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DESIGN PARAMETERS OF MOSFET SOLID STATE RELAYS IN FOCUS[2]

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Abstract: *The paper summarises the main design parameters of Solid State Relays and MOSFET SSR in particular. a number of technical papers and datasheets cover aspects of MOSFET SSR design theory and technical features of relevant commercial products. However, a detailed survey on the topic is not available, which is explained with the limited information provided by the production companies and the variety of devices. in this respect, the paper contributes with the proposed model of precise SSR specification and the review of main calculations and design considerations depending on the required electrical parameters and working conditions.*

Keywords: *Solid State Relay, MOSFET SSR, Design*
JEL Codes: *L60*

INTRODUCTION

Relays are an important part of many electrical and electronic devices due to their switching functionality. With the development of semiconductor electronics the so-called "solid state" semiconductor relays (SSR) or only semiconductor relays become popular circuit breakers both in low-voltage and power electronics. Nowadays they are more widely used than the electromechanical ones, though still there are areas where the latter cannot be displaced.

The main goal of this study is to provide a usefull methodology for design of MOSFET semiconductor relays according to given initial electrical parameters.

MOSFET semiconductor relays (MOSFET SSR) have advantages in terms of speed, compactness, reliability and low noice operation. In technology they are used for switching DC and AC loads, the latter dating from the practical implementation of the first thyristors and triacs. Like many other electronic devices there are variety of structures SSR distinguished by their circuit and product features. The choice of the appropriate device is made depending on the need to obtain certain input and output electrical parameters (currents and voltages), the requirement for an electrical insulation, appropriate placing and working conditions. Refer to the MOSFET relays in particular, another advantage of these relays is the good temperature stability, consequently they are often used as temperature regulators. All the listed features determine the matter of the current study as an update development as power MOSFET technology rapidly progresses both in terms of cost and performance.

EXPOSITION

MOSFET SSR structure and basic circuit operation

MOSFET semiconductor relays are implemented as integrated circuits or modules – fig.1. Depending on the manufacturer and required electrical parameters their dimensions very significantly with some designs exactly repeating those of similar electromechanical relays for easier replacement. As an alternative of the electromechanical relays the Solid State Relays can be switched much faster and are not prone to wear because of the absence of moving parts. Another advantage is that less current and voltage is needed for SSRs to control high-voltage AC loads.

