ (no current to the lamp) relative to ground potential. The current relay, CR, now senses the ‘off’ period as a failure and the interlocking immediately returns the signal to a danger aspect. The current can thus not be zero during the ‘off’ period. Appendix C shows that the current relay will still be energized if a current of at least 135mA (27%) flows through the lamp. The flasher must thus switch between ‘on’ (100% current) and ‘off’ (more than 27% current).

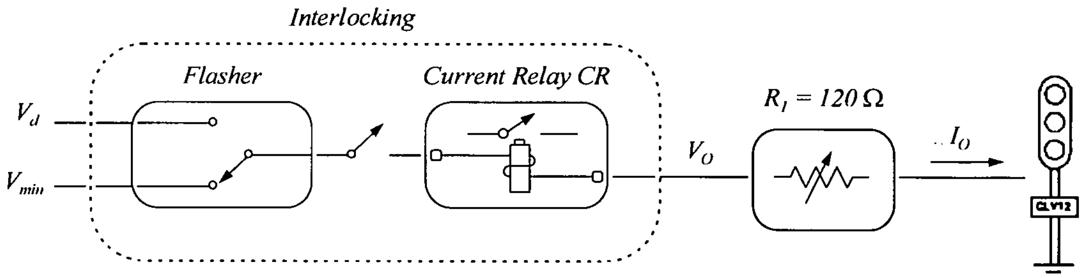

Figure 3-3 : Flasher feeding a signal lamp

In Figure 3-3 the flasher unit is depicted as a switch that simply connects either the V_d source or a V_{min} source, that supplies the ‘off’ current, to the lamp. Because the V_{min} source is not available, the flasher unit must generate this source from V_d. The simplest way to achieve this is by using a linear supply to generate a V_{min} voltage. The overall efficiencies of linear power supplies are usually in a range of 30%-60% and this will mean a significant amount of power loss.

As opposed to linear power supplies, in switching power supplies, the transformation of dc voltage from one level to another, is accomplished by using dc-to-dc converter circuits. These circuits employ solid state devices, which operate as a switch: either completely on or completely off. Since the power devices are not required to operate in their active region, this mode of operation results in a lower power dissipation. The characteristics of these supplies make them ideal for this application.

3.2 SYSTEM REQUIREMENTS[1]

The signal lamp intensity, by definition, is low enough to be accepted as off, if the lamp current is less than 200mA (40%). Although this seems like a logical state for the 'off' period, a signal with no aspect is considered to be a danger aspect and requires the train to stop. In order to ensure the safety of train movement, the aspect will not be switched completely off but rather dimmed. Thus, the current through the lamp in the 'off' period ($T\text{-}t_{ON}$) will be 60% of the current through the lamp in the 'on' period (t_{ON}). This will ensure that the lamp does not switch 'off' completely but rather changes intensity.

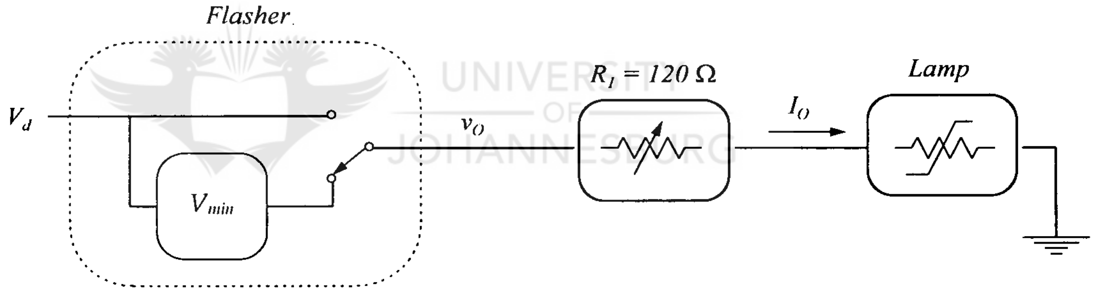

Figure 3-4 : Simplified interlocking diagram.

Figure 3-4 shows a simplified diagram of the flasher feeding a signal lamp with the current-relay coil-resistance included in R_1. The required output voltage v_O of the flasher unit for a lamp current I_O is as follows :

$$V_O = I_O \cdot (120 + R_{lamp})$$

The lamp has a non-linear VI-characteristic as shown in appendix B and the resistance changes with changes in current.

If I_O = 500mA (100%) then $R_{lamp} = 100\Omega$ and $v_O = V_d = 110V$
If I_O = 300mA (60%) then $R_{lamp} = 66.66\Omega$ and $v_O = 56V$

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[1] For a full description of requirements see Appendix E

This unit must produce an output voltage v_O to the interlocking as shown in Figure 3-5.

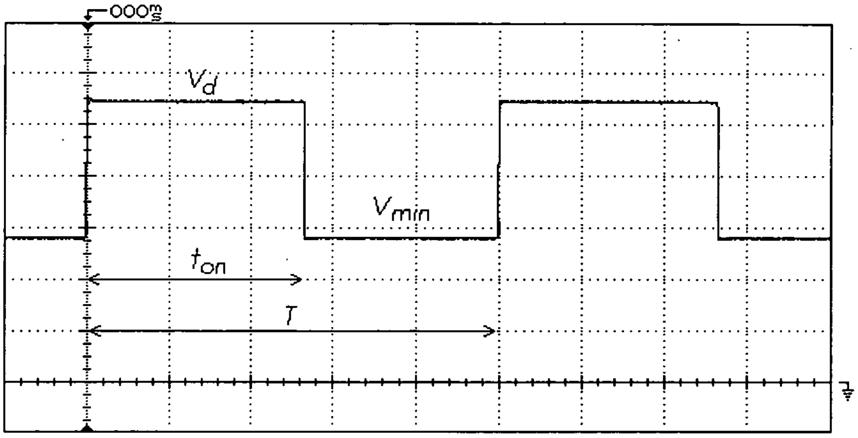


Figure 3-5: Output waveform v_o of the flasher unit (20V/div)

$$v_O = 110\text{V} \ (V_d) \ ; \ \ v_O = 56\text{V} \ (V_{min})$$

1. The flashing rate will be adjustable between 40 flashes per minute (fpm) and 60 flashes per minute (fpm). This means that the output frequency of the unit must be : 0.6Hz ≤ f_O ≤ 1Hz with $f_o = \frac{1}{T}$ with T the period of one cycle.

2. The duty-ratio will be adjustable between 50% and 60% where the duty-ratio is defined as: $DS = \frac{t_{on}}{T}$ with t_{on} the lamp 'on' time per cycle and T the period of one cycle.

3. In order to avoid confusion, all signals aspects flashed at the same time, will flash in synchronism.

4. The system must also be able to flash up to 160 lamps at the same time.

4. SOLUTIONS

Systems available on the market for producing flashing aspects, the Flasher Regulator model FR-1 (Appendix F) and the Thermo Flasher Unit (Appendix G), do not provide acceptable solutions. These systems both switch the lamps entirely on and entirely off thus incorporating failure into the interlocking.

A system needs to be integrated into the interlocking to generate the required V_{min} voltage. The output of the flasher must then alternate between V_{min} and the supply voltage, V_d. As previously mentioned, dc-to-dc converters are ideal for generating the V_{min} voltage level. The reliability of the system can be improved by a modular design of flasher units with equal current sharing. In order to establish equal current sharing, current-mode control will be implemented in the converters.

4.1.1 DC-TO-DC CONVERTERS

Dc-to-dc converters are widely used in regulated switch-mode dc power supplies [3]. The input to these converters is an unregulated dc voltage and the switch-mode dc-to-dc converters are used to convert this input into a controlled dc output at a desired voltage level.

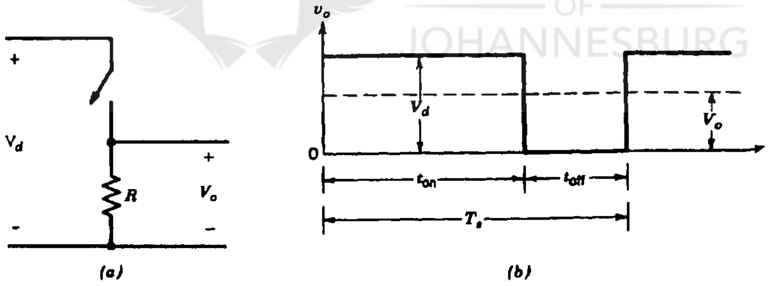
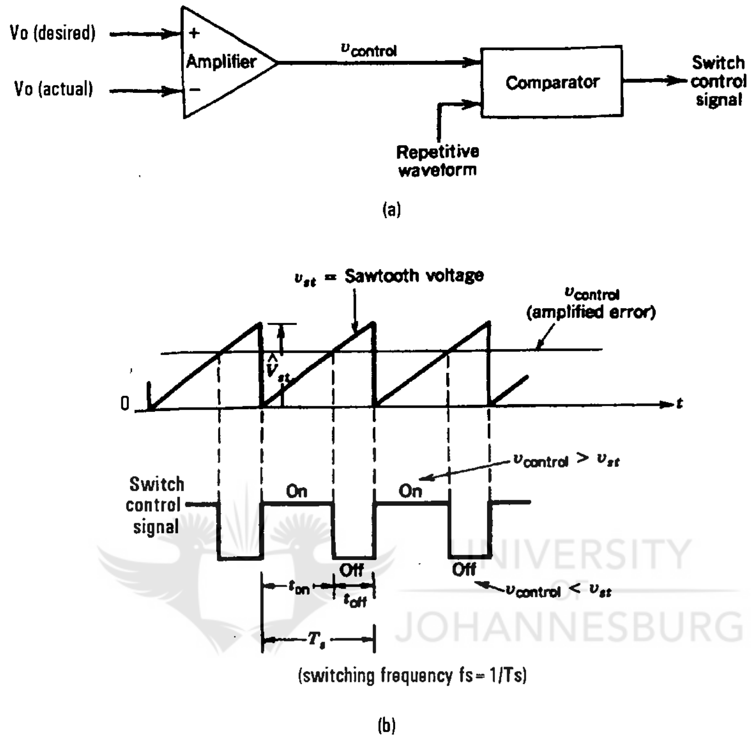


Figure 4-1 : Switch mode dc-dc conversion

In dc-dc converters, the average dc output voltage must be controlled to equal a desired level, though the input voltage and the output load may fluctuate. Switch-mode dc-dc converters utilize one or more switches to transform dc from one level to another. In a dc-dc converter with a given input voltage, the average output voltage is controlled by controlling the switch 'on' and 'off' duration (t_{on} and t_{off}). To illustrate the switch-mode conversion concept, consider a basic dc-dc converter shown in Figure 4-1a. The average value V_o of the output voltage v_O in Figure 4-1b depends on t_{on} and t_{off}. One of the methods for controlling the output voltage employs switching at a constant frequency (hence, a constant switching time period $T_S = t_{on} + t_{off}$), and adjusting the on-duration of the switch to control the average output voltage. In this method, called Pulse-Width Modulation

(PWM) switching, the switch duty ratio D, which is defined as the on-duration to the switching time period, is varied.

In the PWM switching at a constant switching frequency, the switch control signal, which controls the state (on or off) of the switch, is generated by comparing a signal level control voltage $v_{control}$ with a repetitive waveform as shown in Figure 4-2a and Figure 4-2b.



(a)

(b)

Figure 4-2 : Pulse-width modulator (PWM) switching : (a) block diagram, (b) comparator signals.

The control voltage signal generally is obtained by amplifying the error, or the difference between the actual output voltage and the desired value. The frequency of the repetitive waveform with a constant peak, which is shown to be a sawtooth, establishes the switching frequency. The frequency is kept constant in a PWM control and is chosen to be in a few kilohertz to a few hundred kilohertz range. When the amplified error signal, which varies very slowly with time relative to the switching frequency, is greater than the sawtooth waveform, the switch control signal becomes high, causing the switch to turn on. Otherwise, the switch is off.

In terms of $v_{control}$ and the peak of the sawtooth waveform $\hat{V}_{st}$ in Figure 4-2, the switch duty ratio can be expressed as

$$D = \frac{t_{on}}{T_S} = \frac{v_{control}}{\hat{V}_{st}} \qquad \text{Equation 4-1}$$

The average output voltage can thus be made to follow a pattern, as indicated in Figure 3-5 by varying the control voltage $v_{control}$. This technique can be incorporated into a number of dc-to-dc converter topologies whereof the following will be considered :

1. Step down (buck) converter
2. Step down/up (buck-boost) converter

4.1.1.1 Buck Converter

Conceptually, the basic circuit of Figure 4-1a constitutes a step-down converter for a purely resistive load. Assuming an ideal switch and purely resistive load, the instantaneous output voltage depends on the switch position. From Figure 4-1b the average output voltage can be calculated in terms of the switch-duty ratio:

$$V_O = \frac{1}{T_S}\int_0^{T_S} v_0(t)\,dt = \frac{1}{T_S}\left(\int_0^{t_{on}} V_d\,dt + \int_{t_{on}}^{T_S} 0\,dt\right) = \frac{t_{on}}{T_S}V_d = DV_d \qquad \text{Equation 4-2}$$

Substituting equation 4-1 in equation 4-2

$$V_o = \frac{V_d}{\hat{V}_{st}}.v_{control} = k.v_{control} \qquad \text{Equation 4-3}$$

where

$$k = \frac{V_d}{\hat{V}_{st}} = constant \qquad \text{Equation 4-4}$$

By varying the duty ratio $\frac{t_{on}}{T_S}$ of the switch, V_o can be controlled.

Another important observation is that the average output voltage V_o varies linearly with the control voltage, as is the case in linear amplifiers. In an actual application, the foregoing circuit has two drawbacks: (1) In practice the load would be inductive. This means that the switch would have to dissipate the inductive energy and therefore it may be destroyed. (2) The output voltage fluctuates between 0 and V_d, which is not acceptable in most applications.

