

IXYS P-channel Power MOSFETs and Applications

Abdus Sattar, Kyoung-Wook Seok, IXAN0064

Introduction:

IXYS P-Channel Power MOSFETs retain all the features of comparable N-Channel Power MOSFETs such as very fast switching, voltage control, ease of paralleling and excellent temperature stability. These are designed for applications that require the convenience of reverse polarity operation. They have an n-type body region that provides lower resistivity in the body region and good avalanche characteristics because parasitic PNP transistor is less prone to turn-on [1]. In comparison with N-channel Power MOSFETs with similar design features, P-channel Power MOSFETs have better FBSOA (Forward Bias Safe Operating Area) and practically immune to Single Event Burnout phenomena [2]. **Main advantage** of P-channel Power MOSFETs is the simplified gate driving technique in high-side (HS) switch position [3].

The source voltage of P-channel device is stationary when the device operates as a HS switch. On the other hand, the source voltage of N-channel device used as HS switch varies between the low-side (LS) and the HS of the DC bus voltage. So, to drive an N-channel device, an isolated gate driver or a pulse transformer must be used. The driver requires an additional power supply, while the transformer can sometimes produce incorrect operations. However, in many cases the LS gate driver can drive the P-channel HS switch with very simple level shifting circuit. Doing this simplifies the circuit and often reduces the overall cost. **Main disadvantage** of P-channel device is relatively high $R_{ds(on)}$ in comparison with that of N-channel device. This means the cost effective solutions with P-channel power MOSFETs require optimization of devices toward reduced $R_{ds(on)}$ [4].

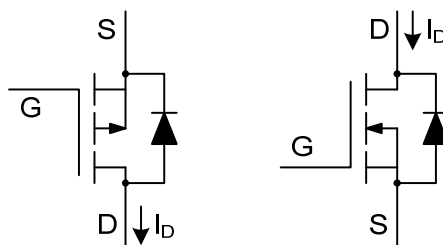


Figure 1: P-channel (left) and N-channel (right) MOSFET

IXYS Corporation has developed two families of P-channel Power MOSFETs covering V_{DS} range of -50V to -600V and I_{D25} range of -10A to -170A. Details of the product selections are given in the appendix A. P-channel TrenchP™ Power MOSFETs in the range of -50V to -150V offer very low on-resistance, low gate charge, very fast switching and fast body diode. Planar Polar™ P-channel Power MOSFETs offer excellent power performance in the range of -100V to -600V voltage. Both families offer “best in class” performance in industry standard power packages and IXYS proprietary ISOPLUS family packages.

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Gate driving for High-Side (HS) Switch:

In this section, various gate driving techniques for half bridge circuit are presented. Driving P-channel MOSFET is much simpler and more cost effective than driving N-channel MOSFET as a HS switch [5].

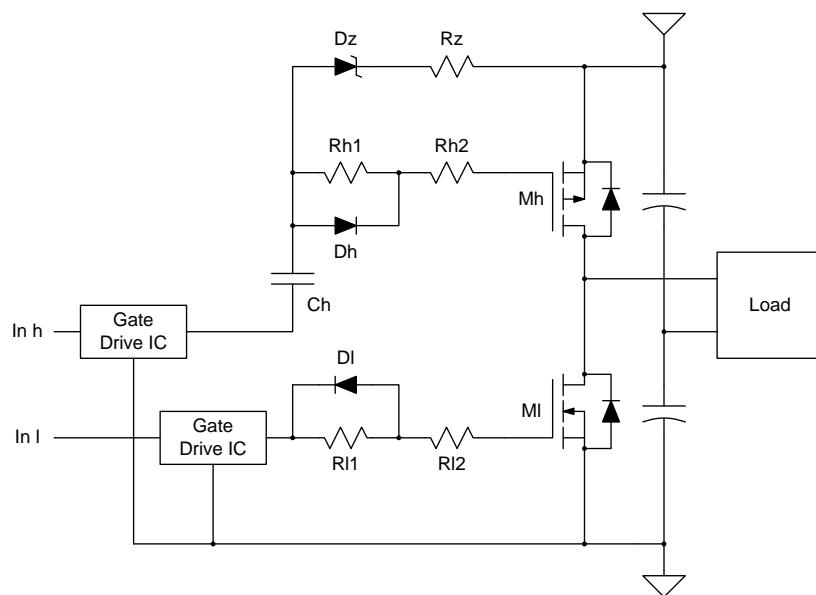


Figure 2: P-channel gate driving example for PWM application

Figure 2 shows one example of gate driving circuit for HS P-channel power MOSFET. This is much simpler and more cost effective than the driving circuits in Figure 5 and 7 for N-channel MOSFET. In the circuit, Dz, Rz, and Ch were added to the typical gate driving circuit for an N-channel power MOSFET. The capacitor “Ch”, which holds DC voltage between the higher and lower gate drive circuits, must be much larger than the input capacitance of the P-channel MOSFET. Dz keeps the gate to source voltage in the range of $-Zener\ voltage$ to 0.