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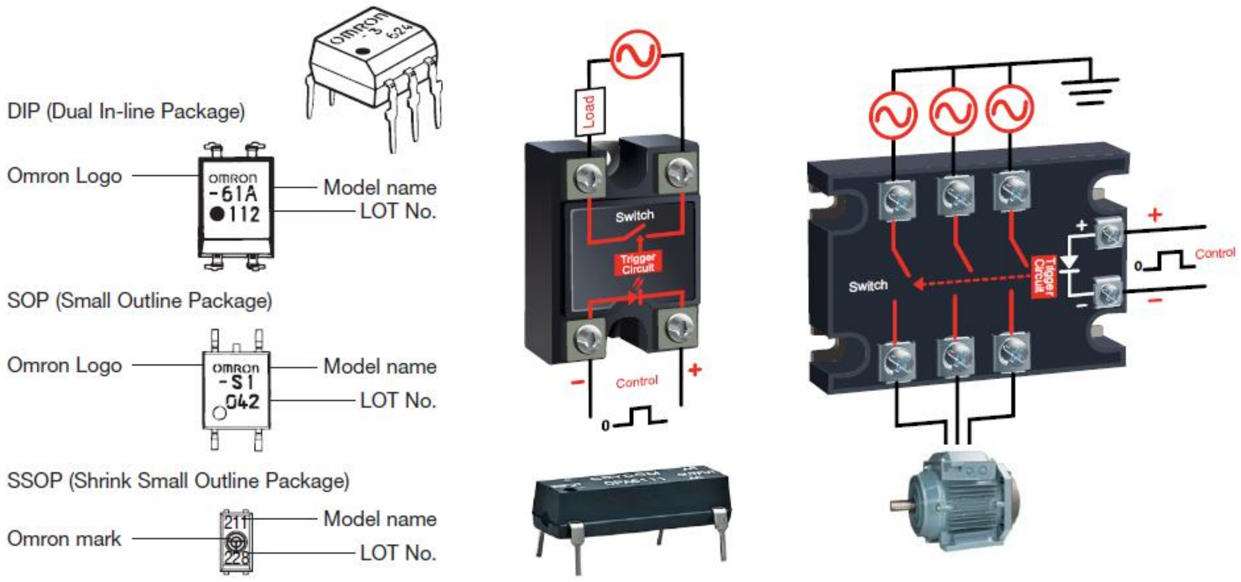
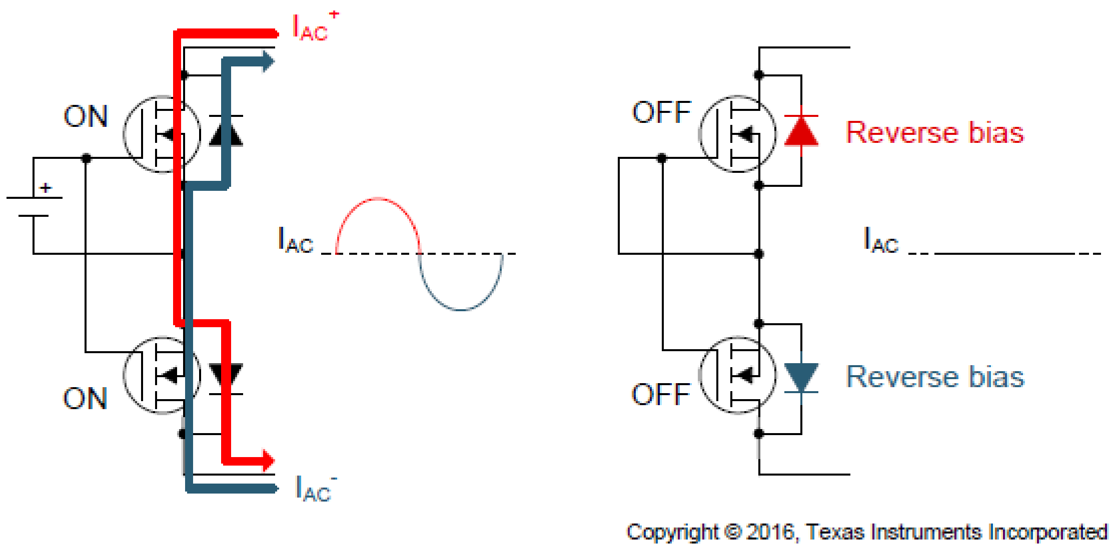


Fig. 1. Solid State Relay structures

The MOSFET SSR basic circuit is presented in fig. 2. Two N-Channel switching MOSFETs are used with their sources and gates joined separately. The signal and load are connected to each of the drain terminals and the 'switch' is symmetrical. Since there are two MOSFETs in series, the effective R_{DS} (on) is double that for a single device. The MOSFET topology serves two main functions. The first function is to perform switching. By using two MOSFETs, both positive and negative currents are allowed to flow during the ON time, as shown in Fig. 2a. During the OFF time, the body diodes block the current flow because the top and bottom body diode become reverse bias, as shown in Fig. 2b. The second function is to self-power the system by assisting in the AC voltage rectification, which is completed with the addition of a pair of rectifying diodes in the circuit.



a) b)

Fig. 2. MOSFET SSR basic circuit operation for ON (a) and OFF (b) times.

