LAMPIRAN

Lampiran 1

Data Tegangan Sekunder Koil Tesla

I. Tegangan sumber, Vdc = 9.01 Volt
Jumlah lilitan primer, Np = 460
Time/div. = 50 micro-Second
Volt/div. = 5 mili-Volt

Jumlah lilitan sekunder, Ns	Tegangan primer Vp (mV)	Tegangan sekunder, Vs (mV)				
		R1 = 4,5 cm	R2 = 5,5 cm	R3 = 6,5 cm	R4 = 7,5 cm	R5 = 8,5 cm
704	5	4	3	2	2	1
875		6	4	3	3	1.5
959		7	5	4	3	2
1125		8	6	5	4	2.5
1208		9	6	5	4	2.5

II. Tegangan sumber, Vdc = 9.01 Volt
Jumlah lilitan primer, Np = 920
Time/div. = 5 micro-Second
Volt/div. = 10 mili-Volt

Jumlah lilitan sekunder, Ns	Tegangan primer Vp (mV)	Tegangan sekunder, Vs (mV)				
		R1 = 4,5 cm	R2 = 5,5 cm	R3 = 6,5 cm	R4 = 7,5 cm	R5 = 8,5 cm
704	16	8	4	4	3	2
875		10	6	5	4	3
959		13	7	6	4	4
1125		18	12	8	7	5
1208		18	12	8	7	5

III. Tegangan sumber, Vdc = 13.23 Volt
Jumlah lilitan primer, Np = 460
Time/div. = 50 micro-Second
Volt/div. = 5 mili-Volt

Jumlah lilitan sekunder, Ns	Tegangan primer Vp (mV)	Tegangan sekunder, Vs (mV)				
		R1 = 4,5 cm	R2 = 5,5 cm	R3 = 6,5 cm	R4 = 7,5 cm	R5 = 8,5 cm
704	10	9	5	4	3	2
875		13	7	6	4	2.5
959		15	9	7	5	3
1125		19	12.5	9	6	5
1208		19	12.5	9	6	5

IV. Tegangan sumber, Vdc = 13.23 Volt
Jumlah lilitan primer, Np = 920
Time/div. = 5 micro-Second
Volt/div. = 20 mili-Volt

Jumlah lilitan sekunder, Ns	Tegangan primer Vp (mV)	Tegangan sekunder, Vs (mV)				
		R1 = 4,5 cm	R2 = 5,5 cm	R3 = 6,5 cm	R4 = 7,5 cm	R5 = 8,5 cm
704	36	14	8	8	6	4
875		20	12	10	8	6
959		24	16	12	10	8
1125		36	24	18	16	10
1208		36	24	18	16	10

Lampiran 2

Spesifikasi Fisis Koil Tesla

Spesifikasi	Sirkuit Primer	Sirkuit Sekunder
Diamater kumparan	3,2 cm	4,3 cm
Radius kawat	0,15 mm	0,4 mm
Panjang kumparan	6,9 cm	6,3 cm
Jumlah lilitan	460	959 dobel
Induktansi	644,3 mikro-Henry	6,96 mili-Henry
Frekuensi terukur	1,9 KHz	1,9 KHz
Resistansi kumparan	8,2 Ohm	5,56 Ohm
Kapasitansi	39,3 mikro-Farad	3,63 nano-Farad

Karakteristik Elektrik DC T_A = 25° C, V_{CC} = +5 – +15 V kecuali kalau dinyatakan lain.

PARAMETER	TEST CONDITIONS	SE555 Min	SE555 Typ	SE555 Max	NE555/SE555C Min	NE555/SE555C Typ	NE555/SE555C Max	UNIT
Supply voltage		4.5		18	4.5		16	V
Supply current (low state)[1]	V_{CC} = 5V R_L = ∞		3	5		3	6	mA
	V_{CC} = 15V R_L = ∞		10	12		10	15	mA
Timing error (monostable)	R_A = 2KΩ to 100KΩ							
Initial accuracy[2]	C = 0.1µF		0.5	2.0		1.0	3.0	%
Drift with temperature			30	100		50		ppm/°C
Drift with supply voltage			0.05	0.2		0.1	0.5	%/V
Timing error (astable)	R_A, R_B = 1kΩ to 100kΩ							
Initial accuracy[2]	C = 0.1µF		1.5			2.25		%
Drift with temperature	V_{CC} = 15V		90			150		ppm/°C
Drift with supply voltage			0.15			0.3		%/V
Control voltage level	V_{CC} = 15V	9.6	10.0	10.4	9.0	10.0	11.0	V
	V_{CC} = 5V	2.9	3.33	3.8	2.6	3.33	4.0	V
Threshold voltage	V_{CC} = 15V	9.4	10.0	10.6	8.8	10.0	11.2	V
	V_{CC} = 5V	2.7	3.33	4.0	2.4	3.33	4.2	V
Threshold current[3]			0.1	0.25		0.1	0.25	µA
Trigger voltage	V_{CC} = 15V	4.8	5.0	5.2	4.5	5.0	5.6	V
	V_{CC} = 5V	1.45	1.67	1.9	1.1	1.67	2.2	V
Trigger current	V_{TRIG} = 0V		0.5	0.9		0.5	2.0	µA
Reset voltage[4]		0.4	0.7	1.0	0.4	0.7	1.0	V
Reset current			0.1	0.4		0.1	0.4	mA
Reset current	V_{RESET} = 0V		0.4	1.0		0.4	1.5	mA
Output voltage (low)	V_{CC} = 15V							
	I_{SINK} = 10mA		0.1	0.15		0.1	0.25	V
	I_{SINK} = 50mA		0.4	0.5		0.4	0.75	V
	I_{SINK} = 100mA		2.0	2.2		2.0	2.5	V
	I_{SINK} = 200mA		2.5			2.5		V
	V_{CC} = 5V							
	I_{SINK} = 8mA		0.1	0.25		0.3	0.4	V
	I_{SINK} = 5mA		0.05	0.2		0.25	0.35	V
Output voltage (high)	V_{CC} = 15V							
	I_{SOURCE} = 200mA		12.5			12.5		V
	I_{SOURCE} = 100mA	13.0	13.3		12.75	13.3		V
	V_{CC} = 5V							
	I_{SOURCE} = 100mA	3.0	3.3		2.75	3.3		V
Turn off time[5]	V_{RESET} = V_{CC}		0.5	2.0		0.5		µs
Rise time of output			100	200		100	300	ns
Fall time of output			100	200		100	300	ns
Discharge leakage current			20	100		20	100	na