The product of Ch and Rz determines the speed of the DC voltage adjustment across Ch. If it's too small, there will be a large current, which can damage the gate drive IC or Dz. If it's too big, the P-channel MOSFET will switch on too slowly. This is due to the slower rise time of the gate pulse amplitude and can damage the MOSFET. Rh2 and Rl2 are resistors for controlling MOSFET turn off speed. (Rh1 + Rh2) and (Rl1 + Rl2) are resistors for controlling MOSFET turn on speed. In most cases, slower turn on speed than turn-off speed is desirable [4].

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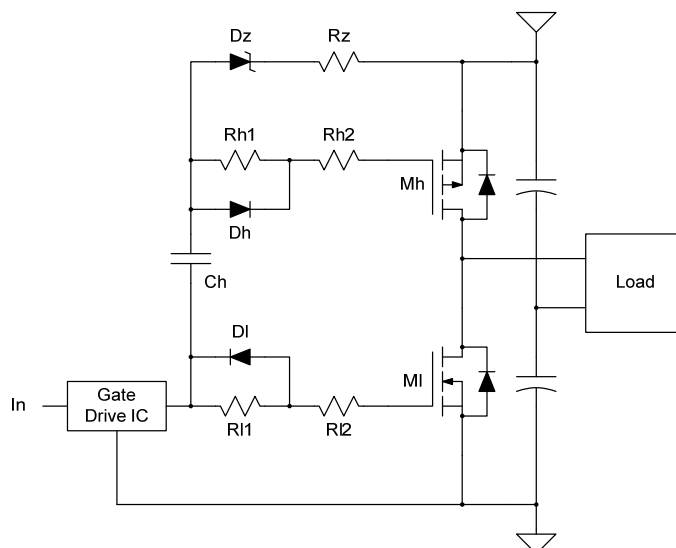


Figure 3: Single gate drive IC drives both P-channel and N-channel MOSFETs

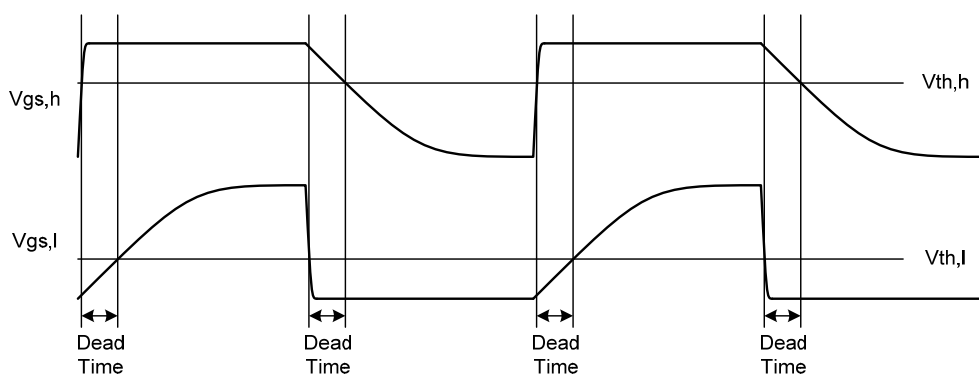


Figure 4: Dead times in single gate drive IC case

In many cases, both P-channel and N-channel MOSFETs can be driven by a single gate drive IC as shown in Fig. 3. This is the most cost effective and simplest gate driving method of half-bridge. To avoid cross conduction, dead time is to be provided by the difference of turning on and turning off speed. If dead time is too short, there is a chance of too much heat generation and risk of MOSFET failure. If dead time is too long, the output voltage of the bridge circuit may be reduced. With this circuit, at the beginning of turn on period of each MOSFET, the gate source voltage is not enough to fully turn on the MOSFET and it will make some additional power loss. So, this circuit may not be suitable for hard switching applications. But, for some ZVS (Zero Voltage Switching) applications, in which MOSFETs are turned on while opposite MOSFET operates in diode mode, this circuit can be cost effective [4].