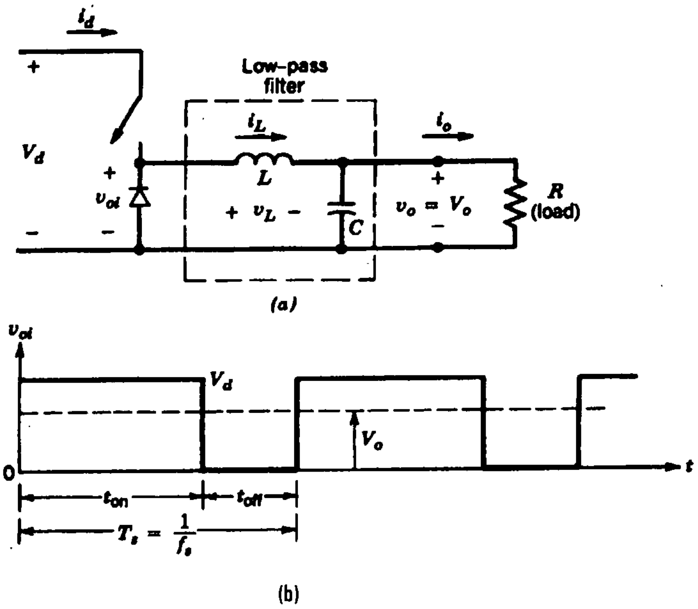


Figure 4-3 : Buck dc-dc converter.

The problem of stored inductive energy is overcome by using a diode as shown in Figure 4-3. The output voltage fluctuations are very much diminished by using a low-pass filter consisting of an inductor and a capacitor.

From Figure 4-3a we observe that in a step down converter, the average inductor current is equal to the average output current I_o, since the average capacitor current in steady state is zero.

4.1.1.2 Buck-Boost Converter

A buck-boost converter can be obtained by the cascade connection of two basic converters: the step-down converter and the step-up converter. In steady state the output-to-input voltage conversion ratio is the product of the conversion ratios of the two converters in cascade. (assuming that he switches of both converters have the same duty ratio):

$$\frac{V_o}{V_d} = D\frac{1}{1-D} \qquad \textit{Equation 4-5}$$

This allows the output voltage to be higher or lower than the input voltage, based on the duty ratio D.

The cascade connection of the step-down and the step-up converters can be combined into the single buck-boost converter shown in Figure 4-4. When the switch is closed, the input provides energy to the inductor and the diode is reverse biased. When the switch is open, the energy stored in the inductor is transferred to the output. No energy is supplied to the input during this interval. In the steady state analysis presented here, the output capacitor is assumed to be very large, which results in a constant output voltage $v_o(t) \approx V_o$

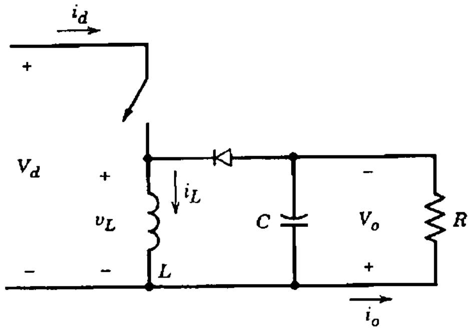


Figure 4-4 : Buck-Boost Converter

4.1.2 COMPARISON OF NON-ISOLATED DC-DC CONVERTERS

To evaluate how well the switch is utilized in the previously discussed converter circuits, we make the following assumptions:

1. The average current is at its rated (designed maximum) value I_O. The ripple in the inductor current is negligible; therefore $i_L(t)=I_L$. This condition implies a continuous-conduction mode for all converters.
2. The output voltage v_o is at its rated (designed maximum) value V_O. The ripple in v_o is assumed to be negligible; therefore $v_o(t)= \hat{V}_o$.
3. The input voltage V_d is allowed to vary. Therefore the switch duty ratio must be controlled to hold V_O constant.

With the foregoing steady-state operating conditions, the switch peak voltage rating V_T and the peak current rating I_T are calculated. The switch power rating is calculated as $P_T= V_T I_T$. The switch utilization is expressed as P_O/P_T, where $P_O=V_O I_O$ is the rated output power. In Figure 4-5 the switch utilization factor P_O/P_T is plotted for the previously considered converters. This shows that in the step-down converter if the input and output voltages are of the same order of magnitude, then the switch utilization is very good. In the buck-boost converter, the switch is poorly utilized. The maximum switch utilization of 25% is realized at D=0.5, which corresponds to $V_O= V_d$.

In conclusion for these non-isolated dc-dc converters, it is preferable to use the step-down converter from a switch utilization consideration [3],[4].

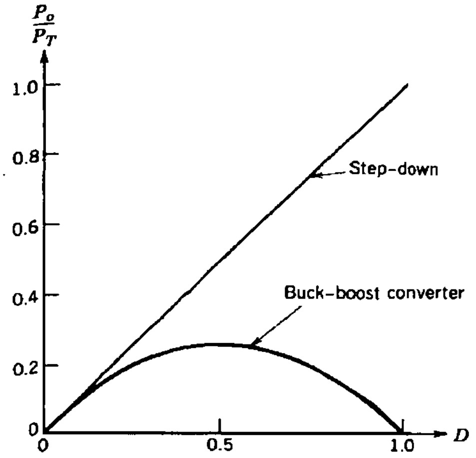


Figure 4-5 : Switch utilization in dc-dc converters

4.1.3 CONTROL OF SWITCH-MODE DC POWER SUPPLIES

As mentioned, the reliability of the system can be improved by a modular design of flasher units with equal current sharing. In order to establish equal current sharing, current-mode control will be implemented in the converters.

4.1.3.1 Current-Mode Control

The PWM direct duty ratio control discussed so far is shown in Figure 4-6a, where the control voltage v_C (amplified error signal between the actual output and the reference) controls the duty ratio of the switch by comparing the control voltage with a fixed-frequency sawtooth waveform. This control of the switch duty ratio adjusts the voltage across the inductor and hence the inductor current (which feeds the output stage) and eventually brings the output voltage to its reference value.

In current-mode control, an additional inner control loop is used as shown in Figure 4-6b, where the control voltage v_C directly controls the output inductor current that feeds the output stage and thus the output voltage. Ideally, the control voltage should act to directly control the average value of the inductor current for the fastest response. Though, various types of current-mode control tends to accomplish the same thing differently. The fact that the current feeding the output stage is controlled directly in current-mode control has a profound effect on the dynamic behavior of the negative feedback control loop.

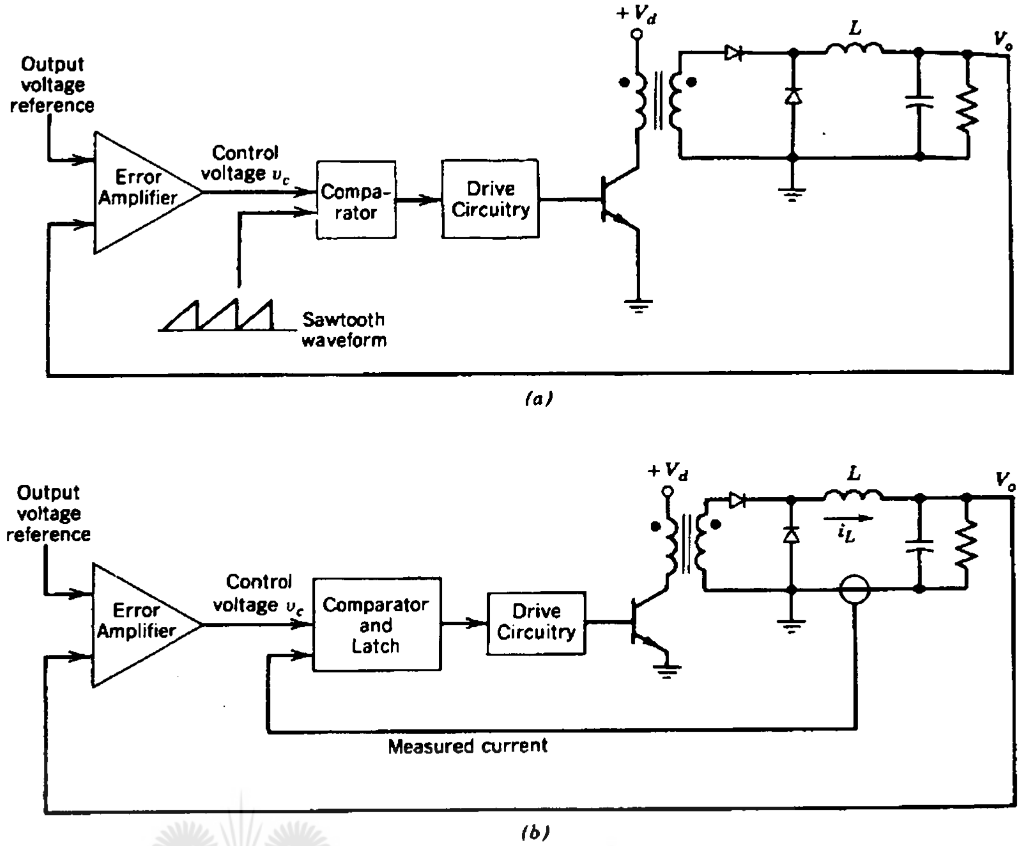


Figure 4-6 : PWM duty ratio versus current-mode control

There are three basic types of current mode controls of which "constant frequency control with turn-on at clock time" will be considered. In all these types of controls, either the inductor current or the switch current, which is proportional to the output inductor current, is measured and compared with the control voltage.

The *constant-frequency control with a turn-on at clock time* is thus far the most common type of current-mode control. Here the switch is turned on at the beginning of each constant-frequency switching time period. The control voltage dictates $\hat{I}_L$ and the instant at which the switch is turned off, as shown in Figure 4-7. The switch remains off until the beginning of the next switching cycle. A constant switching frequency makes it easier to design the output filter.

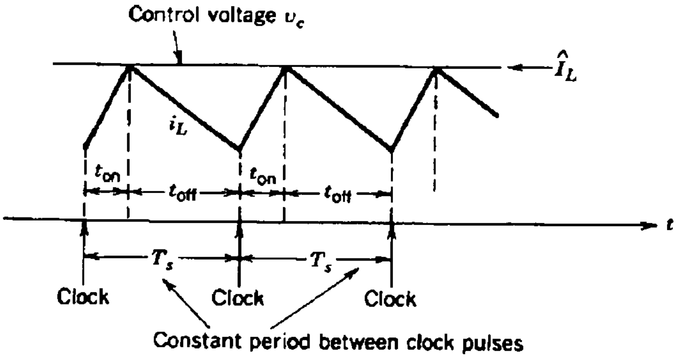


Figure 4-7 : "Constant-frequency control with a turn-on at clock time" current-mode control

In the current mode control in practice, a slope compensation is added to the control voltage, as shown in Figure 4-8, to provide stability, to prevent subharmonic oscillations, and to provide a feed-forward property. Figure 4-8 shows the waveforms for a forward converter, where the slope of the slope compensation waveform is one-half of the slope of the inductor current when the switch is off. With given input and output voltages, the duty ratio is D_1 and the waveform of the inductor current i_L is shown by the solid line. If the input voltage is increased but the output voltage is to remain unaffected, the duty ratio is decreased to D_2 and the inductor current waveform is shown by the dashed line. The average value of the inductor current, which equals the load current, remains the same in both cases in spite of a change in the input voltage. This shows the voltage feed forward property of the current-mode control with a proper slope compensation.

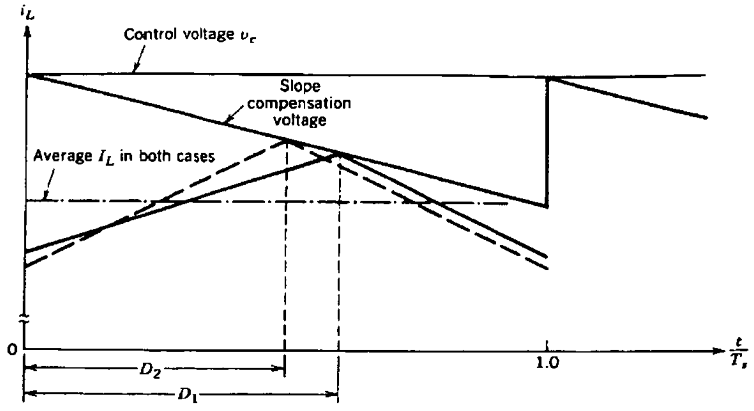


Figure 4-8 : Slope compensation in current-mode control

The current-mode control has several advantages over the conventional direct duty ratio PWM control:

1. It limits peak switch current. Since either the switch current is directly measured or the current is measured somewhere in the circuit where it represents the switch current without delay, the peak value of the switch current can be limited by simply putting an upper limit on the control voltage. This can be easily accomplished in the controllers that control $\hat{I}_L$.
2. It removes one pole (corresponding to the output filter inductor) from the control-to-output transfer function, thus simplifying the compensation in the negative-feedback system, especially in the presence of the right-halve-plane zero.
3. It allows a modular design of power supplies by equal current sharing where several power supplies can be operated in parallel and provide equal currents, if the same control voltage is fed to all the modules.
4. It results in a symmetrical flux excursion in a push-pull converter, thus eliminating the problem of transformer core saturation.
5. It provides input voltage feed-forward. As shown by Figure 4-8, an input voltage feed-forward is automatically accomplished, resulting in an excellent rejection of input line transients.

4.1.4 POWER SUPPLY PROTECTION

4.1.4.1 Soft Start

A soft start in switch-mode dc power supplies is provided by increasing the duty ratio and hence the output voltage slowly, subsequent to the input voltage switch-on.

4.1.4.2 Voltage Protection

Overvoltage and undervoltage protection can be incorporated by adding a shut-down to the converter.