CATATAN

1. Arus catu bila keluaran tinggi, lumrahnya 1 mA atau kurang
2. Diuji pada V_{CC} = 5 V dan V_{CC} = 15 V
3. Ini akan menentukan harga maksimum $R_A + R_B$, untuk pengoperasian pada 15 V, total maksimum R = 10 MΩ, untuk pengoperasian pada 5 V, total maks. R = 3,4 MΩ
4. Ditentukan dengan masukan sulut tinggi
5. Waktu terukur dari denyut mengarah ke positif dari 0 hingga 0,8 × V_{CC} ke ambang, sampai keluaran jatuh dari tinggi ke rendah.

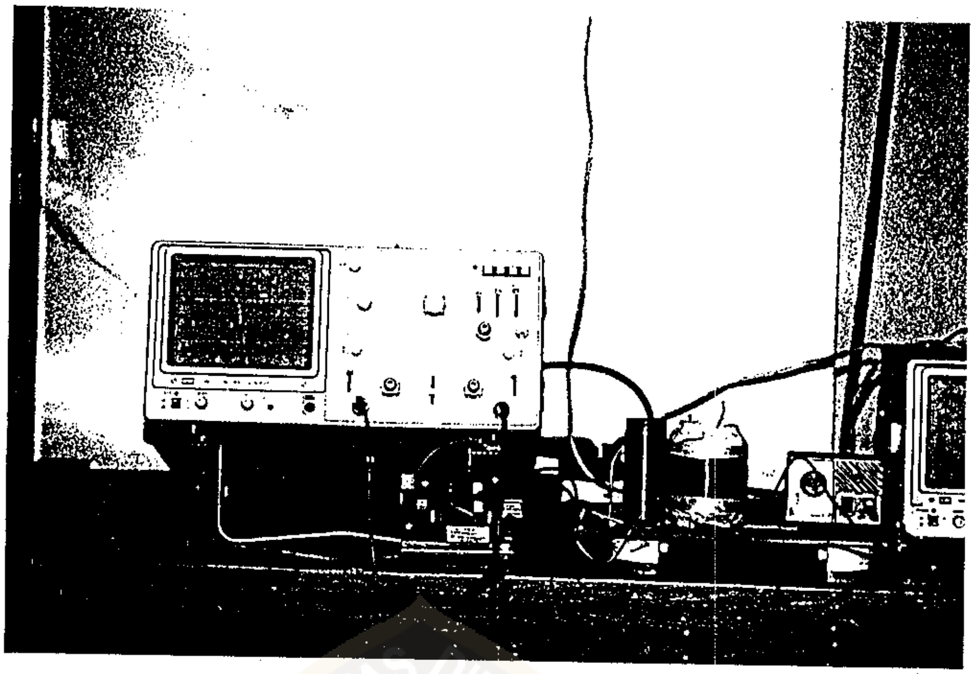
Monostabil:
$t \approx 1{,}1 \times R_A \times C$
Takstabil:
$t_1 \approx 0{,}7 \times (R_A + R_B) \times C$
$t_2 \approx 0{,}7 \times R_B \times C$
$T = t_1 + t_2$

Penerapan

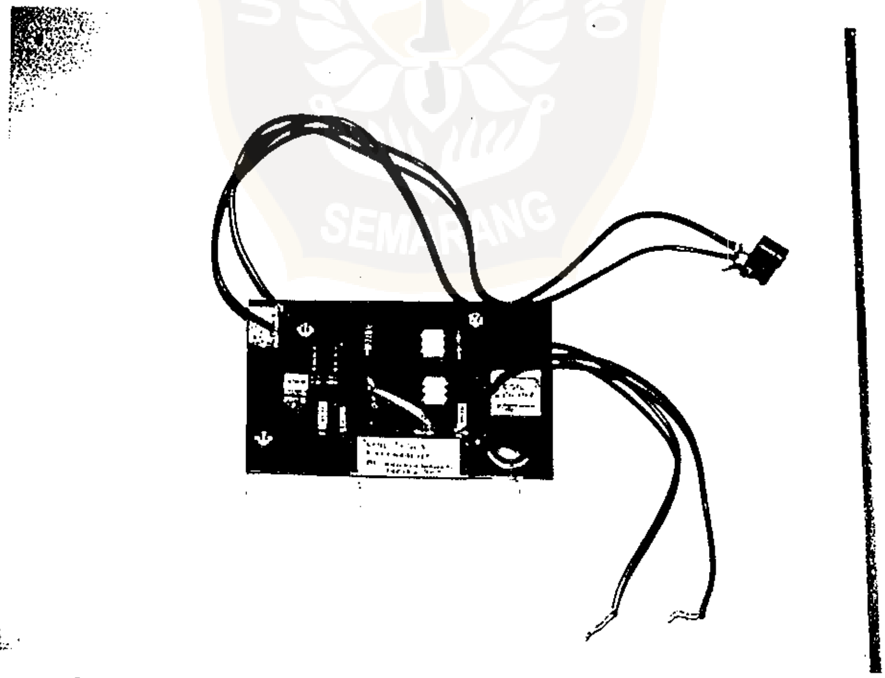
- Pewaktuan *(timing)* dengan cermat
- Pembangkit denyut
- Pewaktuan sekuensi
- Pembangkitan tundaan waktu
- Pemodulasian lebar denyut
- Pemodulasian posisi denyut
- Detektor denyut hilang