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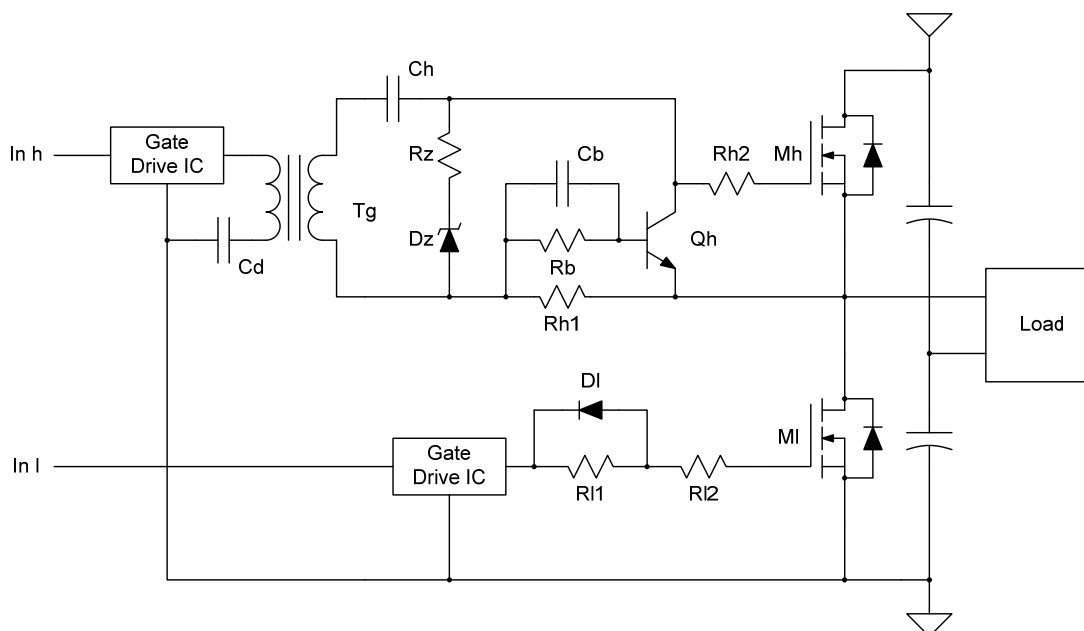


Figure 5: N-channel MOSFET driving with pulse transformer

Figure 5 shows an example of N-channel MOSFET driving circuit using a pulse transformer. The gate pulse height of this circuit is not sensitive to the duty ratio variation, unlike trivial pulse transformer driving circuit. Theoretically, there is no limitation in duty ratio. But, in the actual circuit, several parasitic components limit the usable duty range. At gate turn-off, the transistor Q_h discharges the gate charge. R_b is the base resistor for Q_h . The small capacitor C_b is used to accelerate the speed of Q_h . $(R_{h1} + R_{h2})$ is the turn on gate resistance and (R_{h2}) is turn off gate resistance. D_z keeps the gate to source voltage staying in the range of 0 to the Zener voltage.

Figure 6 shows an isolated gate driver circuit driving both N-channel and P-channel MOSFET with a single pulse transformer. The N-channel MOSFET is used as a high side switch, while the P-channel MOSFET is the low side switch. They are connected in a source to source configuration. This circuit provides dead time by the time constant difference of charging and discharging the gate input capacitance.

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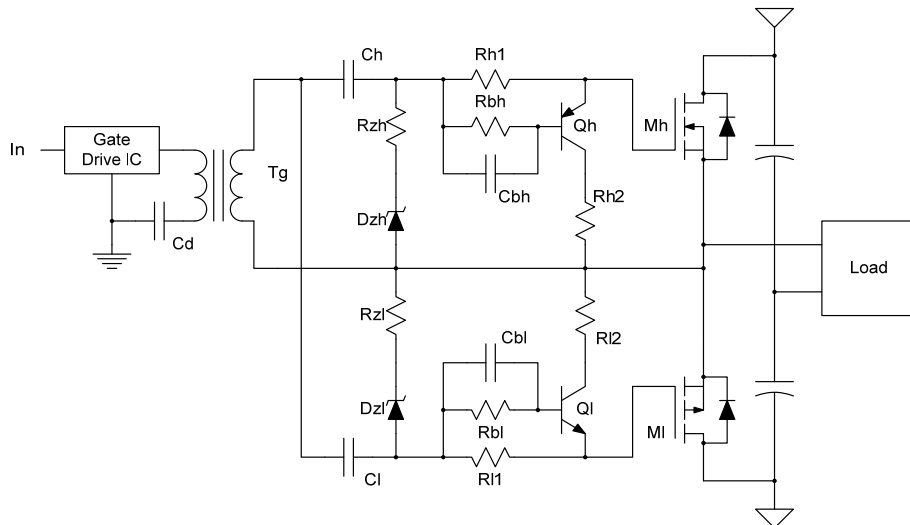