4.1.4.3 Current Limiting

For protection against overcurrent at the output, the circuit output current can be sensed by measuring the voltage across a sensing resistor. When the sensed voltage exceeds a threshold, the output of the error amplifier is pulled towards ground and linearly decreases the output pulse width.

In a constant current-limited power supply, if the gain of the current limiting stage is high, the supply V_O-I_O characteristics can be as shown in Figure 4-9a where once a critical value of current I_{limit} is reached, I_O is not allowed to increase any more and the output voltage V_O depends on the load line.

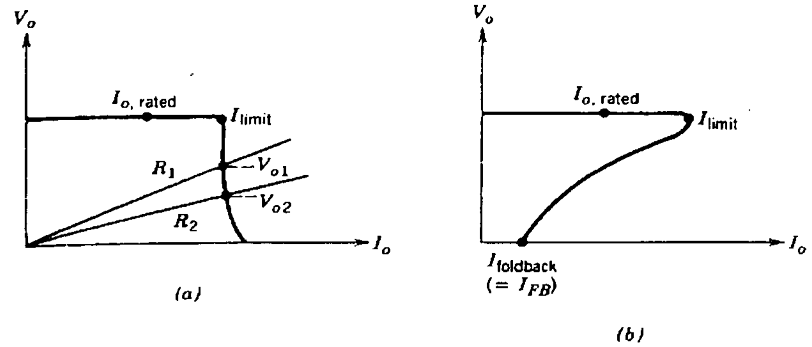


Figure 4-9 : Current limiting

In many applications, the output current exceeding a critical value represents an abnormal load condition, and a foldback current limit is introduced where, as the load resistance decreases, the output current also decreases (along with the decreasing output voltage V_O), as shown in Figure 4-9b. Here, in case of a short circuit across the output, the current will have a much smaller value I_{FB} in comparison to I_{limit}.

5. IMPLEMENTATION

5.1 OVERVIEW

The previously discussed buck switch-mode converter (paragraph 4.1.1.1) will be used to produce an alternating voltage for the flashing aspects. The reliability of the system will be improved by a modular design of power supplies with equal current sharing. With current mode control it is relatively easy to parallel several supplies. All the supplies to be paralleled will have identical current sensing, and identical current control loops and a single control voltage (common to all supplies) will cause them to deliver identical output currents. A single reference signal and error amplifier will be used to supply the control voltage v_C to all units (see Figure 4-6b), enabling the outputs to be paralleled to share a common load equally.

As the load requirements change, the system will automatically add units, to share a larger load, and remove units to distribute a smaller load between the remaining units. This reduces the requirements on the units and enables for a more reliable system (faulty units can automatically be removed). The advantages of current-mode control will be illustrated and a full description of a prototype system will be given as illustration.

5.2 EVALUATING THE ADVANTAGES OF CURRENT-MODE CONTROL [2]

As discussed previously, the PWM duty-ratio controlled Buck converter topology does not offer an acceptable solution to modular operation. The advantages of rather using current-mode control will be illustrated by simulation both topologies in PSpice.

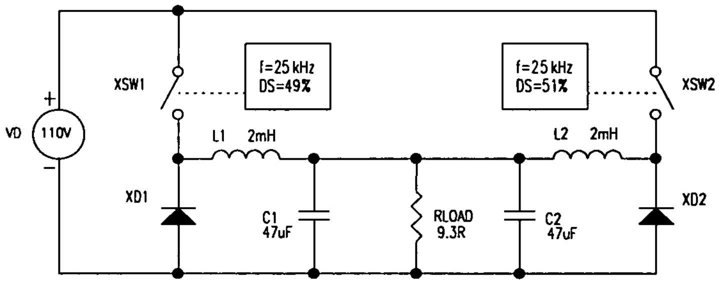


Figure 5-1 : Two PWM duty-ratio controlled Buck-Converters in parallel

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[2] Details of simulations in Appendix D

Figure 5-1 shows the configuration of two buck converters connected in parallel. Conventional PWM duty-ratio switching schemes are used and both converters are switched at a constant frequency of 25kHz. The switches in the converters are switched at a slightly different duty-ratio, which is almost unavoidable in reality, and the initial inductor currents are set to 3A. An output voltage of 56V (V_{min}) ensures a load current of 6A which must be supplied by both converters.

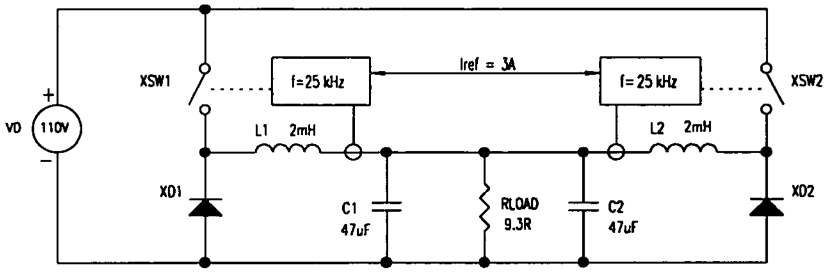
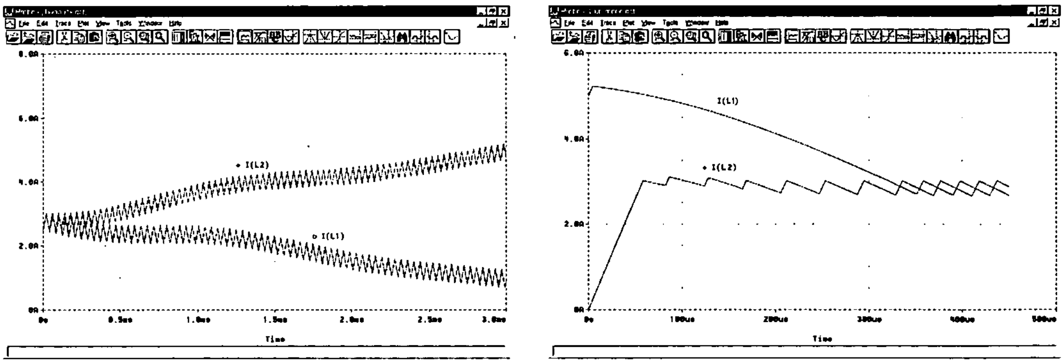


Figure 5-2 : Two Current-Mode Controlled Buck-Converters in Parallel

Figure 5-2 shows two paralleled buck switch-mode converters with current-mode control. Constant-frequency control with a turn-on at clock time has been used and a control voltage, requiring each converter to deliver a current of 3A to the load, is applied to the control circuitry. The operating frequency of the switches deviate slightly from 25kHz to simulate reality. The initial current conditions in the inductors are set so that the control is opposite for each converter.



(a) (b)

Figure 5-3 : Inductor Currents for (a) PWM and (b) Current-Mode Control

Figure 5-3(a) show the inductor currents for the PWM duty-ratio controlled converters. It can be seen that although both inductor currents start off at the same point, the converter with the longer on-period (larger duty-ratio), eventually supplies more current and current sharing becomes unbalanced.

It is therefore not possible to parallel supplies with conventional duty-ratio control.

The inductor currents for current-mode control is shown in Figure 5-3(b). It can be seen that, even though the currents start off at opposite values, the inductor current of each converter converges and the load current is shared equally. As indicated, current-mode control offers a better solution to modular power supply design.

5.3 CIRCUIT DESCRIPTION

Figure 5-5 depicts the flashing power supply unit in diagrammatic form consisting of “Open-Loop Buck Converters”, a “Control Loop” and an “Internal Supply”.

The “open-loop buck-converters” are current-mode controlled buck-converters, as shown in Figure 4-6(b) and repeated in Figure 5-4, without the outer voltage control loop and error amplifier. The input to this stage is the control voltage v_C which directly controls the output inductor current i_L, that feeds the output stage, and thus indirectly the output voltage V_O.

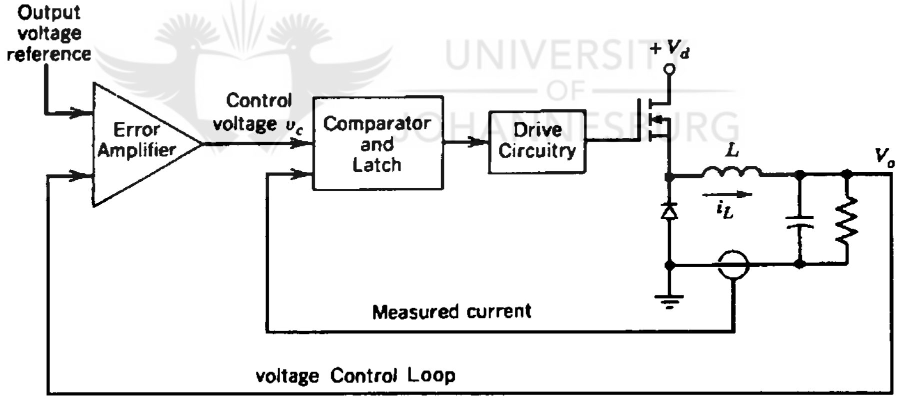


Figure 5-4 : Current-Mode Controlled Buck-Converter

The outer voltage control loop in Figure 5-4 forms the heart of the “control loop”. The actual output voltage v_O is compared with the output-voltage reference-value (as defined in Figure 5-4) and the output voltage of the error amplifier defines the common control voltage v_C fed to all the open-loop buck-converters. By varying the output-voltage reference value, the output voltage of the converter can be controlled. The control-loop also decides to either add open-loop buck converters to the system or remove open-loop buck-converters from the system based on the current requirements of the load. The control loop can handle a total of up to 8 buck-converter modules which increase the capacity of the overall system quite considerably.

The Internal Supply is a magnetically coupled self oscillating Royer inverter providing regulated supply voltages to the "control loop" and the "open-loop buck-converters".

Each of these blocks will now be discussed in detail.

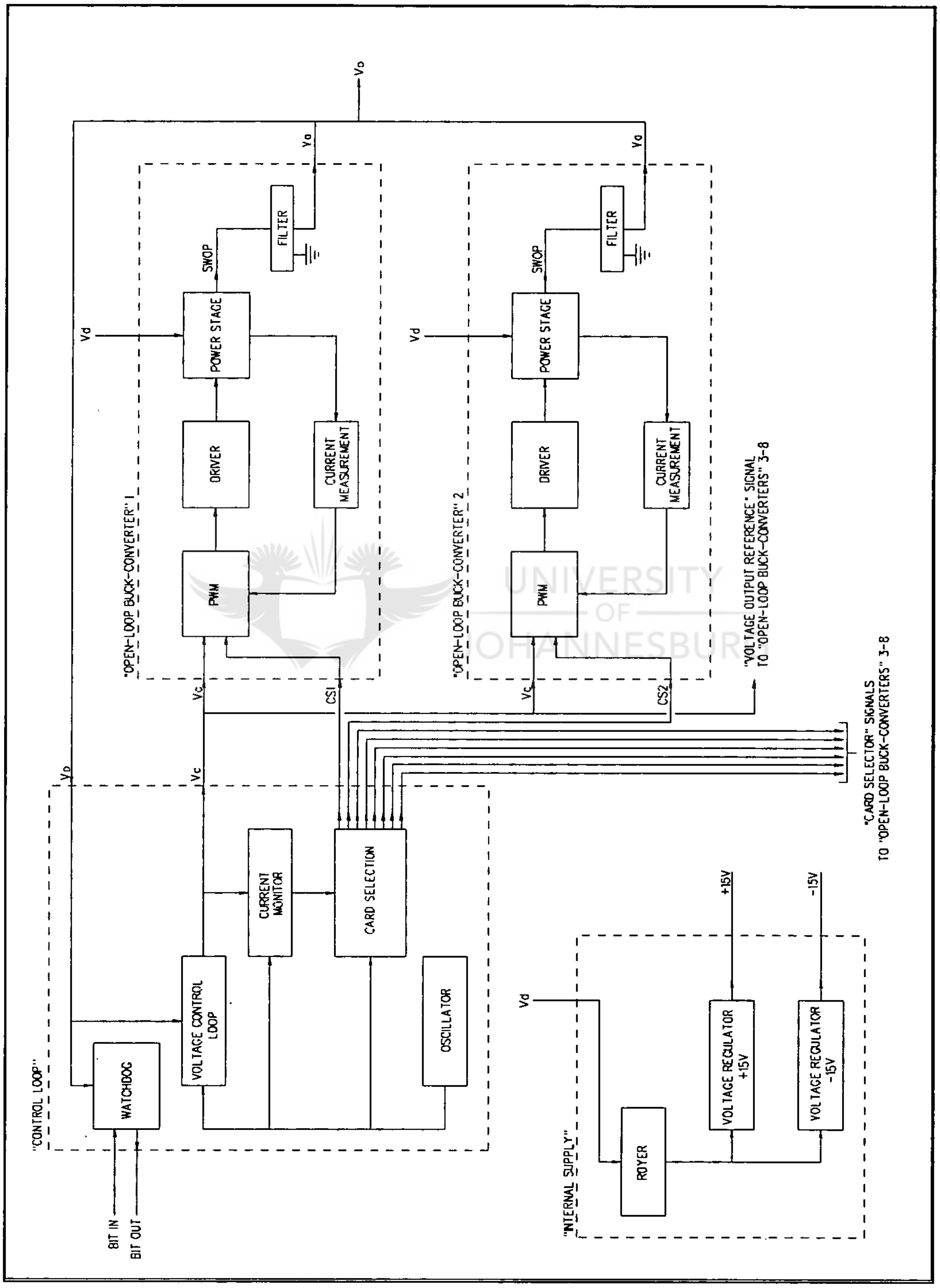


Figure 5-5 : Functional Flow Diagram of the Flashing Power Supply Unit

5.3.1 OPEN-LOOP BUCK-CONVERTERS

The "Open-Loop Buck-Converters" are current-mode controlled buck-converters as discussed previously. Figure 5-6 represents a block diagram of this stage.