With no voltage between the gate and source terminals, each MOSFET is OFF, there is no current flowing. Depending on the MOSFETs used, they will conduct fully when the gate-source voltage exceeds around 7 Volts. An appropriate 10-12V gate drive can ensure that they always turn on fully. A zener diode in the input circuit may be used to protect the delicate insulation between the gate and MOSFET channel. The gate insulation is typically rated for a maximum of around ±20V. In real conditions, even a bit of stray capacitance or resistance (in case of moisture on the PCB for example) can easily allow the voltage to rise to destructive levels because of the very high impedance. This imposes the use of the zener diode. Even drain-gate capacitance can cause problems without the zener.

The control circuit must generally be completely isolated from the switching MOSFETs. As a result the two pairs of MOSFETs cannot be connected together in any way, other than sharing a common control drive circuit such as a dual optocoupler or miniature double pole relay.

Refer to the significant design parameters a number of reference technical papers are found. Namely, a good exposition of the SSR timing parameters and approaches for increasing swiching speed is presented in (Vishay Semiconductors). The latter describes the use of a photovoltaic driver (VO1263) feeding the MOSFET semiconductor relay. Herein the advanteges of MOSFET AC relay over the more traditional thyristor switch approach are accentuated in the following: lower R_{on} losses, higher output dV/dt performance, higher operating frequencies, lower power consumption, faster switching rates, AC/DC switching capability. A practical summary on the SSR design features in terms of safety and reliability is included in (Omron). This paper is ment to provision all details in the system design that may result in damage, malfunction, or deterioration of relay performance characteristics. The significant features of the input SSR circuit and output SSR cuircuit are outlined respectively by means of input side connections, input noise (pulse and inductive), input conditions (input voltage ripples, countermeasures for leakage current, ON/OFF frequency, input impedance) and AC/DC swiching SSR output noise and surges, output connections, selectind an SSR for different loads, load power supply. In addition, the main precautions in operating and storage environments are listed. Other general issues on the topic are production catalogs of (Zomel (Omron), Schneider Electric, Texas Instruments).

A comprehensive understanding of the MOSFET basics, both in term of structural and electrical parameters and typical characteristics, may be gained from (Alpha&Omega Semiconductor, Fairchild Semiconductor, NXP Semiconductors). Fundamentals of Power Semiconductor Devices can be found in (Baliga, B. J., 2008; Voronin, P. A.,2001).

In order to demonstrate the main design parametrs of a MOSFET SSR the initial conditions listed in Table 1 are considered.

Table 1. Initial electrical parameters.

	Initial electrical parameters/Description
1	SSR Input parameters: - input control voltage U_{in} = 3 – 12 V DC; - input current I_{in} = 5 – 10 mA.
2	SSR Output parameters: - output voltage U_0 = 12 – 24 V DC or AC; - maximal load current I_0 = 5 A.
3	Posibility for swiching DC and AC loads.

MOSFET selection

The required output voltage ranges from 12 to 24 V DC or AC and maximal load current 5A. Therefore, each MOSFET must be able to handle a drain-to-source voltage and current of about 35 VDC and at least 10 A, respectively. The MOSFET IRF540N was chosen for its 50 V drain-to-source voltage, drain current 33 A and package size and cost.

Desing parameters of MOSFET SSR

When choosing a proper SSR relay general parametrs needed are Input voltage, Output voltage, Load rating, Contact configuration, Ambient temperature, In-rush currents and Mounting style. Product catalogs or online parametric search are available for this purpose. Some interactive tools such as Time Delay Relay Interactive Demo (Schneider Electric) visually demonstrate the different timing functions offered.

The additional parameters mentioned herein should be considered when designing AC MOSFET SSR and analysing the relay operation.

1) Control current Ic calculation.

The circuit in fig. 3 is considered to determine the control current. Most Solid State Relays require at least 3 V control/trigger voltage. Refering the structure of opto-coupling shown in fig.3, the control current is defined as (3 V - 1 V) divided by 1000 Ω, which gives 2.0 mA. Herein, 1 V is the voltage across the LED. For higher control voltages, a series-connected resistor is additionally placed to limit the control current. The latter is reduced to around 2 mA, calculating the external resistor as R_C = 500 (E_C-3), where E_C is the control voltage.