Figure 6: Single pulse transformer driving both N-channel and P-channel MOSFET

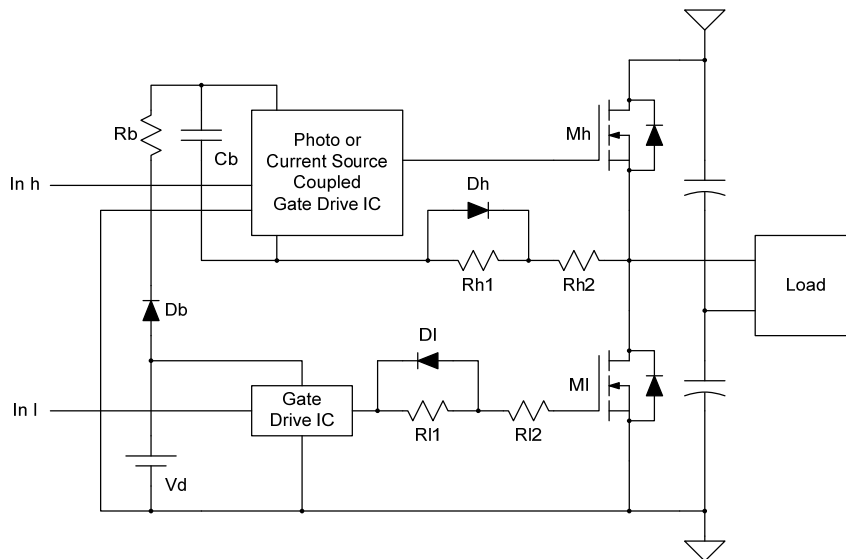


Figure 7: N-Channel MOSFET Driving with driver IC

As pulse transformers are bulky and not so reliable; many application circuits use expensive photo or current source coupled gate drive ICs. The simplest method for supplying power to the IC is using the bootstrap technique, shown in Figure 7. While Ml is turned on and the source voltage of Mh is near zero, the dc link capacitor Cb is charged by Db and Rb. In case of the ground voltage of the upper gate drive IC goes below its reference ground, the IC can cause failure. To reduce this possibility, the gate resistors are located at the source side of Mh.

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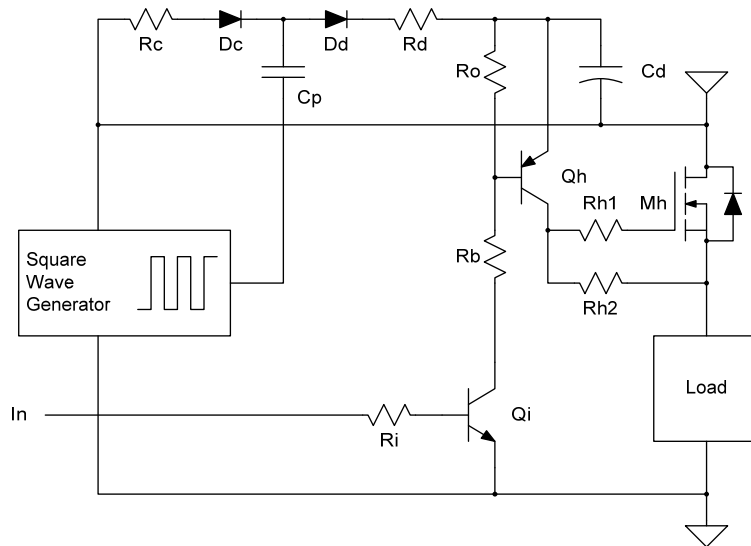


Figure 8: Low frequency N-channel MOSFET Driving with charge pump

Commonly used in automotive applications, almost all loads are connected between switches and body ground. All switches in automotive applications are located at the positive side. To drive the positive side n-channel Power MOSFET at a very low frequency, pulse transformer or bootstrap techniques can not be used. Figure 8 shows the circuit for providing a gate voltage higher than the DC-link voltage. When the square wave generator output is at ground, the diode Dc charges the charge pump capacitor Cp. When the square wave generator output is at the positive DC-link voltage, diode Dd discharges Cp. The charge is transferred to Cd, which is the power source of the high side gate drive circuit.

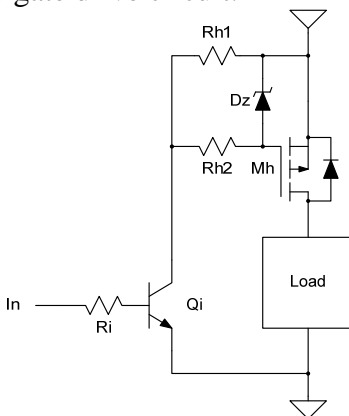


Figure 9: Low frequency P-channel MOSFET driving circuit

As shown in Figure 9, P-channel MOSFET greatly simplifies the overall circuit of Figure 8. Generally, the simpler circuit is more reliable. Although the P-channel MOSFET has higher $A \cdot R_{ds(on)}$ than that of the N-channel MOSFET, in many cases, this simple circuit makes the larger expensive P-channel MOSFET the most cost effective solution [4].

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Matching P-channel MOSFET to N-channel MOSFET:

It is impossible to produce the P-channel Power MOSFET which has the same electrical characteristics as an N-channel Power MOSFET. As the mobility of carriers in N-channel Power MOSFET is about 2.5 - 3 times higher, for the same $R_{ds(on)}$ value, the P-channel Power MOSFET size must be about 2.5-3 times of N-channel Power MOSFET. Because of larger area, P-channel device will have lower thermal resistance and higher current rating. Its dynamic performance (capacitance, gate charge, etc.) would be affected proportionally by the chip area.

In low frequency switching application in which conduction loss is dominant the P-channel MOSFET should have similar current rating to that of N-channel MOSFET. If two MOSFETs have the same current rating, their junction temperatures can be thought to be similar at the same case temperature and the same current. In this case, the P-channel MOSFET chip area is 1.5 ~ 1.8 times of N-channel MOSFET chip area.

In high frequency switching application in which switching loss is dominant the P-channel MOSFET should have similar total gate charge to that of N-channel MOSFET. If two MOSFET have the same gate charge and driven in similar way, their switching losses are similar. In this case, the P-channel MOSFET has similar chip area and the current rating is lower than that of N-channel MOSFET.