Lampiran 3

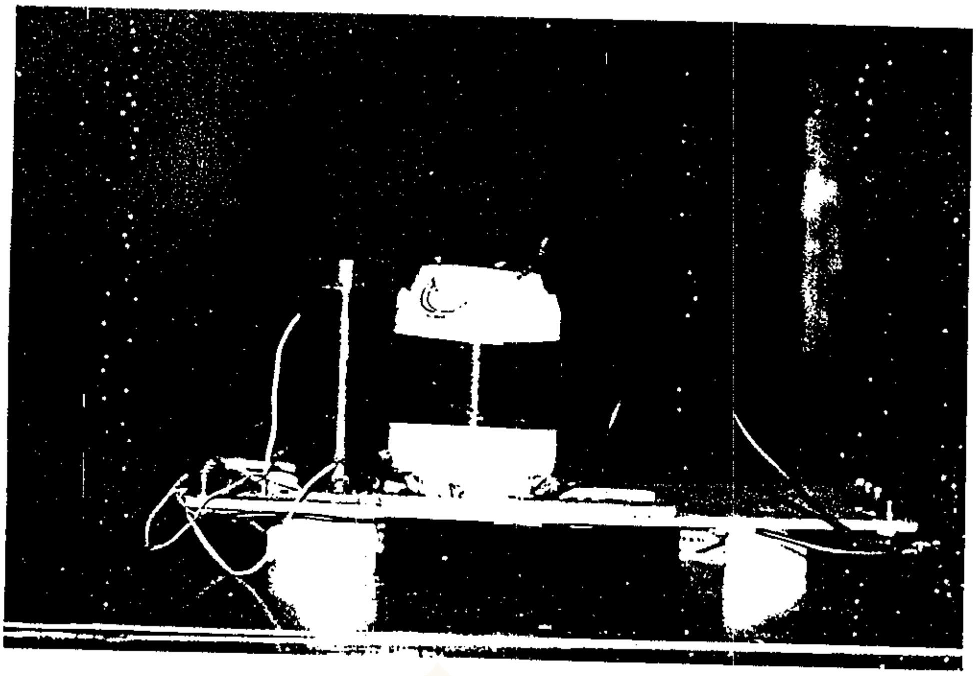
Foto Alat-alat Percobaan



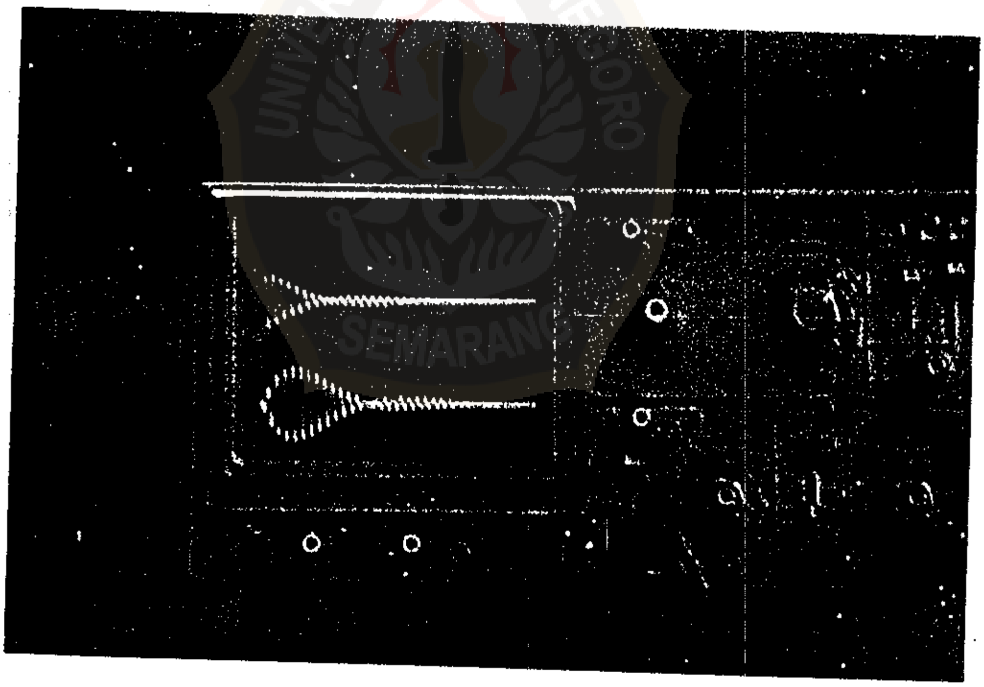
3 .1. Alat Percobaan Simulasi Koil Tesla



3.2. Rangkaian Pembangkit Gelombang Persegi dan MOC 3011



3.3. Koil Tesla



3.4. Osiloskop dan grafik transfer energi hasil percobaan

Lampiran 4

Data NE 555

NE/SE 555
Pewaktu *(Timer)*

Penjelasan Umum

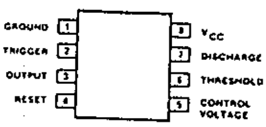
Rangkaian pewaktu monolit NE/SE 555 adalah pengatur yang mantap yang mampu membangkitkan tundaan waktu atau pun guncangan yang cermat. Ada terminal-terminal tambahan guna penyulutan atau pengondisian-ulang *(reset)*, kalau diinginkan.

Dalam ragam operasi tundaan waktu, waktu dikemudikan dengan teliti dengan sebuah resistor dan kondensator ekstern. Untuk beroperasi takmantap sebagai osilator, frekuensi bebas, dan daur aktif *(duty cycle)* dikemudikan dengan teliti oleh dua resistor dan satu kondensator ekstern.

Rangkaiannya akan dapat disulut dan di-*reset* pada bentukgelombang yang sedang jatuh, dan susunan keluarannya akan dapat merupakan sumber ataupun benaman *(sink)* sampai 200 mA ataupun dapat menggerakkan rangkaian-rangkaian TTL.

RC 555 dapat beroperasi dalam jelajahan suhu dari 0° C hingga +70° C. RM 555 tahan terhadap suhu lebih tinggi, dan beroperasi dalam −55° C hingga +125° C.