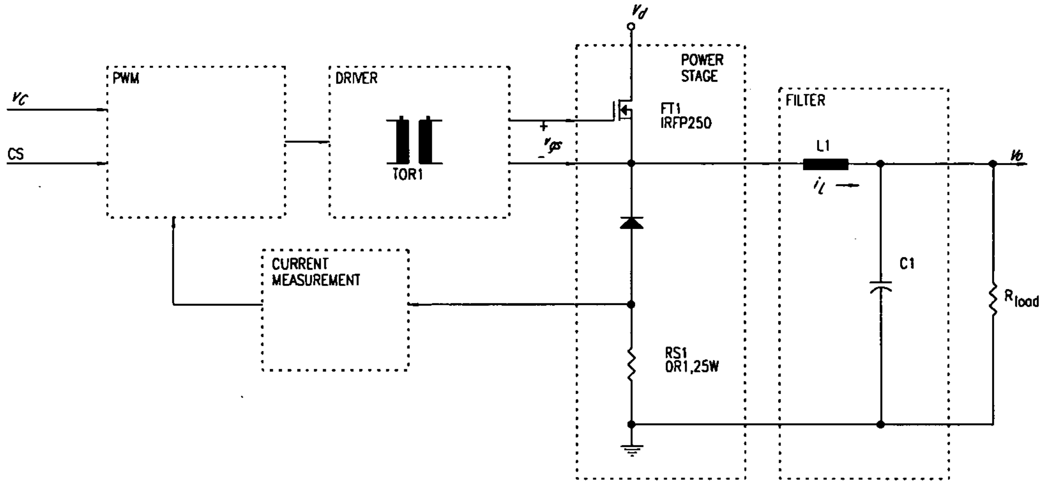


Figure 5-6 : Block diagram of Open-Loop Buck-Converter

A pulse width modulated drive signal is impressed on FT1 via the pwm-and driver stages. The PWM stage consists of a LM494 which is a fixed-frequency pulse width modulation control circuit, incorporating the primary building blocks required for the control of a switching power supply. An internal linear sawtooth oscillator is frequency-programmable by two external components, to 25kHz. The pulse width modulator comparator provides a means for the error-amplifiers to adjust the output pulse width from the maximum percent on-time, down to zero.

The driver stage in Figure 5-6 provides a low-impedance answer to drive the mosfet FT1, a duty-cycle ratio of 1-99% and furthermore provides electrical isolation. A low-power hexfet such as the IRFD1Z0, is used to control the drive signal to FT1, and TOR1 is a small 1:1 driver transformer providing electrical isolation from, and coupling to, the low level circuitry.

In the current measurement stage, the peak current flowing through the inductor (L1), $\hat{i}_L$, is measured via a current sense resistor (RS1), an inverting amplifier, a positive peak detector and this control signal is fed into the error amplifier input of the PWM. A control voltage v_C defines the peak inductor [5] current $\hat{i}_L$, and is fed into the remaining error amplifier input of the PWM. The error amplifier minimizes the difference between the measured current and the control voltage signal v_C to implement constant-frequency control with a turn-on at clock time.

Each open-loop buck-converter can be disabled by setting a card select input (CS) active and forcing the PWM to a minimum duty cycle.

5.3.1.1 Semiconductor Switch Capabilities

The semiconductor switches used in the buck-converters, do not have ideal characteristics and will dissipate power when they are used in the configurations mentioned. A major contribution to the power loss in the switch is the average power dissipated during the on-state P_{ON}, which varies in proportion to the on state resistance $R_{S_{ON}}$ of the switch.

$$P_{ON\ \ N\,LAMPS} = N^2 \cdot I_O^2 \cdot R_{S_{ON}} \cdot \frac{t_{ON}}{T} \qquad \text{Equation 5-1}$$

The current I_O is the current drawn by a single lamp and equation 5-1 represents the power dissipation in a switch driving N lamps. The switching power loss P_S in the semiconductor switch varies linearly with the switching frequency and the switching times. Here $t_{C(on)}$ is the turn-on crossover interval and $t_{C(off)}$ is the turn-off crossover interval between voltage and current.

$$P_{S\ \ N\,LAMPS} = N \cdot \tfrac{1}{2} V_d I_O f_S (t_{C(ON)} + t_{C(OFF)}) \qquad \text{Equation 5-2}$$

The total average power dissipated P_T in a switch equals the sum on P_S and P_{ON}. A wide variety of semiconductor switches are available with very short switching times, high power dissipating capabilities and current ratings of up to 100A. This makes it easy to reach very high power ratings.

In the buck converter (Figure 5-6) the semiconductor switch, with an on resistance of $R_{SON}=0.085\Omega$ is operated at a frequency $f_S=25$kHz. The total load connected to the converter is N lamps with $Io=500$mA per lamp. Further $V_d=110$V and $t_{C(on)}+t_{C(off)}=148$ns. The total continuous drain current that the semiconductor switch can handle is 30A.

As shown by equation 4.2, if V_O = 110V (V_d) then D=1 and if V_O = 56V (V_d) then D=0.51. With D=1 a pessimistic value of the maximum power dissipated in the switch is obtained. Figure 5-7 shows the maximum power dissipated in the semiconductor switch as the load increases.

Semiconductor switches are available that can easily handle large loads in an environment where an ambient temperature of up to 50°C can be expected. With a maximum junction temperature of the device at 148.5°C and a junction to ambient thermal resistance $R\theta(J\text{-}A)=2.65$°C/W the maximum power that can be dissipated in the semiconductor switch is

$$P_J = \frac{T_J - T_A}{R_{\Theta}(J-A)} = 37.17W .$$

The converter load will be limited to 10A per buck-converter which equals a total average power dissipation of 10.6W in the device, and provides a safe margin under these operating conditions.

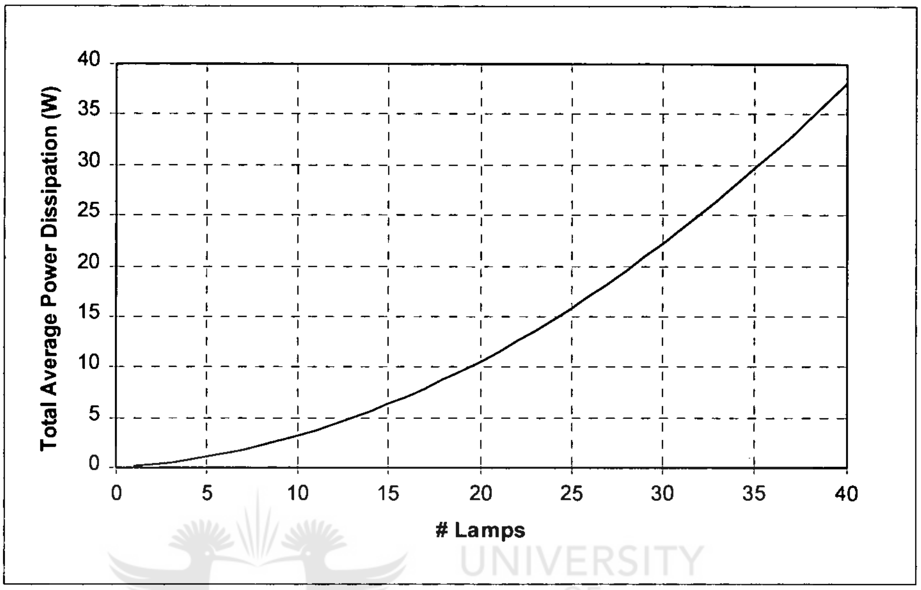


Figure 5-7 : Total Average Power Dissipation of the Semiconductor Switch

5.3.2 CONTROL LOOP

The Control Loop's (see Figure 5-8) main function is the implementation of current programming for the open-loop buck-converters. The average output voltage of a buck-converter can be calculated in terms of the switch-duty ratio:

$$V_O = DV_d$$ *Equation 5-3*

For an output voltage as indicated in Figure 3-5 (repeated in Figure 5-9), the duty ratio will be varied as follows:

With V_O = 110V (V_d), D=100% and
V_O = 56V (V_{min}), D=51%

Thus, the output voltage of the flasher unit will be made to alternate between the V_d and V_{min} levels, by letting the duty ratio vary between 51% and 100%.

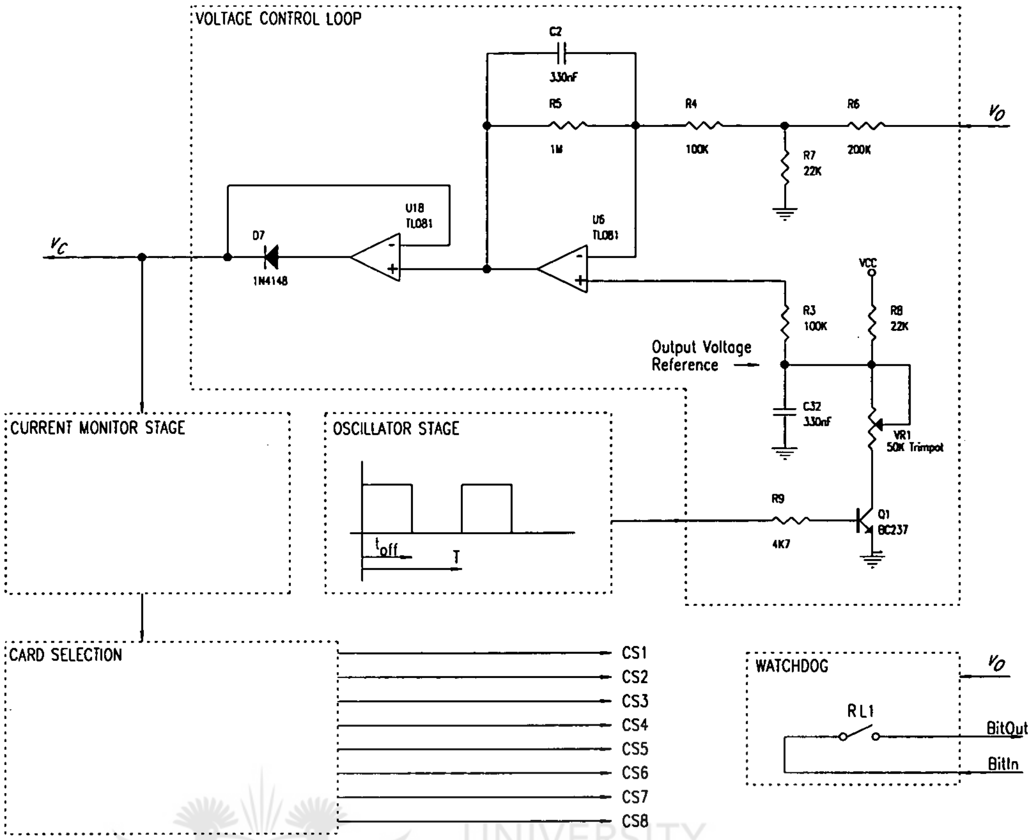


Figure 5-8 : Block diagram of the Control Loop

An 'output voltage reference' signal is compared with a measured value of the output voltage (10% of v_O) and an error signal is buffered to supply the control voltage v_C to the open-loop buck-converters. By changing the output voltage reference signals between $V_d/10$ and $V_{min}/10$, the desired duty ratios can be established and the output of the flasher unit will follow the pattern as indicated in Figure 5-9. The speed at which the output voltage reference signal is changed (the flashing frequency 1/T), as well as the flashing duty ratio (t_{on}/T) , can be adjusted.

The Current-monitor-stage monitors the control voltage v_C and based hereon, adds Open-Loop Buck-Converters to the system, or removes Open-Loop Buck-Converters from the system through the card selection stage. The Card-selection stage provides 8 output signals (CS1-8) to Open-Loop Buck-Converters to either enable or disable them.

The Watchdog-stage compares the output from the open-loop buck-converters with a voltage window. If the average of the oscillating output voltage does not fall within the window, a relay (RL1) is de-energised and the connection between BitIn and BitOut signals is broken indicating that the system is faulty.

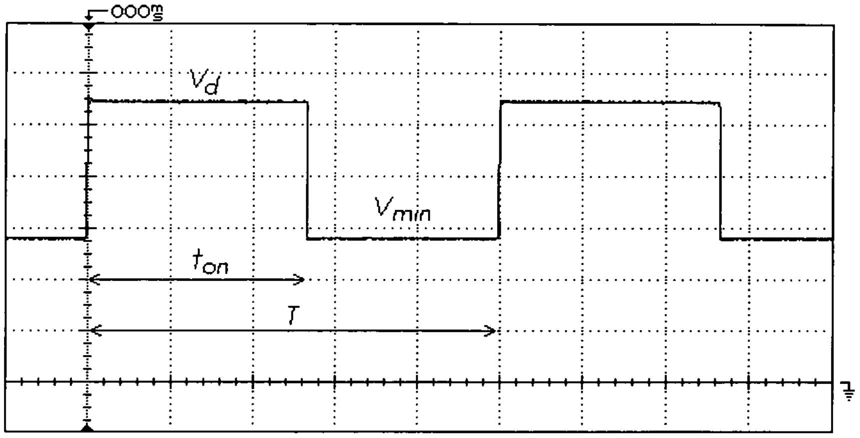


Figure 5-9 : Output waveform v_O of the flasher unit (20V/div)

5.3.3 INTERNAL SUPPLY

The Internal Supply is a magnetically coupled self oscillating Royer [6,7] inverter providing regulated supply voltages (+15V and -15V) to the control-loop and the open-loop buck-converters. Here a Royer inverter is applied for its simplicity and robustness. The input to the inverter is 110V direct current from a battery-bank.