For operation in linear mode, one needs to match P-ch and N-ch devices with similar FBSOA characteristics in the real operating area. This frequently means the same rated P_d , but attention needs to be paid to ability of the device to operate in this mode [8].

In real applications, the suitable P-channel must be carefully selected in between the same current rating and the same gate charge. The applications requiring the same $R_{ds(on)}$ are very rare.

Application Examples:

Maybe, audio amplifier is the most important application of P-channel MOSFET. In Figure 11 (a), N-channel MOSFET is high side (HS) and P-channel MOSFET is low side (LS). The audio amplifier output stage is a sort of source follower circuit. As source follower circuit voltage gain is near 1, this circuit is stable. In Fig. 11 (b), a Darlington configuration of PNP transistor and N-channel is used instead of P-channel MOSFET. The MOSFET is in common source circuit which has high voltage gain and feed back controlled by high gain PNP transistor. So, this circuit can be unstable. After compensating this, the frequency range can be not wide enough for high fidelity audio.

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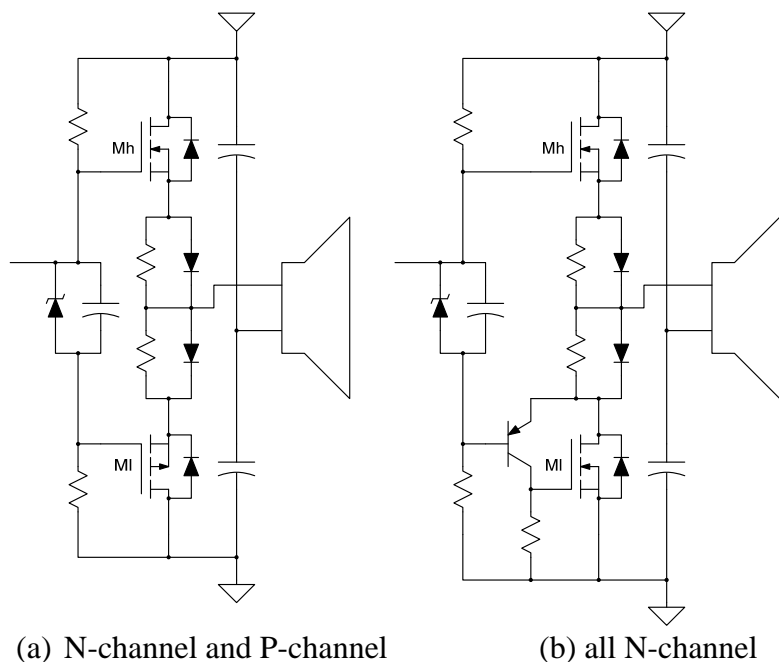


Figure 11: Output stage of MOSFET audio amplifier

Class AB Audio Amplifier:

Figure 12 shows a class AB audio amplifier circuit, which has a complementary Power MOSFET output stage, a differential input stage and a biasing circuit for the output stage. It offers performance improvements over the equivalent bipolar output stage and allows a reduction in the complexity of the driver circuit.

The input stage has a PNP differential comparator, which receives input signal through R1 and C1 and the negative feedback of the output stage to the base of Q2 through the resistor R6. The comparator drives the transistor, Q4, which drives the output stage. Components R6 and R5 determines the feedback loop gain as $\beta = R5 / (R5 + R6)$. R2 determines the bias current at the input stage and typically 2mA. R4 and C3 create a filter that provides additional power supply ripple suppression.

VBE multiplier consisting of R7, R8, R9, C5, and Q3 provides a bias voltage, Vb, between the gates of transistor Q5 and Q6. The capacitor C5 holds the voltage. If Vbe of Q3 is ~0.6V, R9 ~10K and R7 ~ 100K, the value of the bias voltage would be about $Vb \sim 10 \times Vbe \sim 6V$. The purpose of this voltage is to bias the gates of Q5 and Q6, keeping them in a slightly ON state that results a quiescent current flowing through in the output stage. The quiescent current reduces the zero crossing

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distortion associated with the output stage. The small capacitors C2 and C4 make the entire circuit stable [6].

The output stage comprises N and P-channel Power MOSFETs (Q5 & Q6) connected in series between the high voltage (+VDD) and low voltage (-VDD) terminals. The sources of Q5 and Q6 are connected to the OUTPUT terminal, which delivers an output signal to the LOAD (speaker). The output stage is a source follower circuit with gain very close to 1 (but <1.0), which is almost an ideal voltage source. Its output voltage is practically insensitive to the output current [6].