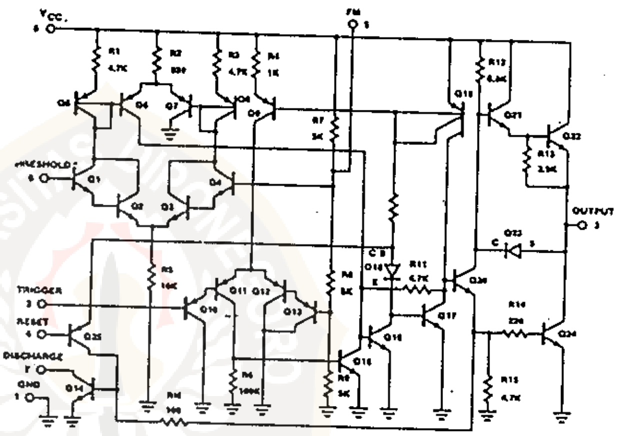
Diagram koneksi

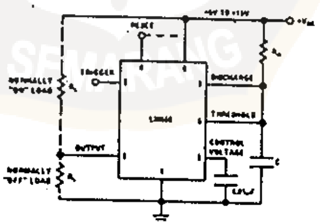


Tarif Maksimum Mutlak

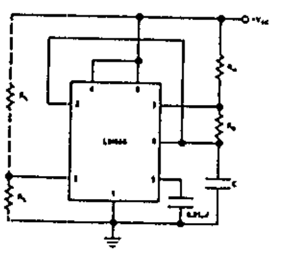
Parameter	Tarif	Satuan
Tegangan catu		
SE555	+18	V
NE555, SE555C	+16	V
Borosan daya	600	mW
Jelajahan suhu operasi		
NE555	0 s/d+70	°C
SE555, SE555C	-55s/d+125	°C
Jelahan suhu simpan	-65s/d+150	°C
Suhu timah (penyolderan 60 detik)	300	°C

Skema





Monostabil



Takstabil

Sifat-sifat

- Waktu mati *(off)* kurang dari 12 µdet
- Frekuensi operasi tertinggi besar dari 500 kHz
- Pewaktuan *(timing)* dari mikrodetik hingga jam
- Beroperasi dalam ragam takstabil dan monostab
- Arus keluaran tinggi
- Daur aktif *(duty cycl.* dapat distel
- Serba-cocok dengan TI
- Kemantapan suhu 0,005 per °C

ELECTRICAL CHARACTERISTICS (T_A = 25°C unless otherwise noted)

Characteristic	Symbol	Min	Typ	Max	Unit
INPUT LED					
Reverse Leakage Current (V_R = 3 V)	I_R	—	0.05	100	μA
Forward Voltage (I_F = 10 mA)	V_F	—	1.15	1.5	Volts
OUTPUT DETECTOR (I_F = 0 unless otherwise noted)					
Peak Blocking Current, Either Direction (Rated V_{DRM}(1))	I_{DRM}	—	10	100	nA
Peak On–State Voltage, Either Direction (I_{TM} = 100 mA Peak)	V_{TM}	—	1.8	3	Volts
Critical Rate of Rise of Off–State Voltage (Figure 7, Note 2)	dv/dt	—	10	—	V/μs
COUPLED					
LED Trigger Current, Current Required to Latch Output (Main Terminal Voltage = 3 V(3)) MOC3010	I_{FT}	—	8	15	mA
MOC3011		—	5	10	
MOC3012		—	3	5	
Holding Current, Either Direction	I_H	—	100	—	μA

1. Test voltage must be applied within dv/dt rating.
2. This is static dv/dt. See Figure 7 for test circuit. Commutating dv/dt is a function of the load–driving thyristor(s) only.
3. All devices are guaranteed to trigger at an I_F value less than or equal to max I_{FT}. Therefore, recommended operating I_F lies between max I_{FT} (15 mA for MOC3010, 10 mA for MOC3011, 5 mA for MOC3012) and absolute max I_F (60 mA).

TYPICAL ELECTRICAL CHARACTERISTICS
T_A = 25°C

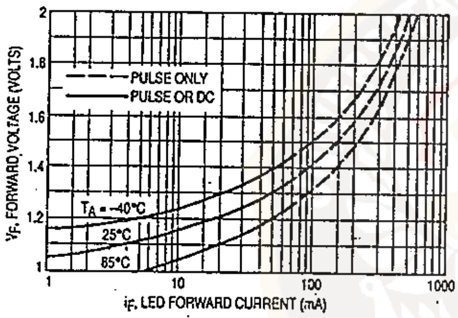


Figure 1. LED Forward Voltage versus Forward Current

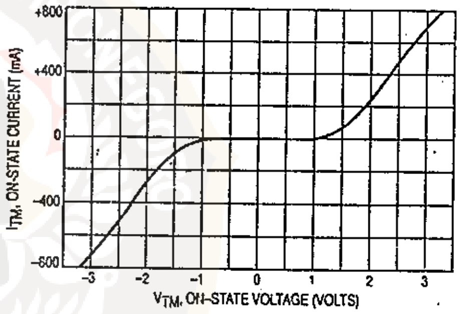


Figure 2. On–State Characteristics

Lampiran 5

Data MOC 3011

MOTOROLA
SEMICONDUCTOR TECHNICAL DATA

GlobalOptoisolator™

VDE | UL | CSA | SETI | SEMKO | DEMKO | NEMKO | BABT

MOC3010
[IFT = 15 mA Max]
MOC3011
[IFT = 10 mA Max]
MOC3012*
[IFT = 5 mA Max]

*Motorola Preferred Device

6-Pin DIP Random-Phase Optoisolators Triac Driver Output

(250 Volts Peak)

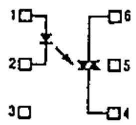
The MOC3010 Series consists of gallium arsenide infrared emitting diodes, optically coupled to silicon bilateral switch and are designed for applications requiring isolated triac triggering, low-current isolated ac switching, high electrical isolation (to 7500 Vac peak), high detector standoff voltage, small size, and low cost.