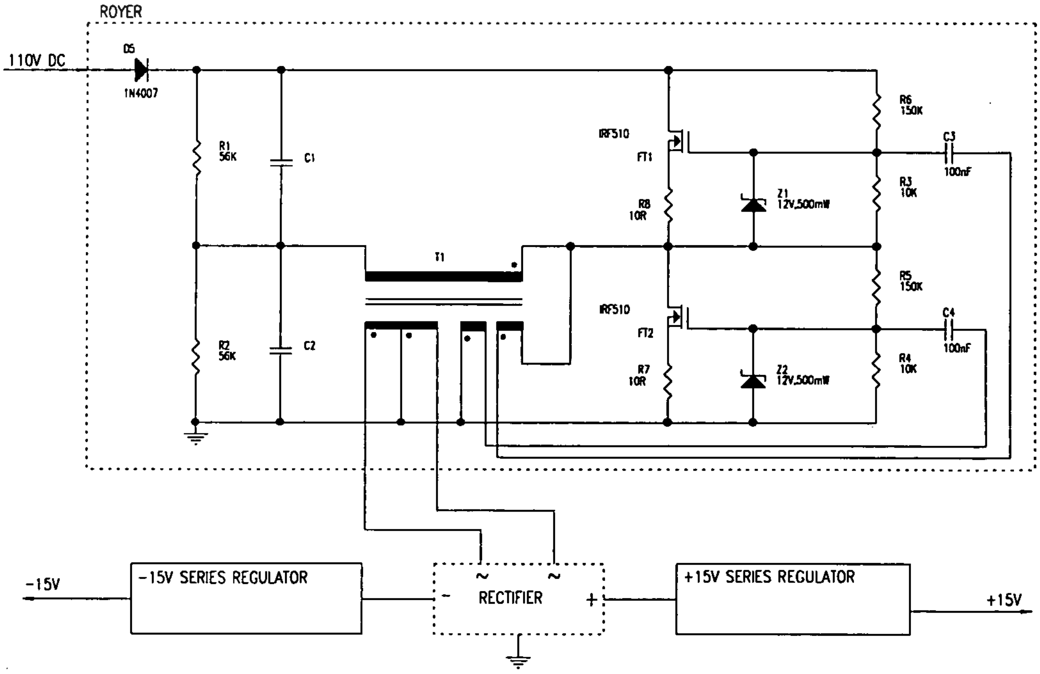


Figure 5-10 : Block diagram of the Internal Supply

Components C1, C2, R1 and R2 provide a mid-voltage of 55V (half of the supply voltage). The load switches from FT1 to FT2 and vice versa when the gate-drive windings (T1) saturate and the primary winding-voltage commutates. Diodes in the rectifier stage provide rectification of the inverter output. The +15V series regulator-stage and -15V series regulator-stage provides regulated outputs from the unregulated inputs.

6. PRACTICAL RESULTS

6.1 OPERATION OF SYSTEM

The flasher system, operated in current control mode, was built to evaluate the functionality of the system. A circuit diagram, depicting the core components of the system is shows in Figure 6-1 with input and output variables as indicated. It will be noted that this system can handle up to 8 open-loop buck converters. The results shown here will however be representative of a system with 2 open-loop buck-converters as it illustrates the principles applied.

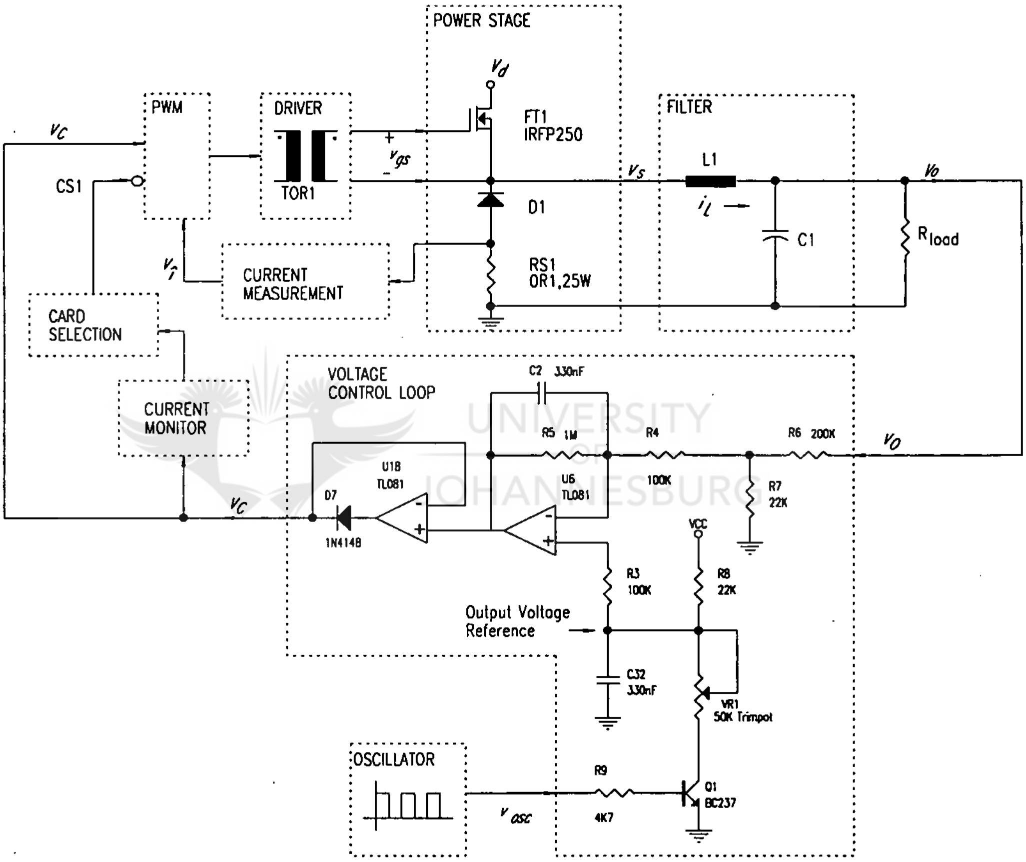


Figure 6-1 : Basic Flasher System with one open-loop buck-converter unit

The output voltage is measured by the voltage control loop and compared with an output voltage reference signal. The output voltage reference signal is clocked by an oscillator and varies between Vcc and ($V_{min}/10$) as shown in Figure 6-2. The error signal from the control loop, v_c, is fed into the pulse-width-modulator input and compared with a measured value of the inductor current $v_{\hat{i}}$. The error signal generated here, adjusts the switching voltage (v_s) duty ratio to ensure that the peak inductor current $\hat{\imath}_L$ equals the control voltage v_c as indicated in Figure 6-3.

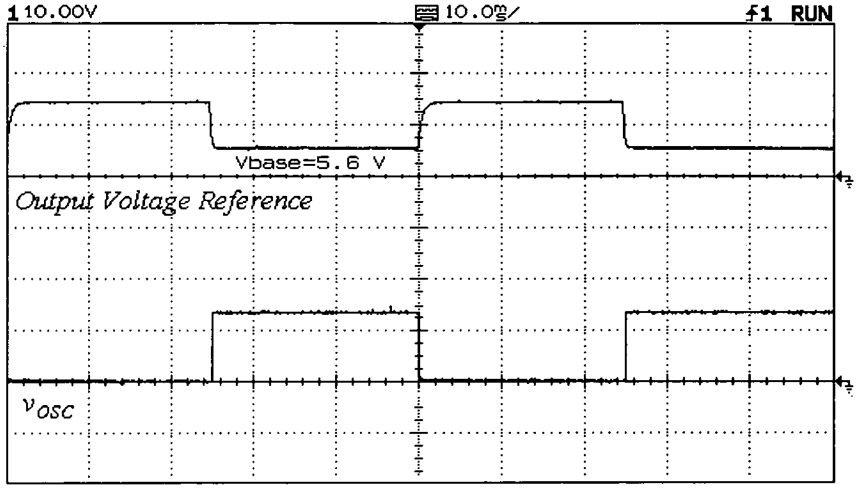


Figure 6-2 : Oscillator and Output Voltage Reference Signal (10V/div)

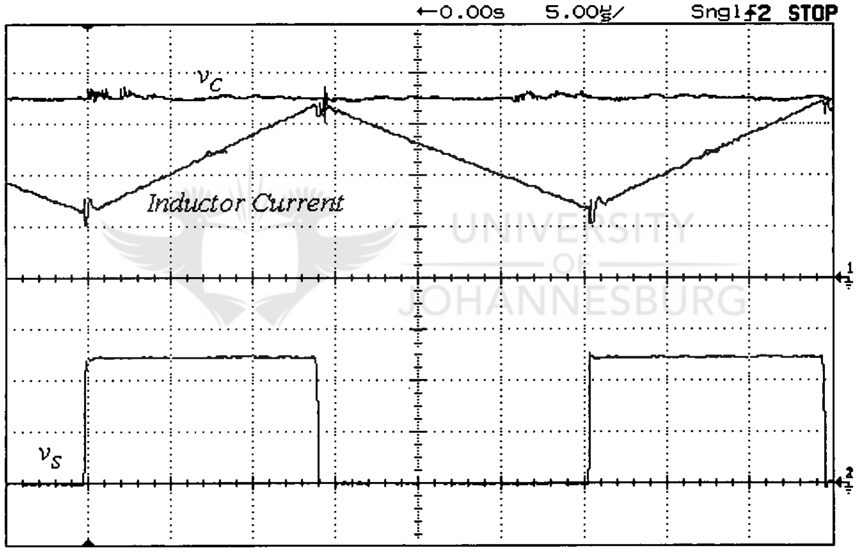


Figure 6-3 : Inductor current (200mA/div), control voltage(v_C) (200mV/div) and switching voltage (v_S) (50V/div)

6.1.1 INPUT

The Flashing Power Supply Unit uses a 55 cell lead-acid batterybank (121V) as input. In order to ensure a stable dc input, a large capacitor was connected to the input of the system for experimental purposes.

6.1.2 OUTPUT

Figure 6-4 represents the output voltage and current waveforms of the flashing power supply unit for a typical load (compare with Figure 3-5). Because the V_d level is not regulated by the system, only the V_{min} level will be discussed here. The transition of the V_d level to the V_{min} level is characterized by an overshoot in both the voltage and current waveforms. This characteristic ensures a rapid decrease in lamp intensity and has been incorporated in the system due to the low-pass characteristic of the signal lamps. This characteristic of the lamps cause a sluggish response which the overshoot very much diminishes.

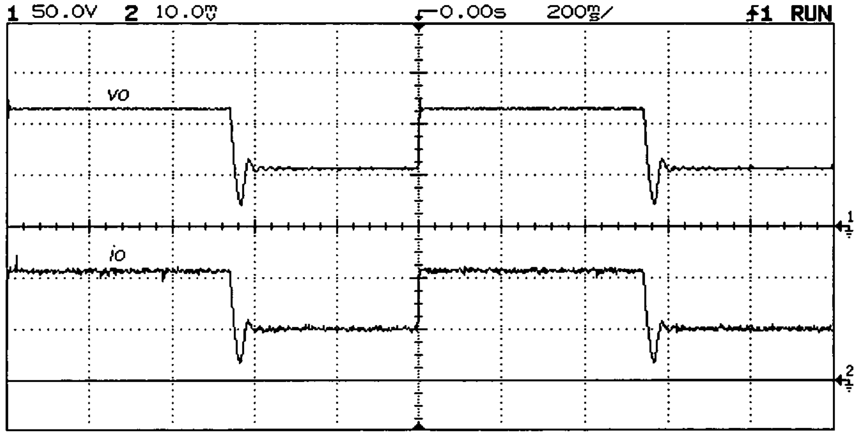


Figure 6-4 : Output Voltage and Current for Resistive Load
v_O *(50V/div)*, i_O *(500mA/div)*

The inverse property can be seen at the lamp switch-on. The filament in an incandescent bulb has a lower cold resistance than when it is warm, so it acts as a resistor with a positive temperature coefficient (PTC). The peak current at switch-on will therefore be much higher than the maximum continuous current (See Appendix B). In order to understand what this high current does to the lamp we must realize that the filament is not smooth and even but rather it is very rough. The switch-on peak will therefore cause hot spots to appear at the points where the filament is thinnest. These points suffer from wear and tear which eventually leads to one of them burning through, usually immediately upon switch-on. This overcurrent at switch-on can be limited by controlling the timed-voltage rise dV/dt with which the supply is switched to the lamp. A simple RC-filter (C32 & R8 in Figure 6-1) in the control loop is sufficient to place this restriction on the output voltage as shown in Figure 6-4.

6.1.3 LOAD REGULATION

Under normal operating conditions, the input voltage to the system is 121V. In the event of a power failure the voltage will eventually drop to a minimum of 100V. The flashing power supply unit must thus be able to produce an acceptable output under these conditions. Figure 6-5, Figure 6-6 and Figure 6-7 shows the load regulation of the V_{min} level (56V) under these input conditions. These levels were measured using a FLUKE Model 75 multimeter.

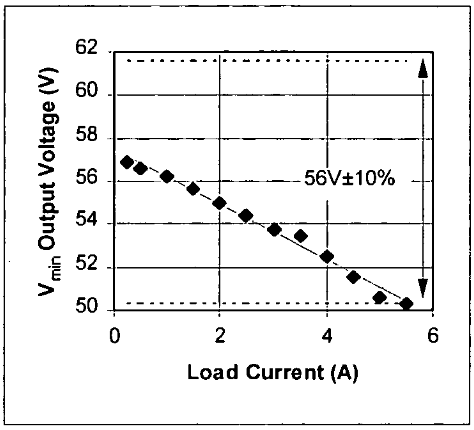


Figure 6-5 : Output Voltage as a function of Load Current. (Vin = 124V)

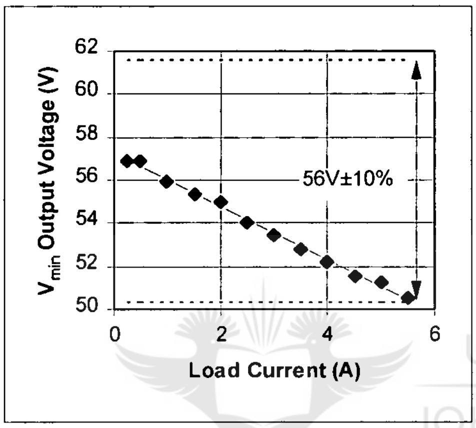


Figure 6-6 : Output Voltage as a function of Load Current. (Vin = 112V)

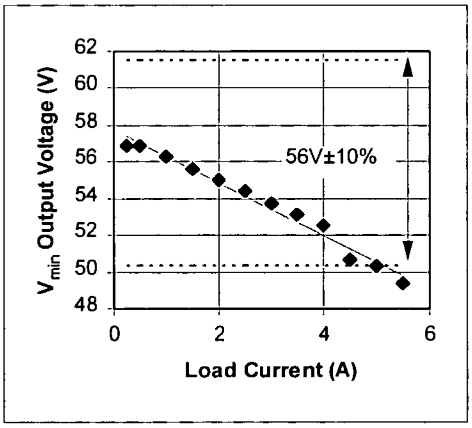


Figure 6-7 : Output Voltage as a function of Load Current. (Vin = 100V)

The load regulation is very poor for this converter and this is due to parasitic oscillations on the output-voltage-reference signal. The circuit thus needs improvements to remove this irregularity. The V_{min} output level however is stil regulated to be within the required limits of ±10% for all input voltages.