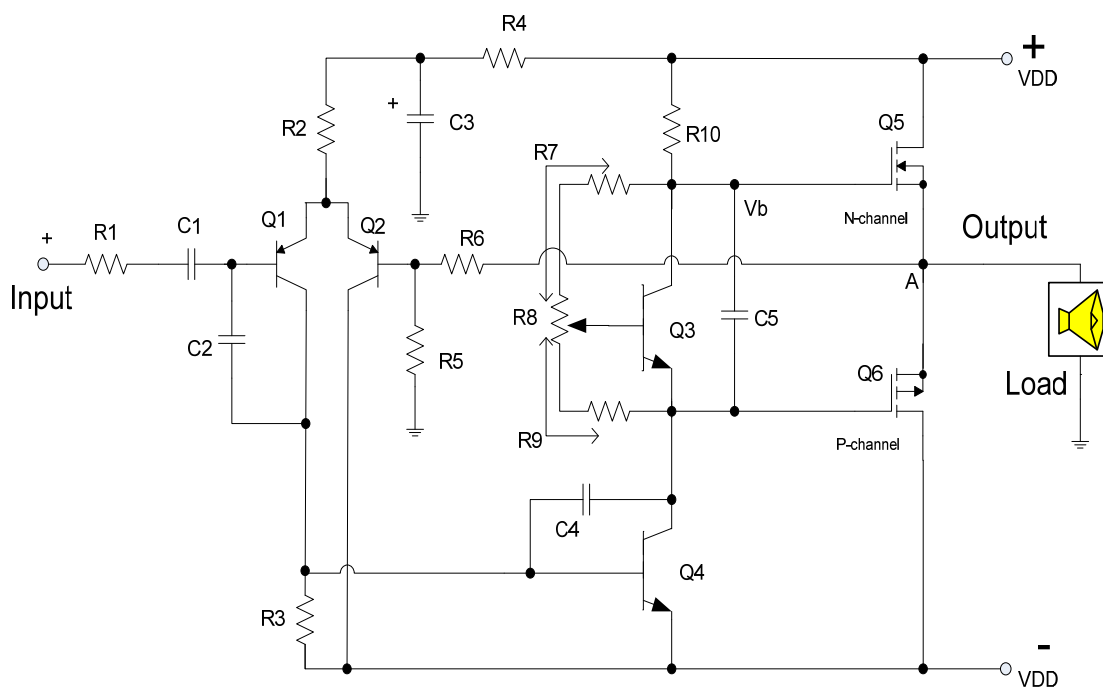


Figure 12: Class AB Audio Amplifier Circuit [6]

Both MOSFETs in Class AB amplifier require extended FBSOA as they operate in linear mode. Power dissipation would be high because of linear operation.

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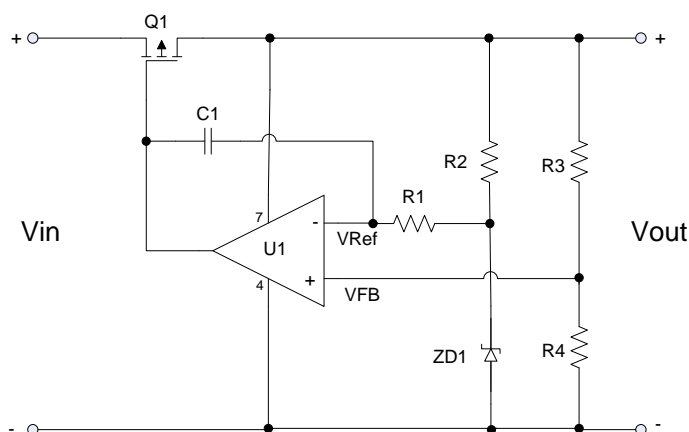


Figure 13: A linear Voltage Regulator

Linear voltage regulators are widely used to supply power to electronic devices. They have a variety of configurations for many different applications. One application example is illustrated in Figure 13. The resistive divider (R3 & R4) monitors the output voltage and provides a voltage feedback (VFB) to the positive (+) terminal of the op-amp (U1). The negative (-) terminal of the op-amp receives a reference voltage (VRef) from a Zener diode (ZD1). The op-amp provides a control voltage to the regulating transistor (Q1), a P-channel power MOSFET. As the voltage drop across the P-channel MOSFET can be lowered nearly zero, this circuit has wide input voltage range.

The power dissipation in the device (Q1) used in the linear voltage regulator is high because it's the function of the difference between input and output voltage and the output current. The P-channel Power MOSFET operates in the linear mode and requires an extended FBSOA characteristic which is offered by both families of IXYS P-channel Power MOSFETs.

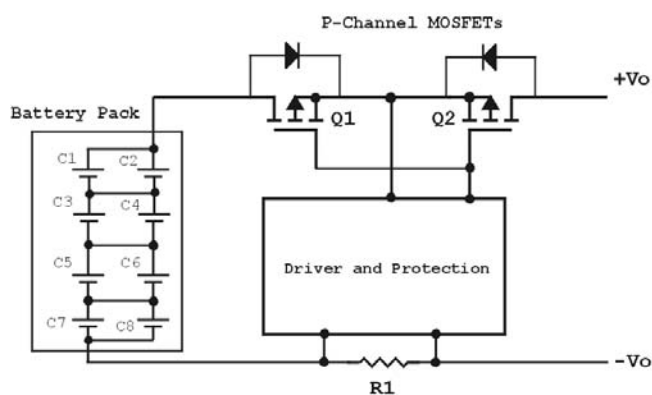


Figure 14: A battery charging and protection circuit using P-channel MOSFETs [7]

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Figure 14 shows a battery charging and discharging system for Lithium-ion (Li+) cells. One MOSFET enables the charging of the battery pack while the other MOSFET enables the discharging. When both MOSFETs are off, the cells are isolated from the external environment to protect the battery. At the beginning of the charging cycle, a constant current can be implemented and the MOSFET will be operated in the linear region. When the battery cell reaches a predefined voltage level, the system voltage loop will begin to reduce the charging current in order to maintain the desired voltage level, hence the constant voltage-mode operation [7].