- *To order devices that are tested and marked per VDE 0884 requirements, the suffix "V" must be included at end of part number. VDE 0884 is a test option.*

STYLE 6 PLASTIC

STANDARD THRU HOLE
CASE 730A–04

COUPLER SCHEMATIC



1. ANODE
2. CATHODE
3. NC
4. MAIN TERMINAL
5. SUBSTRATE DO NOT CONNECT
6. MAIN TERMINAL

Recommended for 115 Vac(rms) Applications:

- Solenoid/Valve Controls
- Lamp Ballasts
- Interfacing Microprocessors to 115 Vac Peripherals
- Motor Controls
- Static ac Power Switch
- Solid State Relays
- Incandescent Lamp Dimmers

MAXIMUM RATINGS (T_A = 25°C unless otherwise noted)

Rating	Symbol	Value	Unit
INFRARED EMITTING DIODE			
Reverse Voltage	V_R	3	Volts
Forward Current — Continuous	I_F	60	mA
Total Power Dissipation @ T_A = 25°C Negligible Power in Transistor	P_D	100	mW
Derate above 25°C		1.33	mW/°C
OUTPUT DRIVER			
Off-State Output Terminal Voltage	V_{DRM}	250	Volts
Peak Repetitive Surge Current (PW = 1 ms, 120 pps)	I_{TSM}	1	A
Total Power Dissipation @ T_A = 25°C Derate above 25°C	P_D	300 4	mW mW/°C
TOTAL DEVICE			
Isolation Surge Voltage(1) (Peak ac Voltage, 60 Hz, 1 Second Duration)	V_{ISO}	7500	Vac(pk)
Total Power Dissipation @ T_A = 25°C Derate above 25°C	P_D	330 4.4	mW mW/°C
Junction Temperature Range	T_J	–40 to +100	°C
Ambient Operating Temperature Range(2)	T_A	–40 to +85	°C
Storage Temperature Range(2)	T_{stg}	–40 to +150	°C
Soldering Temperature (10 s)	T_L	260	°C

1. Isolation surge voltage, V_{ISO}, is an internal device dielectric breakdown rating. For this test, Pins 1 and 2 are common, and Pins 4, 5 and 6 are common.
2. Refer to Quality and Reliability Section in Opto Data Book for information on test conditions.

Preferred devices are Motorola recommended choices for future use and best overall value.

(Replaces MOC3009/D)

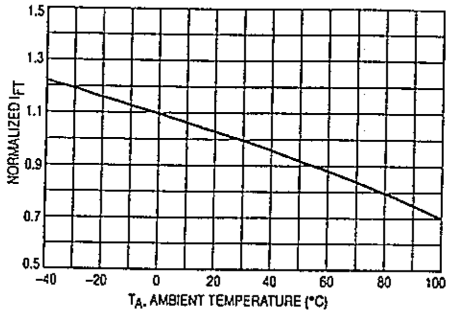


Figure 3. Trigger Current versus Temperature

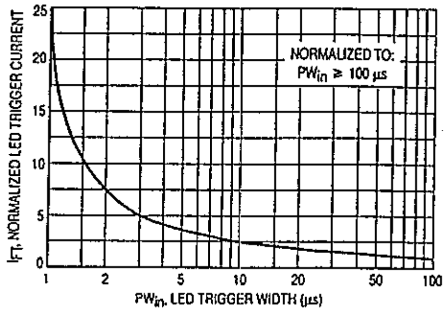


Figure 4. LED Current Required to Trigger versus LED Pulse Width

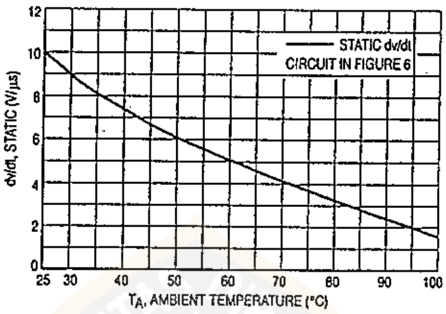
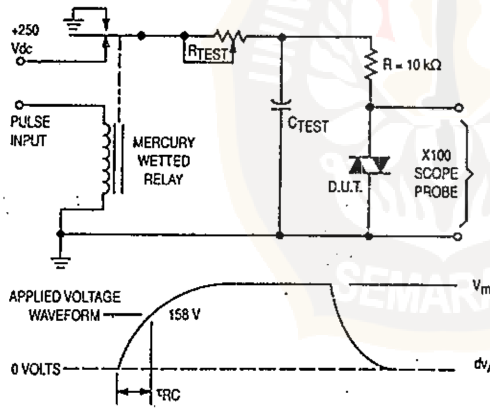


Figure 5. dv/dt versus Temperature



1. The mercury wetted relay provides a high speed repeated pulse to the D.U.T.
2. 100x scope probes are used, to allow high speeds and voltages.
3. The worst–case condition for static dv/dt is established by triggering the D.U.T. with a normal LED input current, then removing the current. The variable R_{TEST} allows the dv/dt to be gradually increased until the D.U.T. continues to trigger in response to the applied voltage pulse, even after the LED current has been removed. The dv/dt is then decreased until the D.U.T. stops triggering. τ_{RC} is measured at this point and recorded.

$$dv/dt = \frac{0.63\ V_{max}}{\tau_{RC}} = \frac{158}{\tau_{RC}}$$

Figure 6. Static dv/dt Test Circuit

Lampiran 6

Data PVR 1300

International
IOR Rectifier
BOSFET® Photovoltaic Relay

PD 1.028C

Series PVR33
Microelectronic
Power IC Relay
Dual-Pole, 400mA, 0-100V AC/DC

General Description

The PVR33 Photovoltaic Relay is a dual-pole, normally open solid state replacement for electro-mechanical relays. It utilizes as an output switch a unique bidirectional (AC or DC) MOSFET power IC termed a BOSFET. The BOSFET is controlled by a photovoltaic generator of novel construction, which is energized by radiation from a dielectrically isolated light emitting diode (LED).

The PVR overcomes the limitations of reed relays by offering the solid state advantages of long life, high operating speed, low pick-up power, bounce-free operation, low thermal voltages and miniaturization. These advantages allow product improvement and design innovations in many applications such as process control, multiplexing, telecommunications, automatic test equipment and data acquisition.