6.1.4 CURRENT SHARING

The system in Figure 6-1 was expanded with one more open-loop buck-converter. The system was initially operated with a small load and the output was set to oscillate between the V_d and V_{min} levels at 60 flashes per minute with a duty ratio of 50%. Because of the small load, only one open-loop buck-converter was activated and the current was supported by this module only. The load was increased to a level where the current monitor and card selector sages (Figure 6-1) activated the second open-loop buck-converter (0.00s in Figure 6-8) and the current was shared equally between the two. This verifies the advantages of using current mode control.

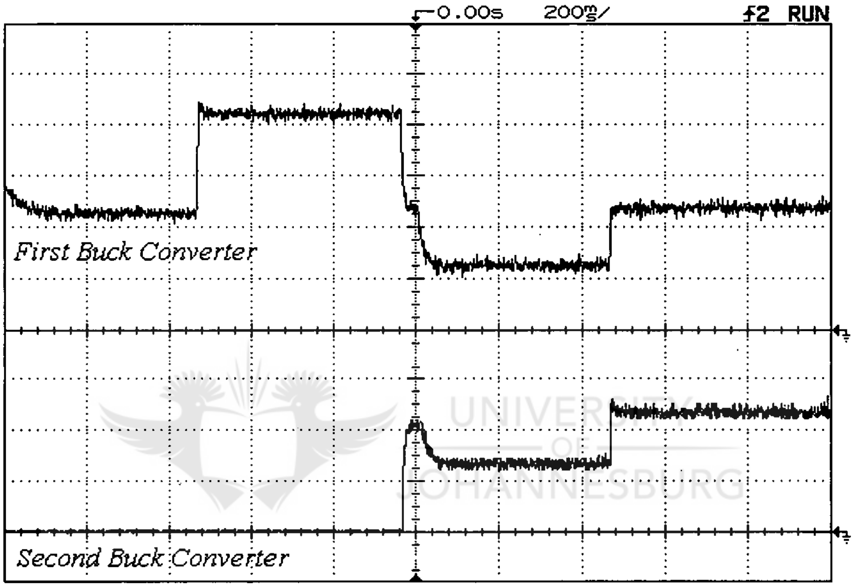


Figure 6-8 : Current sharing between two buck-converter units (2A/div)

6.1.5 DYNAMIC RESPONSE

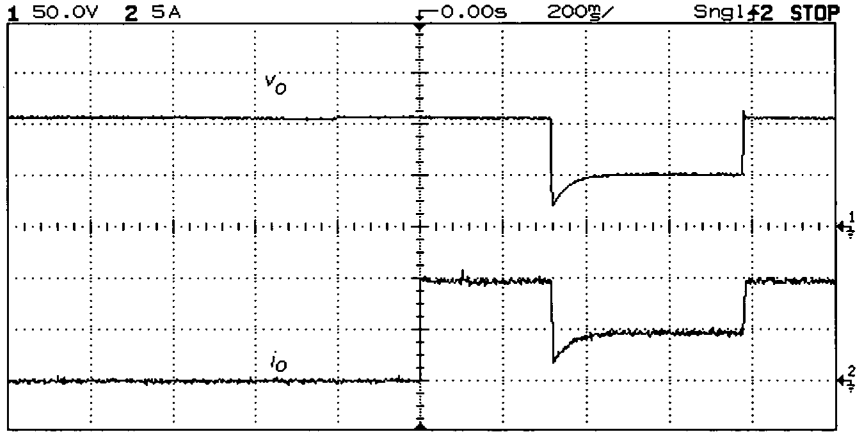


Figure 6-9 : Response to 100% Instantaneous Load (v_O : 50V/div), (i_O : 5A/div)

The dynamic response of the flashing power supply unit is shown by Figure 6-9. Prior to time 0.00s, there is no load on the system and the open-loop buck-converters, being current sources, keeps the output voltage at V_d. Now a full load (resistive) is instantaneously applied to the unit at time 0.00s and the load is easily accommodated by the unit. The fast response of current mode control can also be noted.

6.1.6 LINE REGULATION

Figure 6-10 shows the line regulation of the V_{min} output voltage level as a function of the input voltage. This has been determined for a maximum load and the system delivers a $< 1\%$ line regulation.

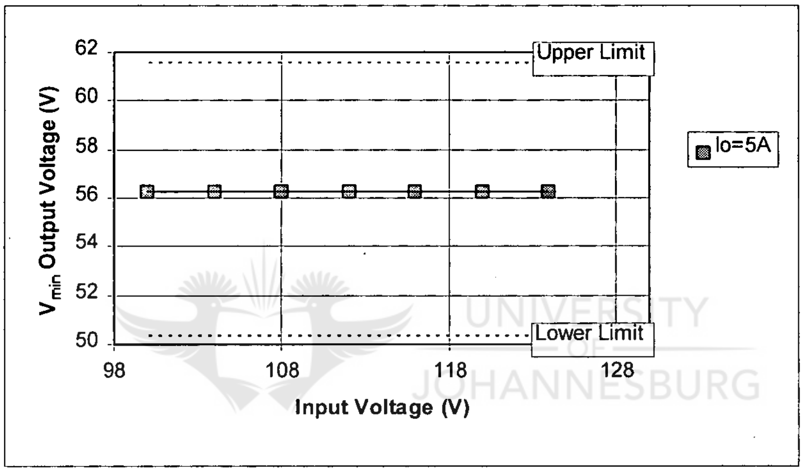


Figure 6-10 : Line Regulation of V_{min} Voltage

6.1.7 EFFICIENCY

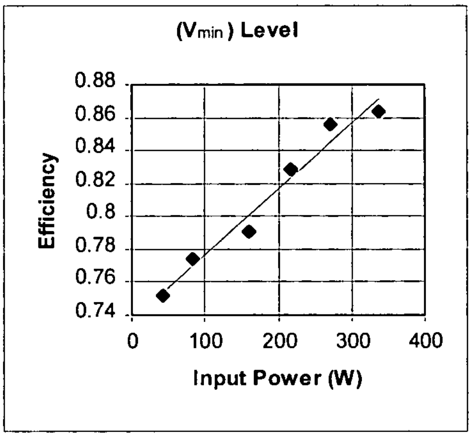


Figure 6-11 : Efficiency of Unit as a Function of Input Power (Resistive Load)

Figure 6-11 shows the efficiency of the flashing power supply unit as a function of the input power for the V_{min} level. The measurements were made with a FLUKE Model 75 multimeter for both input and output voltages and input and output currents. It can be seen that the overall efficiency is in the range of 75%-86% which proves the advantage of using switchmode technology in stead of linear regulation.

6.2 CONCLUSION

The switch-mode power-supply implements an effective solution to flashing aspects. It offers a reliable and cost-effective answer to the demands set on the integration of the system in an interlocking environment. The modular concept has been successfully implemented and offers increased performance. This also allows for ease of maintenance by simply replacing the faulty module during operation.

A converter operated in the current-programmed mode has the properties of overload protection, equal load sharing in parallel operation and simpler control dynamics than in the conventional duty-ratio programmed mode. However, the lack of a complete equivalent circuit model which can guide the design of a regulator feedback loop, is a difficulty that must first be overcome. Solutions to this problem is presented in [8].

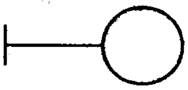
The system has acceptable line regulation and a high efficiency has been achieved but the load regulation needs to be improved.

APPENDIX A : Explanation Of Signal Aspects

No Light

Danger - Stop.

Red

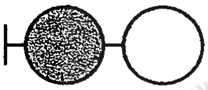


Danger - Stop.

Flashing Red

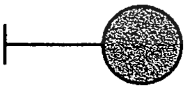
Stop, proceed so that the train can be stopped within sighting distance. Where there are points, they are correctly set, but the state of the track circuits is indeterminate and the line is possibly occupied.

Yellow - Red



Proceed, the train is authorized to enter a goods siding.

Yellow

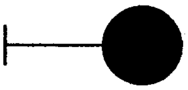


Go, but stop at the next signal unless it is showing a proceed aspect.

Flashing Yellow

Proceed at correct speed for the train to deviate over one or more sets of low speed points. The next signal is displaying a proceed aspect.

Green



Go, the next signal is displaying a proceed aspect.

APPENDIX B : Signal Lamp Characteristics

The signal unit uses 50V,25W incandescent lamps for aspects, with VI-characteristics as shows in Figure B1.

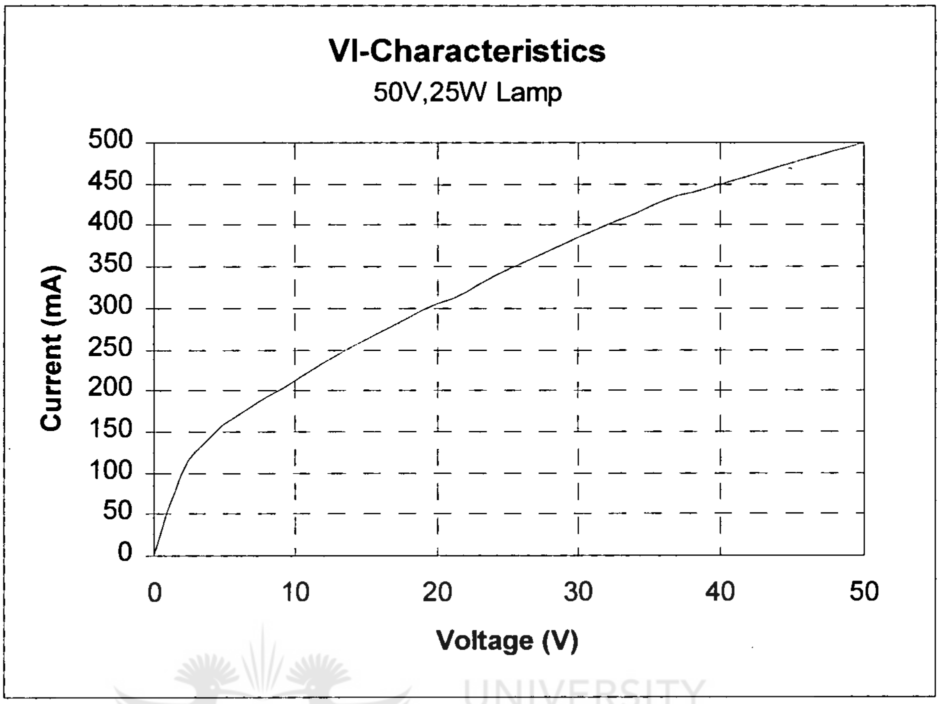


Figure B1 : Lamp VI-characteristics ('Warm' Lamp)

Under normal working conditions (not initial turn-on) the lamp-resistance is as follows:

R_{lamp} = V_{lamp}/I_{lamp}
= 100Ω (I_{lamp} = 500mA)
= 77.15Ω (I_{lamp} = 350mA)
= 66.66Ω (I_{lamp} = 300mA)

The filament in an incandescent bulb has a lower cold resistance than when it is warm, so it acts as a resistor with a positive temperature coefficient (PTC). The peak current at switch-on will therefore be much higher than the maximum continuous current (See Figure B2). In order to understand what this high current does to the lamp we must realize that the filament is not smooth and even but rather it is very rough. The switch-on peak will therefore cause hot spots to appear at the points where the filament is thinnest. These points suffer from wear and tear which eventually leads to one of them burning through, usually immediately upon switch-on.

APPENDIX B : Signal Lamp Characteristics

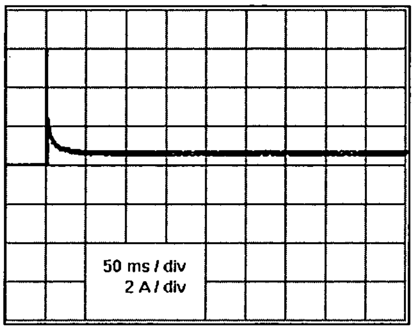


Figure B2 : Peak currents at switch on.

The lifespan of the incandescent lamp is determined by the weakest point in the filament. We can protect this weak spot by switching the lamp on without a peak current (see Figure B3).

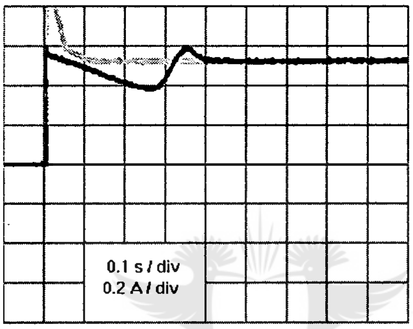


Figure B3 : Switching the lamp on without a peak current

If the lamp is continuously switched on and off these peak currents will be present each time the lamp is switched on. If the rate at which the lamp is switched on and off is high enough, the filament will not have enough time to cool down and these peak currents will be reduced (see Figure B4). The initial peak will however still be high because the lamp will still be cold.