Figure 15 shows a basic diagram of full-bridge converter with P-channel MOSFETs as high-side switches. Each leg uses one P-channel MOSFET as high-side switch and one N-channel MOSFET as low-side switch. For high-side switching, a P-channel MOSFET can be turned on with a voltage lower than the high-side DC bus voltage since it requires a negative gate-to-source voltage ($-V_{GS}$) somewhat lower than the threshold voltage ($-V_{GS(th)}$) of the device to fully turn on. This eliminates the need for extra bootstrap circuitry (or charge pump) and simplifies the DC-DC converter designs [5].

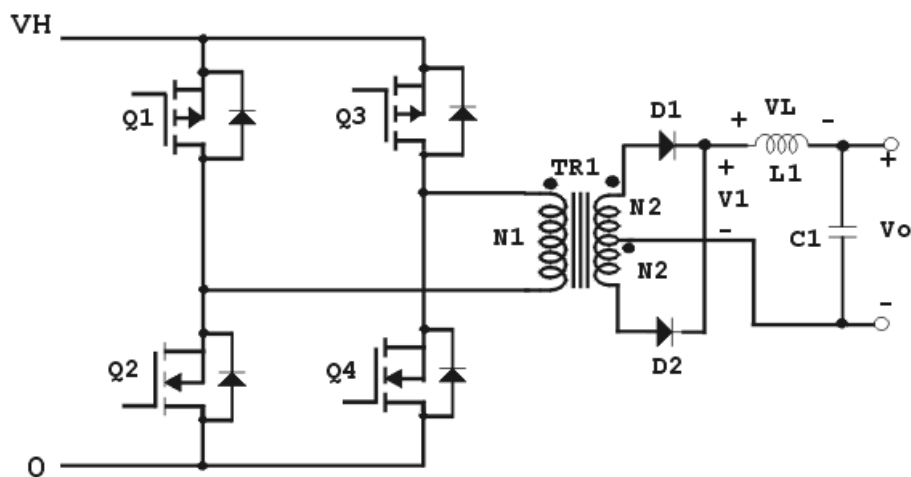


Figure 15: A full-bridge converter with P-channel MOSFETs as high-side switches [3]

Both the battery charging and the full-bridge circuit given in Figure 14 and 15 are examples of switching applications which require enhanced switching performance such as low on-resistance, low gate charge and low input and output capacitances.

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Appendix A:

