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SHOOT-THROUGH PROTECTION CIRCUIT

Abstract

A circuit comprising: first and second transistors connected in series; a third transistor (TT) comprising a source connected to a source of the second transistor (ST), a gate connected to a gate of ST, and a drain connected to a gate of the first transistor (FT); and a gate driver circuit connected to the gates of FT, ST and TT and configured to provide (i) a first drive signal to the gate of FT to cause FT to transition between an on state and an off state and (ii) a second drive signal to the gates of ST and TT to cause ST and TT to transition between on states and off states. The TT is configured to prevent a shoot-through condition in the circuit by pulling the first drive signal down to a level of the source of the ST when the ST is in the on state.

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Background/Summary

BACKGROUND

Description of the Related Art

[0001] Electrical circuits, such as those used in satellites and spacecraft, include many different power requirements. Converting from direct current (DC) to alternating current (AC) and DC to DC involves bridge circuits which utilize two pairs of serially arranged transistors alternately switched to provide proper power conversion. Each serially arranged transistor pair includes an upper switch and a lower switch. Shoot-through or short circuit in the circuit occurs when both upper and lower switches turn on simultaneously. This could happen, for example in space applications, as a result of high energy particles hitting drive circuit components. The duration of such condition could reach 10 μ s resulting in overheating and failure of the affected switches.

SUMMARY

[0002] This document concerns a circuit comprising: first and second transistors connected in series; a third transistor comprising a source connected to a source of the second transistor, a gate connected to a gate of the second transistor, and a drain connected to a gate of the first transistor; and a gate driver circuit connected to the gates of the first, second and third transistors and configured to provide (i) a first drive signal to the gate of the first transistor to cause the first transistor to transition between an on state and an off state and (ii) a second drive signal to the gates of the second and third transistors to cause the second and third transistors to transition between on states and off states. The third transistor is configured to prevent a shoot-through condition in the circuit by pulling the first drive signal down to a level of the source of the second transistor when the second transistor is in the on state.

[0003] This document concerns implementing systems and methods for operating a circuit. The methods comprise: providing, by a gate driver circuit, a first high drive signal to a gate of a first transistor and a first low drive signal to a gate of a second transistor and a gate of a third transistor that is connected in series with the first transistor (whereby the first transistor is transitioned to an on state and the second and third transistors are transitioned to off states); providing a second high drive signal from the gate driver circuit concurrently to the gates of the second and third transistors to cause the second and third transistors to transition from the off states to on states while the first transistor is still in the on state; and using the second transistor to prevent a shoot-through condition by pulling down a voltage of the first high drive signal being output from the gate driver circuit to a level that causes the first transistor to transition from the on state to an off state while the third transistor is in the on state.

[0004] This document further concerns a circuit, comprising: first and second transistors of a P-channel type connected in series; a third transistor comprising a source connected to a source of the second transistor, a gate connected to a gate of the second transistor, and a drain connected to a gate of the first transistor; and gate driver circuits connected to the gates of the first, second and third transistors and configured to provide (i) a first drive signal to the gate of the first transistor to cause the first transistor to transition between an on state and an off state and (ii) a second drive signal to the gates of the second and third transistors to cause the second and third transistors to transition between on states and off states. The third transistor is also a P-channel type that is configured to prevent a shoot-through condition in the circuit by pulling the first drive signal up to a level of the source of the second transistor when the second transistor is in the on state.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

[0005] This disclosure is facilitated by reference to the following drawing figures, in which like numerals represent like items throughout the figures.

[0006] FIG. 1 provides an illustration of a satellite.

[0007] FIG. 2 provides a diagram of a transistor active bridge circuit.

[0008] FIG. 3 provides a diagram of a pair of series transistors.

[0009] FIGS. 4-5 and 8 each provides a diagram of the pair of series transistors shown in FIG. 3 with shoot-through protection.

[0010] FIG. 6 provides a diagram of a bridge converter implementing the present solution.

[0011] FIG. 7 provides a flow diagram of a method for operating a circuit.

DETAILED DESCRIPTION

[0012] It will be readily understood that the solution described herein and illustrated in the appended figures could involve a wide variety of different configurations. Thus, the following more detailed description, as represented in the figures, is not intended to limit the scope of the present disclosure but is merely representative of certain implementations in different scenarios. While the various aspects are presented in the drawings, the drawings are not necessarily drawn to scale unless specifically indicated.

[0013] The present solution may be embodied in other specific forms without departing from its spirit or essential characteristics. The described embodiments are to be considered in all respects only as illustrative and not restrictive. The scope of the present solution is, therefore, indicated by the appended claims rather than by this detailed description. All changes which come within the meaning and range of equivalency of the claims are to be embraced within their scope.