The PVR can switch analog signals from thermocouple level to 300 volts peak AC or DC polarity. Signal frequencies into the RF range are easily controlled and switching rates up to 5kHz are achievable. The extremely small thermally generated offset voltages allow increased measurement accuracies.

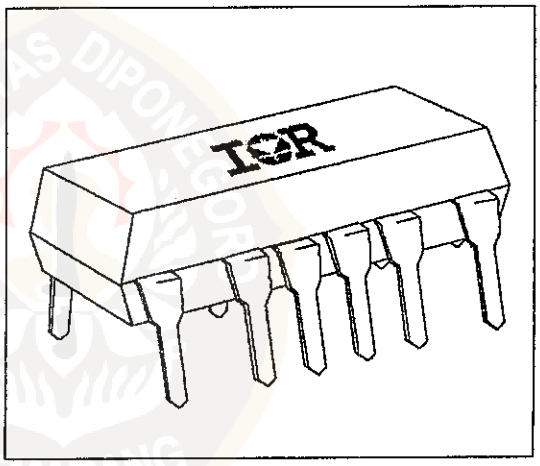
Unique silicon technology developed by International Rectifier forms the heart of the PVR. The monolithic BOSFET contains a bidirectional N-channel power MOSFET output structure. In addition, this power IC chip has input circuitry for fast turn-off and gate protection functions. This section of the BOSFET chip utilizes both bipolar and MOS technology to form NPN transistors, P-channel MOSFETs, resistors, diodes and capacitors.

The photovoltaic generator similarly utilizes a unique International Rectifier alloyed multijunction structure. The excellent current conversion efficiency of this technique results in the very fast response of the PVR microelectronic power IC relay.

This advanced semiconductor technology has created a radically new control device. Designers can now develop switching systems to new standards of electrical performance and mechanical compactness.

PVR33 Features

- BOSFET Power IC
- 10^{10} Operations
- 100µsec Operating Time
- 0.2µVolt Thermal Offset
- 5 milliwatts Pick-Up Power
- 1000V/µsec dv/dt
- Bounce-Free
- 16-pin DIP Package
- -40°C to 85°C



Part Identification

Part Number	Operating Voltage (AC/DC)	Off-State Resistance
PVR2300	0 – 200V	10^8 Ohms
PVR3300	0 – 300V	10^8 Ohms
PVR3301	0 – 300V	10^{10} Ohms

(BOSFET is a trademark of International Rectifier)

Electrical Specifications (-40°C ≤ T_A ≤ +85°C unless otherwise specified)

INPUT CHARACTERISTICS		Units
Minimum Control Current (see figure 1)		DC
For 20mA Continuous Load Current	2.0	mA@25°C
For 100mA Continuous Load Current	5.0	mA@25°C
For 20mA Continuous Load Current	5.0	mA@85°C
Minimum Turn-Off Current	10	μA(DC)
Minimum Turn-Off Voltage	0.6	V(DC)
Control Current Range (Caution: current limit input LED. See figure 6)	2.0 to 25	mA(DC)
Maximum Reverse Voltage	7.0	V(DC)

OUTPUT CHARACTERISTICS	PVR2300	PVR3300, PVR3301	Units
Operating Voltage Range	±200	±300	$V_{(peak)}$
Maxiumum Load Current 40°C (see figure 1)			
AC (A Connection)	180		mA (peak)
DC (B Connection)	200		$mA_{(DC)}$
DC (C Connection)	260		$mA_{(DC)}$
Response Time @25°C (see figure 7)			
Max. $T_{(on)}$ @ 12mA Control, 100 mA Load, 100 VDC	150		μs
Max. $T_{(off)}$ @ 12mA Control, 100 mA Load, 100 VDC	50		μs
Max. On-state Resistance 25°C (Pulsed) (fig. 2) 50 mA Load, 8mA Control			
AC (A Connection)	24		Ω
DC (B Connection)	12		Ω
DC (C Connection)	6		Ω
Min. Off-state Resistance 25°C @ 160 VDC PVR2300, PVR3300	10^8		Ω
@ 240 VDC PVR3301	10^{10}		Ω
Max. Thermal Offset Voltage @ 5.0mA Control	0.2		μvolts
Min. Off-State dv/dt	1000		V/μs
Output Capacitance (see figure 3)	12		pF @ 50VDC

GENERAL CHARACTERISTICS (PVR2300, PVR3300, PVR1301)		Units
Dielectric Strength: Input-Output	1500	V_{RMS}
Insulation Resistance: Input-Output @ $500V_{DC}$	10^9	Ω
Maximum Capacitance: Input-Output	1.0	pF
Max. Lead Soldering Temperature (1.6mm below seating plane for 10 sec)	260	°C
Ambient Temperature Range: Operating	-40 to +85	°C
Storage	-40 to +100	