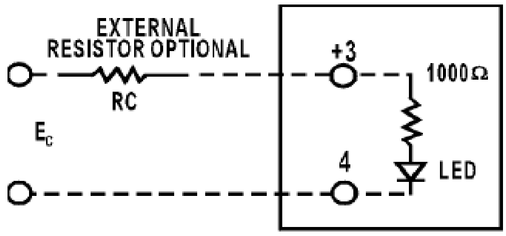


Fig. 3. Input circuit opto-coupling.

For Rc = 0 the control current is determined:

$$I_c = \frac{Ec-1}{1000} \tag{1}$$

Consequently, for Ec = 5 V and U_{LED} = 1 V the control current is obtained:

$$I_c = \frac{5-1}{1000} = 4\ mA \tag{2}$$

2) Time parameters of MOSFET type IRF540N.

Main parameters of IRF540N are V_{DSS} = 100 V, $R_{DS(on)}$ = 44mΩ, I_D = 33 A. Fig.4 and fig. 5 show general characteristics of IRF540N as per datasheet.

Turn-on time t_{on} of the switch is determined simply:

$$t_{on} = \frac{Qg}{Isc} \tag{3}$$

where Q_g – amount of charge required to fully turn-on a MOSFET; I_{SC} – amount of current available from the opto-driver or control current.

This relationship comes from the basic definition of electrical current, which is charge over time. In most cases, the datasheet for a power MOSFETs provide Qg as the total charge required to turn the device on.

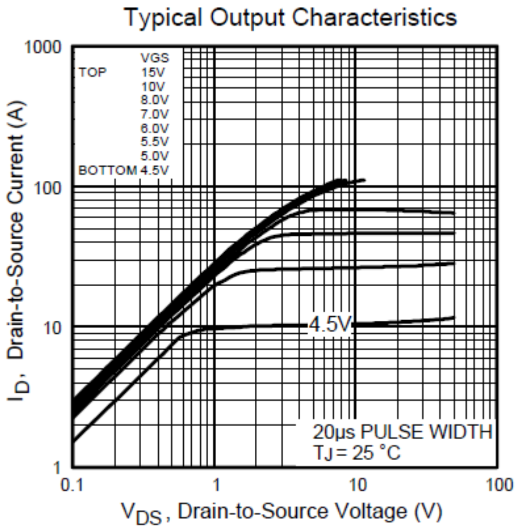


Fig. 4. Typical Output Characteristics of IRF540N.

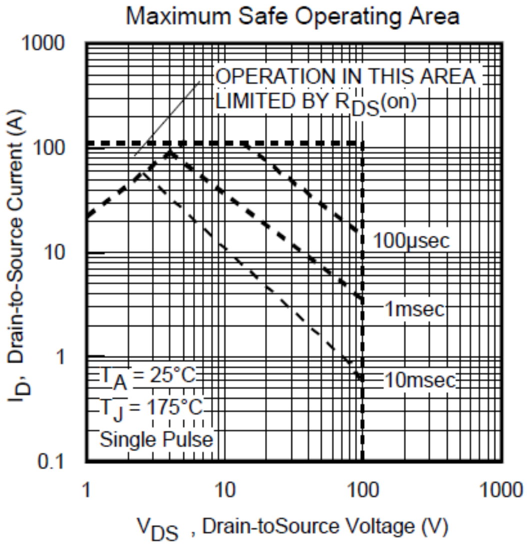


Fig. 5. Maximum Safe Operating Area of IRF540N.