[0014] Reference throughout this specification to features, advantages, or similar language does not imply that all the features and advantages that may be realized should be or are in any single embodiment of the invention. Rather, language referring to the features and advantages is understood to mean that a specific feature, advantage, or characteristic described in connection with an embodiment is included in at least one embodiment of the present invention. Thus, discussions of the features and advantages, and similar language, throughout the specification may, but do not necessarily, refer to the same embodiment.

[0015] Reference throughout this specification to “one embodiment”, “an embodiment”, or similar language means that a particular feature, structure, or characteristic described in connection with the indicated embodiment is included in at least one embodiment of the present solution. Thus, the phrases “in one embodiment”, “in an embodiment”, and similar language throughout this specification may, but do not necessarily, all refer to the same embodiment.

[0016] As used in this document, the singular form “a”, “an”, and “the” include plural references unless the context clearly dictates otherwise. Unless defined otherwise, all technical and scientific terms used herein have the same meanings as commonly understood by one of ordinary skill in the art. As used in this document, the term “comprising” means “including, but not limited to”.

[0017] In this document, when terms such as “first” and “second” are used to modify a noun, such use is simply intended to distinguish one item from another, and is not intended to require a sequential order unless specifically stated.

[0018] As noted above, shoot-through or short circuit in a bridge converter occurs when both upper and lower switches turn on simultaneously. This could happen, for example in space applications, as a result of high energy particles hitting drive circuit components. Noise and other events could additionally or alternatively cause the shoot-through condition. The duration of such shoot-through condition could reach 10 μ s resulting in overheating and failure of the affected switches. Shoot-through protection is usually based on a very fast acting current sense circuit. The current sense circuit is often connected in series with the transistors of the bridge converter below the lower transistor. The current sense circuit is specifically designed to be insensitive to the normal currents so that it detects only relatively high currents that exceed threshold(s). The current sense circuit increases complexity, mass and cost of the bridge converter.

[0019] The present solution provides a novel shoot-through protection circuit that addresses the drawbacks of the conventional current sense solutions. The present solution can be used in various applications. Such applications include, but are not limited to, transistor active bridge applications,

transistor bridge converter applications, transistor switching circuit applications, and/or any other application shoot-through protection is needed. The present solution can be used in transistor circuits designed for terrestrial applications, aerial applications and/or space applications.

[0020] FIG. 1 provides an illustration of a satellite **100** implementing the present solution. Satellite **100** comprises a power source **102** providing power to a load **104** through a power distribution circuit **106**. The load **104** can include, but is not limited to, an electric propulsion unit. Transistor active bridge circuit(s) is (are) employed in the power distribution circuit **106** to condition and distribute power from the power sources **102** to the load **104**. The power distribution circuit **106** can experience damage when a shoot-through overcurrent condition occurs in the transistor active bridge circuit(s). The present solution can be added to the transistor active bridge circuit for protecting the power distribution circuit **106**. The present solution will now be discussed in detail below. However, an illustrative architecture for a transistor active bridge circuit will first be briefly discussed.

[0021] FIG. 2 provides a diagram for the illustrative architecture of a transistor active bridge circuit **200**. The transistor active bridge circuit **200** is useful for a variety of purposes, including AC-to-DC conversion or DC-to-DC conversion. As may be observed in FIG. 2, the transistor active bridge circuit **200** is supplied a voltage waveform. The voltage waveform can be an AC voltage waveform or a DC voltage waveform. As such, the transistor active bridge circuit **200** is connectable to at least one voltage source **202** via two (2) input lines **204**, **206**. The transistor active bridge circuit **200** is also connected between a pair of output lines **264**, **266**. The output lines **264**, **266** can be connected across a load (e.g., load **104** of FIG. 1) so that the load can be supplied an output voltage by the transistor active bridge circuit **200**.

[0022] The transistor active bridge circuit **200** includes a plurality of field-effect transistors (FETs) **208**, **210**, **212**, **214** of an N-channel type (as shown in FIG. 2) or a P-channel type (as shown in FIG. 8). Each of the FETs may comprise a metal-oxide semiconductor FET (MOSFET). The MOSFET may be an enhancement mode MOSFET. Each FET **208**, **210**, **212**, **214** can include, but is not limited to, a gallium nitride FET. In some scenarios, each FET **208**, **210**, **212**, **214** is selected to comprise a transistor having a part number EPC7020 available from EPC Space LLC of Andover, Massachusetts. Other FETs can also be selected depending upon the anticipated voltage and current handling requirements of the transistor active bridge circuit **200**. A similar shoot through protection (both for N-channel and P-channel) can be achieved with Bi-polar Junction Transistors (BJT) (both NPN and PNP) and an insulated-gate bipolar transistor (IGBT) for the third switch (an FET rather than IGBT may be used in that case).