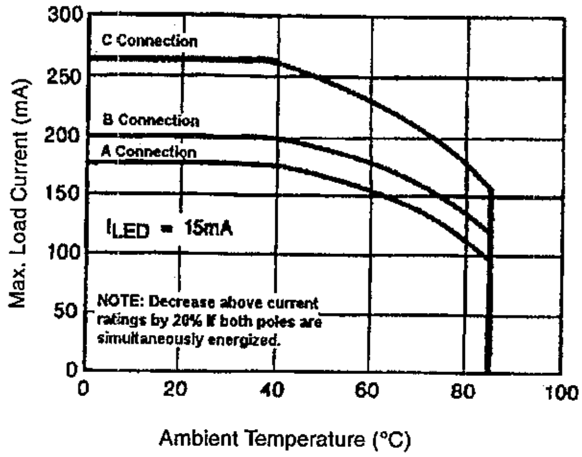


Figure 1. Current Derating Curve

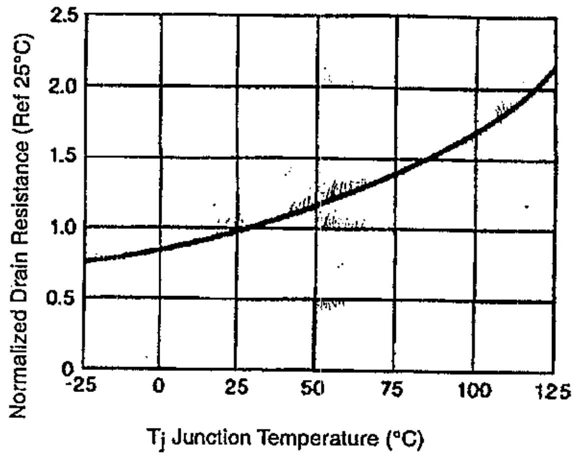


Figure 2. Typical Normalized On-Resistance

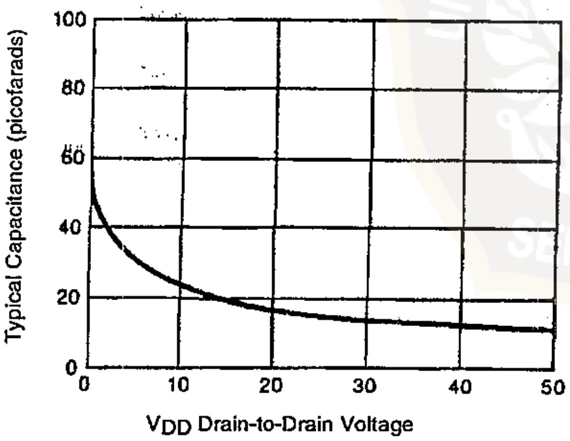


Figure 3.Typical Output Capacitance

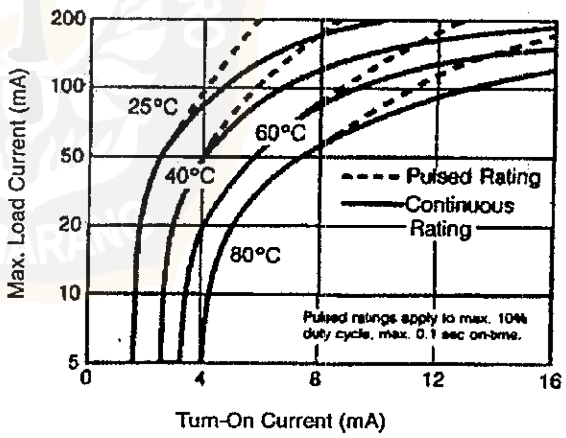


Figure 4. Minimum Control Current for Full Turn-On

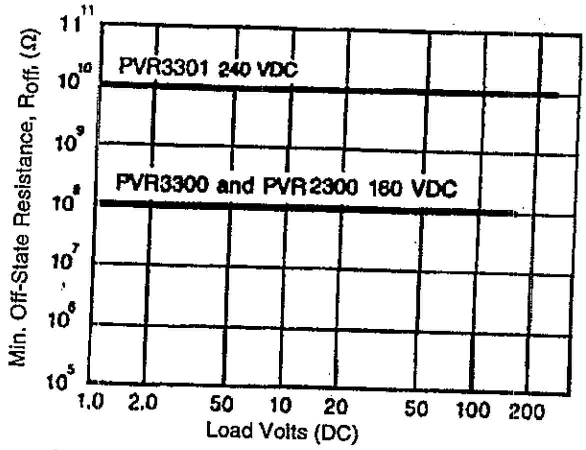


Figure 5. Off-State Resistance

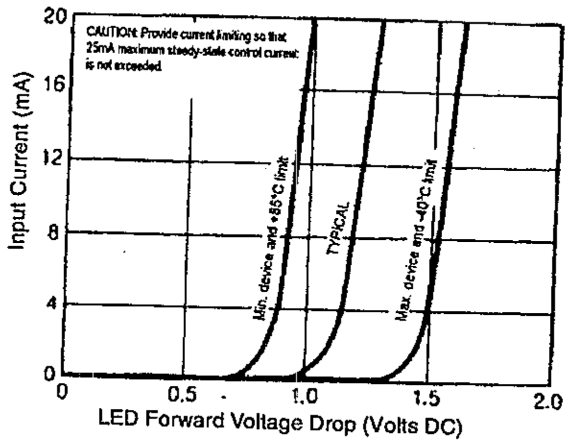


Figure 6. Input Characteristics (Current Controlled)

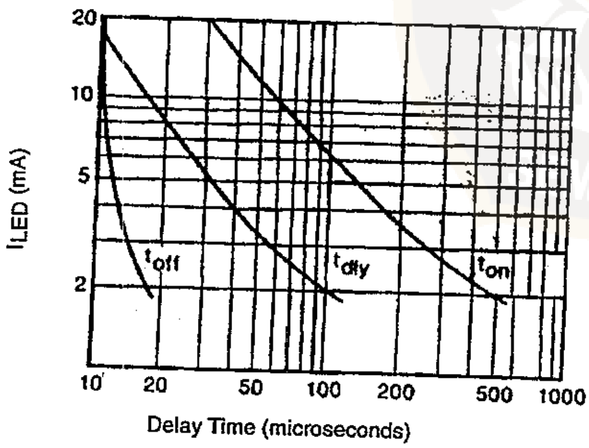


Figure 7. Typical Delay Times

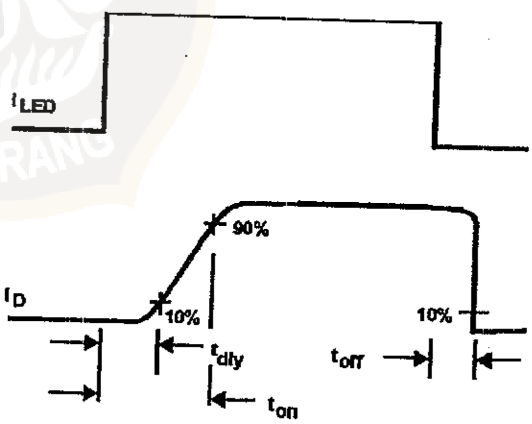
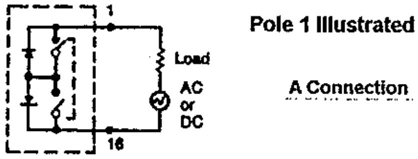
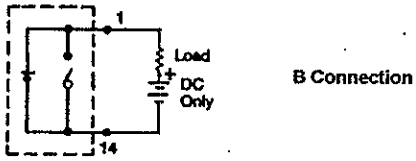
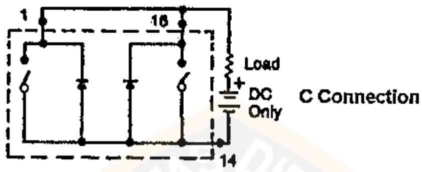