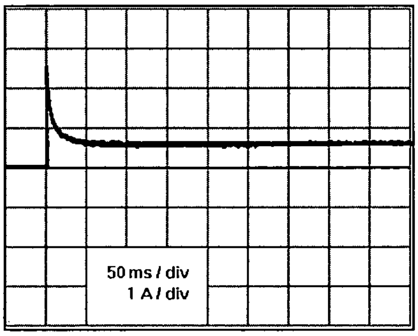


Figure B4 : Continuous switching

The lamp intensity as a function of the applied voltage is shown in figure B5. A typical characteristic of these lamps is the low intensity at a low voltage and saturation at a high voltage.

APPENDIX B : Signal Lamp Characteristics

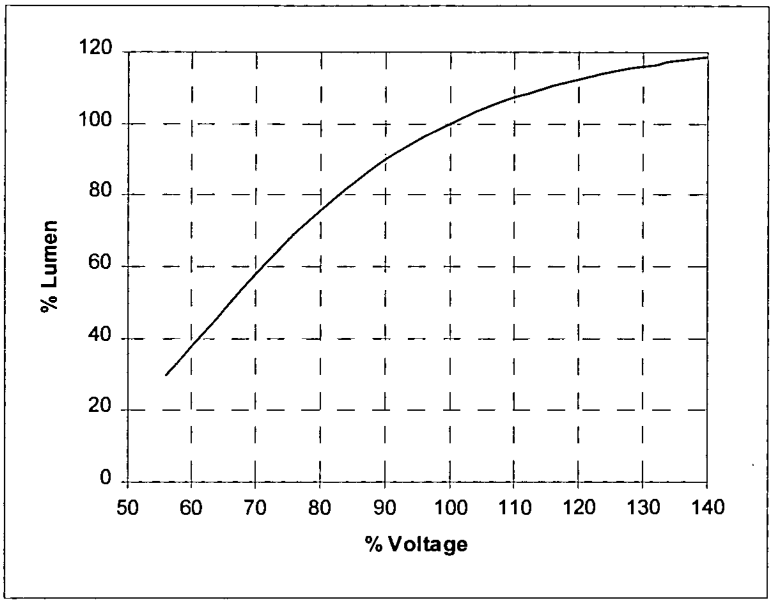


Figure B5 : Signal Lamp Intensity

APPENDIX C : Current Relay Characteristics

Relays are used to sense when the lamp, in a signal unit, has failed. Figure C1 indicates a schematic diagram of the operation thereof.

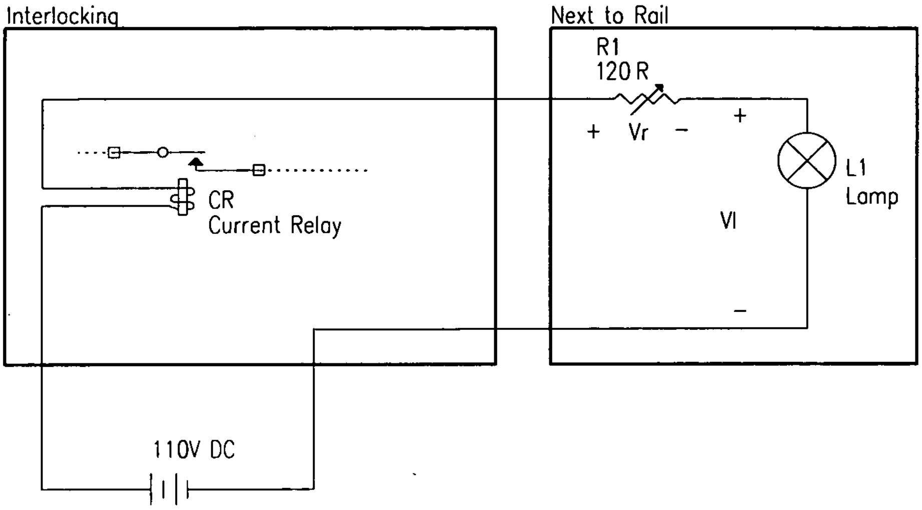


Figure C1 : Schematic diagram of current-relay operation

Current flows through the relay as long as the lamp is still operational. As soon as the lamp fails, the relay is de-energized and indicates that the lamp has blown.

Table 6-1 shows the currents and voltages, as measured, at witch the relay is energized and de-energized.

	Energized Current (mA)	Energized Voltage (V)	De-Energized Current (mA)	De-Energized Voltage (V)
Measurement 1	242.5	5.81	135.2	3.00
Measurement 2	213.5	5.07	106.2	2.26
Average	**228**	**5.44**	**120.7**	**2.63**

Table 6-1 : 'Pick-up' and 'Drop-down' Currents and Voltages.

As long as a current of at least 135mA flows through the lamp, the current-relay will indicate that the lamp is still working.

APPENDIX D : PSpice Simulation FILES

Simulation 1:

```
BUCKCONV.CIR
*Buck (Step-Down) DC-DC Converter
*PWM Duty Ratio Control
.LIB PWR_ELEC.LIB
*
XSW1   1  2 52 0 SWITCH
XD1    0  2 SW_DIODE_WITH_SNUB
*
VCONTL1 52 0 PULSE(0 1 0 .1us .1us 19.6us 40us)
L1      2  3 2mH  IC=3A
C1      3  0 47uF IC=56V
*
XSW2   1  5 42 0 SWITCH
XD2    0  5 SW_DIODE_WITH_SNUB
*
VCONTL2 42 0 PULSE(0 1 0 .1us .1us 20.4us 40us)
L2      5  3 2mH  IC=3A
C2      3  0 47uF IC=56V
*
RLOAD   3  0 9.3
*
VD      1  0 110V
*
.TRAN   0.5us  3.0ms   0ms  5.0us   uic
.PROBE
.END
```

Simulation 2:

```
CUR_MODE.CIR
*Buck (Step-Down) DC-DC Converter
*Current Mode Control
.LIB PWR_ELEC.LIB
.PARAM VCURR=3.25
*
VCLK1  61  0 PULSE(0 10V 0 0 0 4us 39us)
RCLK1  61  0 1MEG
ECOMP1  62   0  TABLE  {  I(VSENSE)  -  VCURR  }=  (-1.0  0.0)  (0.0  0.0)
(0.005, -10.0) + ( 1.0 -10.0)
RCOMP1 62  0 1MEG
ESIG1  63  0 VALUE = {V(61) + V(62)}
RSIG1  63  0 1MEG
XCOMP1 63  64 COMPHYS PARAMS:  VHYS = 1V  IC_SW=-11
EGATE1 65  0  VALUE = {-1.0 * V(64)}
```

APPENDIX D : PSpice Simulation FILES

```
RGATE1 65  0  1MEG
XSW1    1  2 65 0 SWITCH
XD1     0  2 SW_DIODE_WITH_SNUB
L1    2  30 2mH   IC=4A
VSENSE1 30 3  0V
C1     3  0 47uF IC=50.0V
*
VCLK2  612  0 PULSE(0 10V 0 0 0 4us 41us)
RCLK2  612  0 1MEG
ECOMP2 622   0 TABLE { I(VSENSE2) - VCURR }=  (-1.0 0.0)  (0.0 0.0)
(0.005, -10.0) + ( 1.0 -10.0)
RCOMP2 622  0 1MEG
ESIG2  632  0 VALUE = {V(612) + V(622)}
RSIG2  632  0 1MEG
XCOMP2 632  642 COMPHYS PARAMS:  VHYS = 1V  IC_SW=-11
EGATE2 652  0  VALUE = {-1.0 * V(642)}
RGATE2 652  0  1MEG
XSW2    1  22 652 0 SWITCH
XD2     0  22 SW_DIODE_WITH_SNUB
L2     22  302 2mH   IC=0.0A
VSENSE2 302 3  0V
C2     3  0 47uF IC=50.0V
*
VD     1  0 110V
RLOAD  3  0 9.3
*
.TRAN   0.1us  2ms   0  0.1us   uic
.PROBE
.END
```

Appendix E: Required Operational Capability

Background

There are several ways of conveying information to a train driver. The most common way is via light signals. Some of these signals convey more information than others, i.e. some stay one colour, some aspects may be repeated, etc.

Problems encountered in the current methods used are that incorrect information may be conveyed to the train driver when one or more of the aspects fail which, in turn, may cause fatal accidents. A cheaper, more effective and fail safe way of presenting information to the driver will be introduced using flashing aspects. (Details in Appendix 1)

The operation of these aspects require the incandescent lamps in the signal to be switched on and off. Continuously switching an incandescent lamp on and off will shorten its lifespan quite considerably. An unit(s) for producing the flashing aspects is required that will flash the lamps in a fail-safe manner and not damage the lamps or shorten the lifespan.

Mission

Operational Requirement

The Flasher Unit must have the following operational capabilities:

a) Ability to flash at a constant rate for an indefinite period.
b) Ability to flash in a fail safe manner.
c) Ability to flash an incandescent lamp without causing damage to it.

Performance Characteristics

The Flasher Unit must have the following performance characteristics:

a) It must be fail save i.e. a flashing aspect must switch to a non-flashing, bright aspect in the event of failure.
b) The Flasher Unit should be able to operate from the normal power source fed out to the lamps.
c) It should be able to flash 50V,25W DC lamps with a series resistor as per signalling installation.
d) The flashing rate should be not less than 40 flashes per minute (fpm) and not more than 60 flashes per minute (fpm).
e) The duty cycle should not be less than 50% and not more than 60%.

The duty cycle is defined as follows : $DS = \frac{t_{on}}{T}$

with t_{on} the lamp 'on' time per cycle,
t_{off} the lamp 'off' time per cycle and
T the period of one cycle = $t_{on} + t_{off}$

f) The current through the lamp in the off time (t_{off}) should be between 60% and 70% of the current through the lamp in the on time (t_{on}).

Appendix E: Required Operational Capability

g) All flashing aspects of signals fed from the flasher unit should flash in synchronism.

Physical Characteristics

Size

The Flasher Unit should be mountable on a standard relay rack in the relay room.

Availability

The steady state availability of a single system (simplex system) which is maintained and is in continuous operation is defined as:

$$A = \frac{MTBF}{MTBF + MTTR}$$

Where MTTR, the mean time to repair in this case must include the repair time, the fault reporting time and the traveling time.

MTBF, the mean time between failures is the average time elapsed between failures causing the system to fail to a safe condition and being unavailable to perform its functions.

a) The MTBF for the flasher unit must be equal to or greater than 4 Years. ($MTBF \geq 4$ Years)
b) The MTTR excluding fault reporting time and traveling time must be less than or equal to 30 minutes. ($MTTR \leq 30$ minutes)

Maintainability

a) The installation, adjustments and procedures as well as first line maintenance must be possible using a multimeter with specifications similar to that of a FLUKE Model 8060A.
b) The system must provide test points where functionality of each module can be confirmed.
c) The modules must be repairable.
d) Components and modules must be easily accessible to facilitate testing.
e) Only standard components which are locally available may be used.
f) The MTTR excluding fault reporting time and traveling time must be equal to or less than 30 minutes ($MTTR \leq 30$ minutes).

Constraints

a) The unit should be completely fail safe.
b) The reliability of the unit should be high.
c) Only local and readably available material should be used.

Appendix E: Required Operational Capability

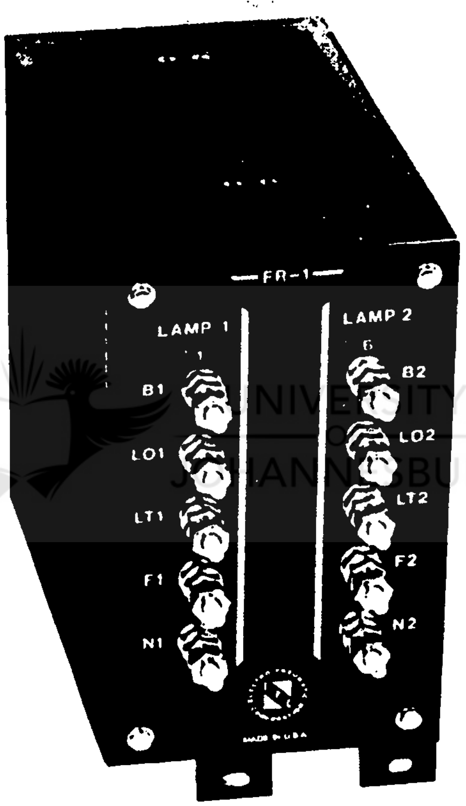
Value system

Value	Relative Weight
Cost	0.1
Fail Safety	0.3
Reliability	0.5
Maintainability	0.1

Appendix F : FLASHER REGULATOR MODEL FR-1

SIGNAL LAMP FLASHER WITH VOLTAGE REGULATOR

SECTION XIV



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Appendix F : FLASHER REGULATOR MODEL FR-1

FLASHER REGULATOR
MODEL FR-1

DESCRIPTION

FLASHER REGULATOR Model FR-1 is a dual signal lamp flasher and regulator for use with dc signal lighting. When flashing aspects are used the "soft flash" technique employed in the FR-1 extends lamp life by reducing filament shock. A lamp voltage regulator is also built in, as investigations into signal lamp life have shown that lamps operated at a constant voltage last longer than lamps operated with a series resistor. Figure 1 is a block diagram of the unit.