However, in some cases, instead of certain gate charge Qg, a capacitance value C_g at a certain gate voltage V_{GS} may be provided. The relationship between gate capacitance, gate charge and gate voltage is as follows:

$$C_g = \frac{Qg}{Vgs} \quad (4)$$

Refer to MOSFET IRF540N with gate total charge required to turn on the device on Q_g = 71 nC, gate voltage V_{GS} = 3 V and I_{SC} = 5 mA the turn-on time is calculated according to formulas (3), (4) $t_{on} = Q_g/I_{sc}$ = 14,2 µs and gate capacity is $C_g = Q_g/V_{GS}$ = 23,7 nF.
The maximum allowable switching frequency is calculated:

$$f_{max} = \frac{Isc(min)}{Qg} = \frac{2\ mA}{71nC} = 28{,}16\ kHz \quad (5)$$

3) **Maximum output ratings taking into account the maximum junction temperature T_J = 175°C at active load.**

IRF540N has the following temperature dependent parameters: T_{jmax} = 175°C, T_A = 50 °C, R_θ = 62 °C/W, r_{ds} = 44 mΩ. Additional parameters needed to calculate the output rated values are Duty cicle D = 0,5 , $t_{on} + t_{off}$ = 28,4 µs at load current I = 5 A ($I_{SD} \leq$ 16A), V = V_{out} = 15 V:

$$\frac{Tjmax - Ta}{Ro} = \frac{I^2 rds.D + F.I.V.(ton + toff)}{Irms} \quad (6)$$

That is *Max Power Dissipated = Power Generated*
Or 125/62 = 25.0,044.0,5 + F.5.15.28,4/6 => F[kHz] = 1,47/(355.10^{-6}) = 4,141 kHz

4) **MOSFET semiconductor relay specification**

High Current DC Outputs (each channel, without heat sink, T_A = 0 to 70°C)	
Output Channels:	1-channel DC/AC output
MOSFET SSR Used:	IRF540N with parameters V_{DSS} = 100 V, $R_{DS}(on)$ = 44mΩ, I_D = 33 A
Isolation:	Optically isolated to ± 2500 V with 10^{11}Ω isolation resistance
Output Protection:	Snub diodes to field supply may be included to protect against inductive spikes
Field Voltage:	+12 to +24 VDC max
OFF Voltage:	+12 to +24 V (field supply)
OFF Leakage:	< 25 µA at 25° C
ON Voltage:	<0.08 V typical at 2 A
Max ON Resistance:	<0.044 Ω при I_{DS} < 16A
Max ON Current:	5 A continuous or pulse current at 15 V and 50 % Duty Cycle at frequency upto 4 кHz.
Switching Times:	t_{on} = 14,2 µs = t_{off} t_{on} (fall time) = 35 nsec, t_{off} (rise time) = 35 nsec at levels 10%-90% t_{on_delay} = 11 ns, t_{off_delay} = 39 ns
Voltage / Switch Inputs (each channel)	
Input High Voltage:	± 3 to ±12 VDC
Input Low Voltage:	< ± 0.8 V
Isolation:	Optically isolated to ± 2500 V with 1011Ω isolation resistance

5) Determination of the maximum DC current.

To calculate the maximum DC current we need IRF540N temperature dependent parameters: T_{jmax} = 175°C, T_A = 50 °C, R_θ = 62 °C/W, r_{ds} = 44 mΩ and the additional parameters Duty cycle D = 1, $t_{on} + t_{off}$ = 28,4 µs at frequency F = 0 Hz, V_{out} = 15 V:

Acc. To (6) it is obtained => I = 45,9 A

This current is much higher than the currents supported by ribbon cables and sockets, so the maximum allowed current will be determined primarily by the selected interfaces (cables, sockets). If the wires are soldered directly to the board, up to 6.5 - 7 A per channel / device can be controlled without the use of MOSFET heatsinks.

CONCLUSION

While the concept of MOSFET SSR is very simple in practice there may be quite a lot of additional circuitry needed because the control circuit must generally be completely isolated from the switching MOSFETs. The paper focuses on significant design parameters of MOSFET SSR and provides a model of precise relay specification.

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