Table 1: IXYS Polar™ P-channel Power MOSFET Family

Part Number	Vdss (max) V	Id @ Tc=25°C (A)	Rds(on) @ Tj=25°C (Ω)	Ciss (pF) typ	Qg (nC) typ	trr @ Tj=25°C (ns)	R(th)JC (°C/W)	Pd (W)	Package
IXTA52P10P	-100	-52	0.05	2845	60	120	0.42	300	TO-263
IXTH52P10P	-100	-52	0.05	2845	60	120	0.42	300	TO-247
IXTP52P10P	-100	-52	0.05	2845	60	120	0.42	300	TO-220
IXTQ52P10P	-100	-52	0.05	2845	60	120	0.42	300	TO-3P
IXTR90P10P	-100	-57	0.27	5800	120	144	0.66	190	ISOPLUS247
IXTH90P10P	-100	-90	0.25	5800	120	144	0.27	462	TO-247
IXTT90P10P	-100	-90	0.25	5800	120	144	0.27	462	TO-268
IXTR170P10P	-100	-108	0.013	12600	240	176	0.4	312	ISOPLUS247
IXTK170P10P	-100	-170	0.012	12600	240	176	0.14	890	TO-264
IXTX170P10P	-100	-170	0.012	12600	240	176	0.14	890	PLUS247
IXTN170P10P	-100	-170	0.012	12600	240	176	0.14	890	SOT-227
IXTC36P15P	-150	-22	0.12	2950	55	150	1	150	ISOPLUS220
IXTR36P15P	-150	-22	0.12	2950	55	150	1	150	ISOPLUS247
IXTA36P15P	-150	-36	0.11	3100	55	228	0.42	300	TO-263
IXTP36P15P	-150	-36	0.11	3100	55	228	0.42	300	TO-220
IXTQ36P15P	-150	-36	0.11	3100	55	228	0.42	300	TO-3P
IXTA26P20P	-200	-26	0.17	2740	56	240	0.42	300	TO-263
IXTH26P20P	-200	-26	0.17	2740	56	240	0.42	300	TO-247
IXTP26P20P	-200	-26	0.17	2740	56	240	0.42	300	TO-220
IXTQ26P20P	-200	-26	0.17	2740	56	240	0.42	300	TO-3P
IXTR48P20P	-200	-30	0.093	5400	103	260	0.66	190	ISOPLUS247
IXTH48P20P	-200	-48	0.085	5400	103	260	0.27	462	TO-247
IXTT48P20P	-200	-48	0.085	5400	103	260	0.27	462	TO-268
IXTR90P20P	-200	-90	0.048	12000	205	315	0.4	312	ISOPLUS247
IXTK90P20P	-200	-90	0.044	12000	205	315	0.14	890	TO-264
IXTX90P20P	-200	-90	0.044	12000	205	315	0.14	890	PLUS247
IXTN90P20P	-200	-90	0.044	12000	205	315	0.14	890	SOT-227
IXTA10P50P	-500	-10	1	2840	50	414	0.5	250	TO-263
IXTH10P50P	-500	-10	1	2840	50	414	0.5	250	TO-247
IXTP10P50P	-500	-10	1	2840	50	414	0.5	250	TO-220
IXTQ10P50P	-500	-10	1	2840	50	414	0.5	250	TO-3P
IXTR20P50P	-500	-13	0.49	5120	103	406	0.66	190	ISOPLUS247
IXTH20P50P	-500	-20	0.45	5120	103	406	0.27	462	TO-247
IXTT20P50P	-500	-20	0.45	5120	103	406	0.27	462	TO-268
IXTK40P50P	-500	-40	0.23	11500	205	477	0.14	890	TO-264
IXTX40P50P	-500	-40	0.23	11500	205	477	0.14	890	PLUS247
IXTN40P50P	-500	-40	0.23	11500	205	477	0.14	890	SOT-227
IXTR16P60P	-600	-10	0.79	5120	92	440	0.66	190	ISOPLUS247
IXTH16P60P	-600	-16	0.72	5120	92	440	0.27	460	TO-247
IXTT16P60P	-600	-16	0.72	5120	92	440	0.27	460	TO-268
IXTR32P60P	-600	-18	0.385	11100	196	480	0.4	310	ISOPLUS247
IXTK32P60P	-600	-32	0.35	11100	196	480	0.14	890	TO-264
IXTX32P60P	-600	-32	0.35	11100	196	480	0.14	890	PLUS247
IXTN32P60P	-600	-32	0.35	11100	196	480	0.14	890	SOT-227

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Table 2: IXYS TrenchP™ P-channel Power MOSFET Family

Part Number	V _{dss} (max) V	I _d @ T _c =25°C (A)	R _{ds(on)} @ T _j =25°C (Ω)	C _{iss} (pF) typ	Q _g (nC) typ	t _{rr} @ T _j = 25°C (ns)	R _{(th)JC} (°C/W)	P _d (W)	Package
IXTA32P05T	-50	-32	0.036	1975	46	26	1.5	83	TO-263
IXTP32P05T	-50	-32	0.036	1975	46	26	1.5	83	TO-220
IXTA140P05T	-50	-140	0.008	13500	200	53	0.42	298	TO-263
IXTP140P05T	-50	-140	0.008	13500	200	53	0.42	298	TO-220
IXTH140P05T	-50	-140	0.008	13500	200	53	0.42	298	TO-247
IXTA28P065T	-65	-28	0.045	2030	46	31	1.5	83	TO-263
IXTP28P065T	-65	-28	0.045	2030	46	31	1.5	83	TO-220
IXTA120P065T	-65	-120	0.01	13200	185	53	0.42	298	TO-263
IXTP120P065T	-65	-120	0.01	13200	185	53	0.42	298	TO-220
IXTH120P065T	-65	-120	0.01	13200	185	53	0.42	298	TO-247
IXTA24P085T	-85	-24	0.065	2090	41	40	1.5	83	TO-263
IXTP24P085T	-85	-24	0.065	2090	41	40	1.5	83	TO-220
IXTA96P085T	-85	-96	0.013	13100	180	55	0.42	298	TO-263
IXTP96P085T	-85	-96	0.013	13100	180	55	0.42	298	TO-220
IXTH96P085T	-85	-96	0.013	13100	180	55	0.42	298	TO-247
IXTA18P10T	-100	-18	0.12	2100	39	62	1.5	83	TO-263
IXTP18P10T	-100	-18	0.12	2100	39	62	1.5	83	TO-220
IXTA76P10T	-100	-76	0.024	13700	197	70	0.42	298	TO-263
IXTP76P10T	-100	-76	0.024	13700	197	70	0.42	298	TO-220
IXTH76P10T	-100	-76	0.024	13700	197	70	0.42	298	TO-247
IXTA44P15T	-150	-44	0.065	13400	175	140	0.42	298	TO-263
IXTP44P15T	-150	-44	0.065	13400	175	140	0.42	298	TO-220
IXTH44P15T	-150	-44	0.065	13400	175	140	0.42	298	TO-247
IXTQ44P15T	-150	-44	0.065	13400	175	140	0.42	298	TO-3P