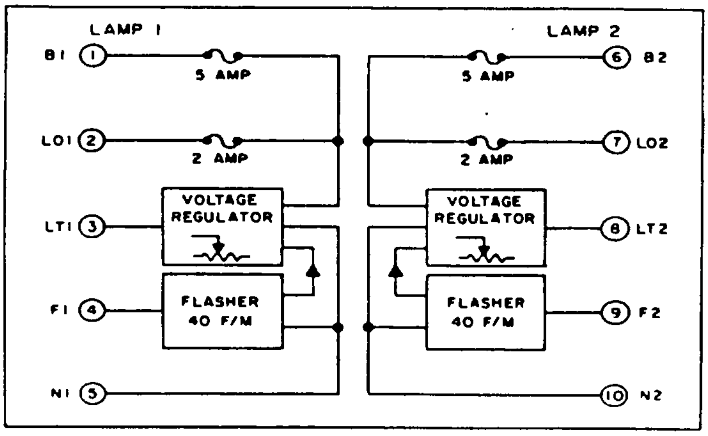


FIGURE 1:
FR-1 BLOCK DIAGRAM

OPERATION

The FR-1 circuit consists of a precision electronic voltage regulator, that can be adjusted for desired lamp brightness, and a signal lamp flasher. With battery applied to either of the two independent FLASHER REGULATOR circuits, regulated lamp voltage will appear on the corresponding "LT" terminal. Each FLASHER REGULATOR circuit has a terminal "LO" that is used with a light out circuit for flashing aspects as shown in Figure 2. When positive battery is 'applied to terminal "F" the lamp wi11 flash at the standard rate of 40 times per minute.

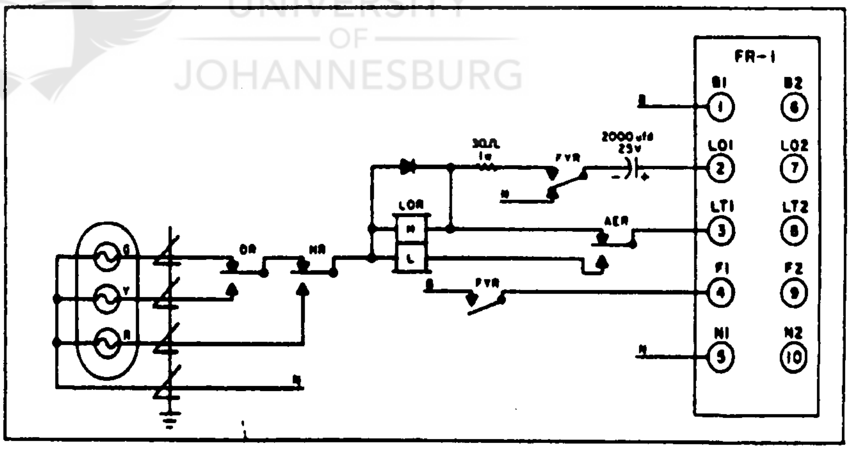


FIGURE 2:
FOUR ASPECT LIGHTING CIRCUIT
FOR COLOR LIGHT SIGNALS

Appendix F : FLASHER REGULATOR MODEL FR-1

INSTALLATION AND ADJUSTMENT

The Model FR-1 FLASHER REGULATOR can be mounted on unistrut or in a B2 relay space. Circuit connections are made to AAR binding posts on the rear cover. Connect "B1" and "N1" or "BR" and "N2" to +/- 12 volt battery and use the corresponding LO and LT connections as specified in the circuit plan. Figures 2 and 3 illustrate typical applications.

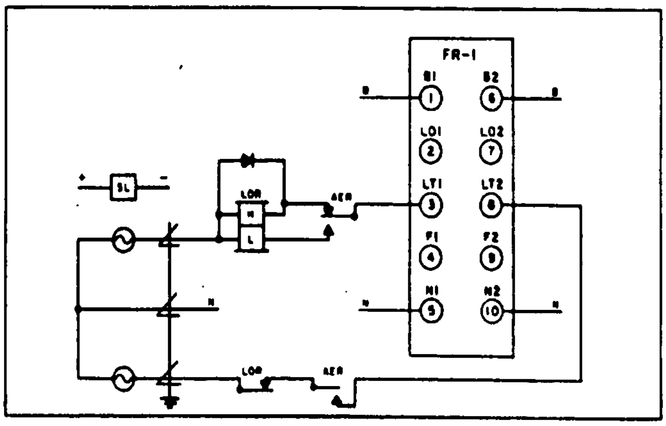


FIGURE 3: LIGHTING CIRCUIT FOR SEARCHLIGHT SIGNAL WITH MARKER

To adjust the FR-1, connect a suitable voltmeter across the signal lamp and adjust the corresponding Lamp 1 or Lamp 2 “Voltage Adjust" screw on the front cover for the specified lamp voltage.

MAINTENANCE

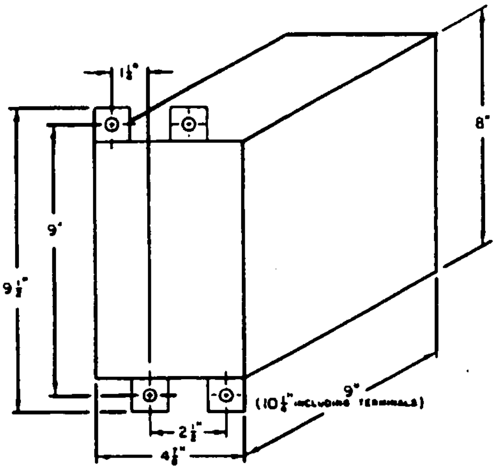
All active circuits are located on two identical plug-in printed circuit boards. If there is no output on both the LO and LT terminals, check the 5 amp fuse. If only the LO terminal has no output, check the 2 amp fuse. Both fuses are located near the connector end of the printed circuit module. If the fuses are not at fault, circuit operation can be restored by replacing the corresponding printed circuit module.

Appendix F : FLASHER REGULATOR MODEL FR-1

SPECIFICATIONS

EACH FR-1 CONTAINS 2 FLASHER REGULATOR
UNITS. SPECIFICATIONS ARE PER UNIT.

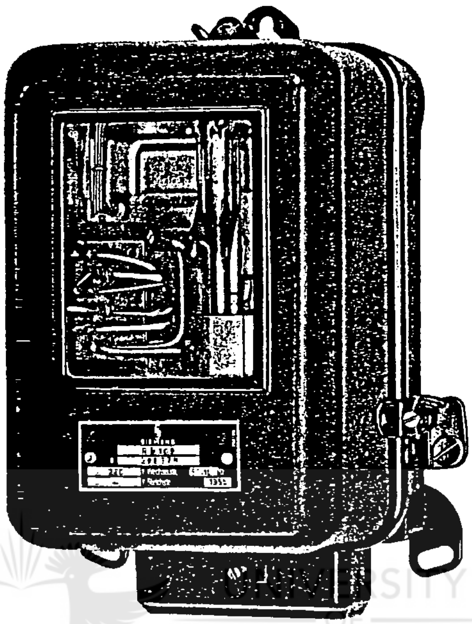
OPERATING VOLTAGE	Nominal: 12 volts Range: 10 - 15 vde
OPERATING CURRENT	20 mA plus lamp current 35 mA nominal flasher control current
OUTPUT VOLTAGE	Range: 9 vdc to battery voltage
LAMP LOAD	25 watts (2.5 amps) maximum
FLASH RATE	40 flashes per minute
FUSES	Input: 5 amp SLO-BLO "LO": 2 amp SLO-BLO
OPERATING TEMPERATURE	-40° F (-40° C) to +160° F (+71° C)
WEIGHT	5 1/2 lbs.
DIMENSIONS	



FR-1 OUTLINE dimensions in inches

Appendix G : Thermo Flasher Unit

SIEMENS



Siemens Thermo Flasher Unit

for 60 flashing impulses per minute

Type RB 109

The thermo flasher serves the purpose of periodically interrupting light circuits thereby bringing about the flashing operation of light signals and indicating lamps. Flashing lights are particularly conspicuous and through their differentiation of the steady light offer new possibilities of indication.

Appendix G : Thermo Flasher Unit

Exterior Characteristics

Operating position	Vertical, attachment by means of three 5 mm. dia. bolts
Vibration sensitiveness	Thermo flasher should be suitably protected against heavy vibration and jolts
Housing	Base plate and cover are of steel. The housing is provided with a seal and is dust and splash water proof Class of protection P 42 as per DIN VDE 40050 Cover is provided with an inspection glass for observation of contacts
Terminals	Sleeve terminals for a conductor cross section of 2.5 mm²
Weight	Approx 3.2 kg.
Maintenance	The thermo flasher does not require any special maintenance
Placing into operation	Before installation or starting operation of the thermo flasher, check if mercury level in the pendulum tube coincides with "full" mark. If not, tilt housing carefully to bring mercury into the pendulum tube

Ordering Data

Terminal voltage	110 V ~ 50 up to 100 c/s	220 V ~ 50 up to 100 c/s	220 V ~ $16^2/_3$ up to 50 c/s	12 V ~ 50 c/s
Nomenclature				
without interference suppression	ZrR 9 690 053/1	ZrR 9 690 053/2	ZrR 9 690 053/2 S 1	—
with interference suppression	ZrR 9 690 054/1	ZrR 9 690 054/2	ZrR 9 690 054/2 S 1	ZrR 9 690 51

When ordering please quote nomenclature

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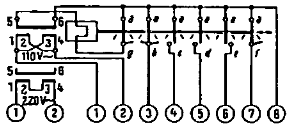
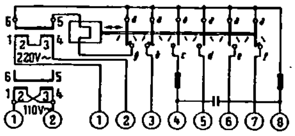
Appendix G : Thermo Flasher Unit

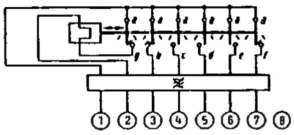
Wiring Diagrams



110/220 V ~ without interference suppression



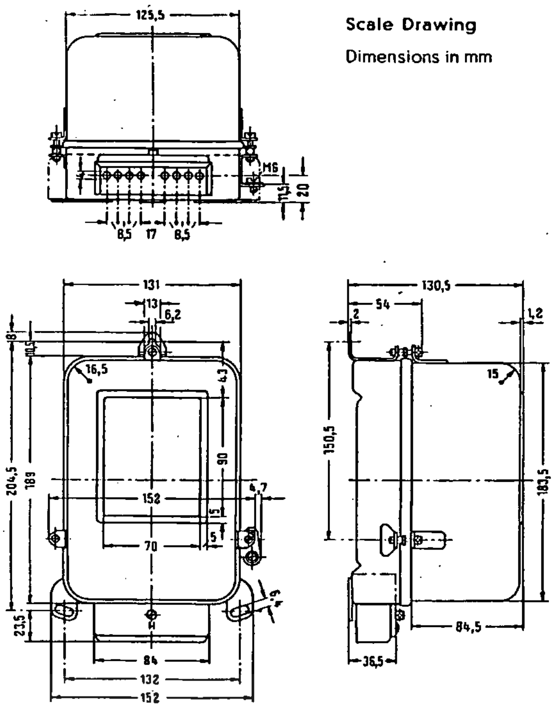
110/220 V ~ with interference suppression



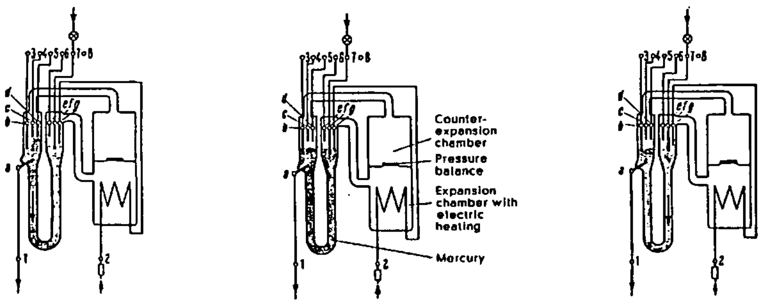
12 V ≂ with interference suppression

Scale Drawing

Dimensions in mm



Schematic Illustration of the Mode of Operation of the 12 V Flasher Unit



Mercury in left arm of tube is in the extreme position. Heating circuit is disconnected at (g)

Mercury is in the normal position (zero position) at "full" mark

Mercury in right arm of tube is in the extreme position. Heating circuit is again connected at (g)

Appendix G : Thermo Flasher Unit

Mode of Operation

The periodical flashing is obtained by an oscillating mercury column enclosed in a U-shape glass tube. The movement of the mercury column is generated by hydrogen gas, enclosed in a chamber. The glass chamber is interconnected with the mercury tube. Under the glass chamber a heating element is situated. When current flows through the filament of the heater, the gas will expand and exert pressure on one side of the surface of the U-shape mercury column.

When one side of the mercury column has been depressed to a certain point, the contact of the heating element will break. By force of gravity, the mercury column then returns to its original position, whereupon the heating circuit is again established. The above procedure will repeat itself and will bring about a swinging movement of the mercury. The duration of the individual switch circuits amounts to $^1/_3$—$^2/_3$ depending on the osciallation movement of mercury.

The flasher relay will operate with a. c. or d. c.

Technical Data

Coil (Heating Circuit)

Nominal voltages
Alternating or direct current, 12 volts.

For higher operating voltages (up to approx. 60 volts) an external compensating resistance is required. For the determination of the resistance value and capacity a heating current of 0.75 ampere at 50 per cent cut-in duration — duration of cycle 1 second — should be adopted.

Alternating current 110, 220 V (with built-in transformer)

Rate of power input with a voltage of	12	110	220 V
Approx. rate of power input during heating impulse	9	20	20 W
Approx. mean rate of power input	4.5	10	10 W

Contacts

Flashing frequency	60/p. m.	
Flashing ratio	for contacts 4/1, 5/1, 6/1	bright/dark 1 : 1
	for contacts 3/1, 7/1	bright/dark 1 : 0.5
Radio interference	As conductors are suppressed, the normal degree of interference as per VDE 0875/11.51 will not be exceeded (see wiring diagram; the 12 V flasher unit is entirely suppressed).	

Contact load

Unblocking potential	12	110	220 V
Current on contact	6	2	1 a
Incandescent lamp load *	72	220	220 W

* These values apply to permanent operation

Insulation test	up to 125 V nominal voltage	2000 V 50 c/s
	above 125 V nominal voltage	2500 V 50 c/s

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