Figure 8. Delay Time Definitions

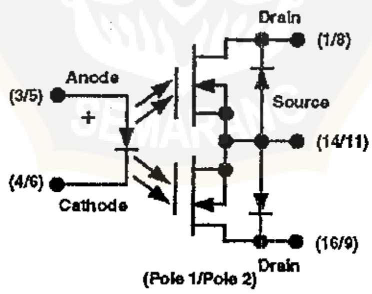
Wiring Diagram





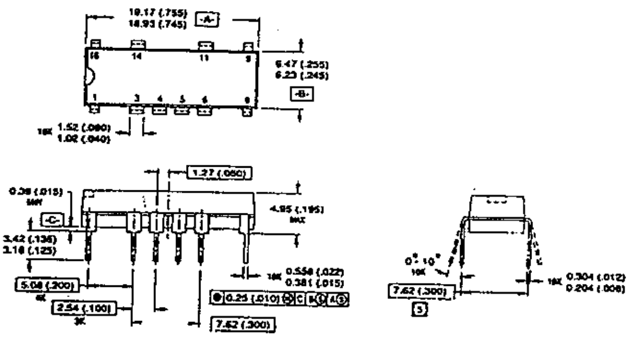


Schematic Diagram



Case Outline

(Dimensions in inches (millimeters))



Mechanical Specifications:

Package: 16-pin DIP
Tolerances: .015 (.38) unless otherwise specified
Case Material: molded epoxy

International
IOR Rectifier

WORLD HEADQUARTERS: 233 Kansas St., El Segundo, California 90245, Tel: (310) 322 3331
EUROPEAN HEADQUARTERS: Hurst Green, Oxted, Surrey RH8 9BB, UK Tel: ++ 44 1883 713215
IR CANADA: 7321 Victoria Park Ave., Suite 201, Markham, Ontario L3R 2Z8, Tel: (905) 475 1897
IR GERMANY: Saalburgstrasse 157, 61350 Bad Homburg Tel: ++ 49 6172 96590
IR ITALY: Via Liguria 49, 10071 Borgaro, Torino Tel: ++ 39 11 451 0111
IR FAR EAST: K&H Bldg., 2F, 3-30-4 Nishi-Ikeburo 3-Chome, Toshima-Ku, Tokyo, Japan 171 Tel: ++ 81 3 3983 0641
IR SOUTHEAST ASIA: 315 Outram Road, #10-02 Tan Boon Liat Building, Singapore 0316 Tel: ++ 65 221 8371
http://www/irf.com/

Data and specifications subject to change without notice. 9/96

Lampiran 7

Tabel Permeabilitas Material (Mitchell, 1992)

Material	Permeabilitas (μ)
Udara/ vakum	$1,26 \times 10^{-6}$
Nikel	$6,28 \times 10^{-5}$
Cobalt	$5,56 \times 10^{-5}$
Cast iron	$1,1 \times 10^{-4}$
Machine steel	$5,65 \times 10^{-4}$
Transformer iron	$6,9 \times 10^{-3}$
Silikon iron	0,126
Permaloy	1,26
Supermaloy	

Lampiran 8

Penurunan Persamaan Matematis

I. Induktansi timbal balik antara dua kumparan

Menurut definisi k_{12} pada persamaan 2.4 dan mengingat persamaan 2.2., didapatkan:

$$\phi_{12} = k_{12}\,\phi_{22} = k_{12}\,L_2\,i_2$$

$$\phi_{12} = M\,i_2$$

yang berarti:

$$M = k_{12}\,L_2$$

Dengan jalan yang sama akan diperoleh

$$M = k_{21}\,L_1$$

Sehingga dengan demikian dapat dirumuskan induktansi timbal balik antara dua kumparan sebagai:

$$M = \sqrt{k_{12}L_{12}.k_{21}L_1}$$

$$= k\sqrt{L_1L_2} \qquad (2.5)$$

dengan $k = \sqrt{k_{12}k_{21}}$

II. Tenaga sistem kumparan yang dialiri arus listrik

Tenaga yang dikandung di lingkaran arus ke j oleh arus i di kumparan itu sendiri diberikan oleh

$$
\begin{aligned}
U_{jj} = \int dU_{jj} = \int i_j \, d\phi_{jj} \\
&= \int i_j L_{jj} \, di_j \\
&= \tfrac{1}{2} L_{jj} i_j^2 \\
&= \tfrac{1}{2} i_j \phi_{jj}
\end{aligned}
$$

Seandainya mula-mula tidak ada arus listrik di masing-masing lingkaran, lalu arus listrik i_1, i_2, i_3, ... dst. dialirkan berurutan ke lingkaran ke 1, 2, 3, ... dst. maka tenaga yang kemudian terdapat dalam sistem lingkaran-lingkaran arus listrik menjadi

$$U_j = i_j \phi_{j1} + i_j \phi_{j2} + \ldots + \tfrac{1}{2} i_j \phi_{jj}$$

$$U = \sum_j U_j$$

$L_{ji} = L_{ij}$ sehingga, $i_j \phi_{ji} = i_j L_{ji} i_i = i_i L_{ij} i_j = i_i \phi_{ij}$

Tenaga sistem lingkaran-lingkaran arus listrik tersebut dapat ditulis sebagai

$$
\begin{aligned}
U &= \sum_j \tfrac{1}{2} i_j \phi_{jj} + \tfrac{1}{2} \sum_j \sum_{i \neq j} i_j \phi_{ji} \\
&= \tfrac{1}{2} \sum_j \sum_i i_j \phi_{ji} \qquad (2.6)
\end{aligned}
$$