[0023] Each FET **208**, **210**, **212**, **214** has three (3) terminals respectively defined as a source, a gate and a drain. With regard to FET **208**, the source, gate and drain terminals are respectively identified with reference numbers **216**, **218** and **220**. With regard to FET **210**, the source, gate and drain terminals are respectively identified with reference numbers **222**, **224** and **226**. The source, gate and drain terminals of the FETs **212** and **214** are respectively identified as **228**, **230**, **232** and **234**, **236**, **238**.

[0024] An electrical path is provided from the source to the drain of each FET **208**, **210**, **212**, **214**. This path is generally referred to herein as the source-drain path. A source-drain path of first FET **208** is connected in series with a source-drain path of the second FET **210**. The series connected transistor pair **208**, **210** form a first series transistor combination that is connected across the input lines **204**, **206**. A source-drain path of the third FET **212** is connected in series with a source-drain path of the fourth FET **214** to form a second series transistor combination connected across the input lines **204**, **206**.

[0025] The transistor active bridge circuit **200** can have an output defined by output lines **264**, **266**. A first one of the output lines **264** can be connected to the first series combination **208**, **210** at an interconnection point **254** between the first and the second field-effect transistors **208**, **210**. A second one of the output lines **266** can be connected to the second series combination **212**, **214** at

an interconnection point **256** between the third and fourth field-effect transistors **212, 214**.

[0026] A gate driver circuit **270, 272, 274, 276** is provided for each FET **208, 210, 212, 214**. Each gate driver circuit **270, 272, 274, 276** is generally configured to supply a voltage to the gate **218, 224, 230, 236** of a respective FET **208, 210, 212, 214** at certain times for switching the FET to its “on” state or “off” state. The voltage applied to the gate **218, 224, 230, 236** of a respective FET **208, 210, 212, 214** has an “on state” or “off state” voltage value selected in accordance with a particular field-effect transistor application. Each gate driver circuit **270, 272, 274, 276** is also generally configured to stop supplying the voltage to the gate **218, 224, 230, 234** of a respective FET **208, 210, 212, 214** at certain times for switching the FET to its “on” state or “off” state. Gate driver circuits are well known. Known or to be known gate driver circuit can be used here.

[0027] The transistor active bridge circuit **200** further include devices for ensuring that each of the FETs **202, 204, 206, 208** is switched to its “on” states and/or “off” states at desirable times.

[0028] The operation of the transistor active bridge circuit **200** will now be described. In some scenarios, one FET is switched to its “on” state while the other three FETs are in their “off” states. In other scenarios, two FETs (one in each series pair of transistors) are concurrently or simultaneously switched to their “on” states while the other two FETs are in their “off” states. The latter case will be discussed in more detail below.

[0029] When the gate driver circuits **270, 276** communicate a gate control signal to the FETs **208, 214**, the FETs **208, 214** will be biased and switch to their “on” states. In effect, current will flow between the drain **220, 238** and source **216, 234** of these FETs **208, 214**. The FETs **208, 214** transition back to their “off” states when the gate control signal is no longer being output from the gate driver circuits **270, 276**.

[0030] Similarly, the gate driver circuits **272, 274** communicate a gate control signal to the FETs **210, 212**, the FETs **210, 212** will be biased and switched to their “on” states. In effect, current will flow between the drain **226, 232** and source **222, 228** of these FETs **208, 214**. The FETs **210, 212** transition back to their “off” states when the gate control signal is no longer being output from the gate driver circuits **272, 274**.

[0031] The gate driver circuits **270, 272, 274, 276** are configured to prevent the two FETs in each series pair **208/210** and **212/214** from being turned “on” simultaneously or concurrently. The FETs **208, 210, 212, 214** are switched alternatively by the gate driver circuits **270, 272, 274, 276** to provide a certain power output across output lines **264, 266**.

[0032] However, for example as a result of high energy particles hitting the gate driver circuits, both FETs in one or more pairs may be turned “on” simultaneously or concurrently. In this case, a shoot-through condition occurs in the transistor active bridge circuit **200**. The duration of such condition may result in overheating or failure of the affected FETs.

[0033] The present solution addresses this shoot-through issue by adding an additional switch to each pair of FETs. The present solution will be discussed below in relation to a single pair of the FETs. This discussion is sufficient for understanding the present solution in relation to both pairs of FETs in the transistor active bridge circuit **200**.

[0034] A pair of FETs **300** is shown in FIG. **3** as comprising FETs **208** and **210** of FIG. **2**. The present solution is not limited in this regard. The pair of FETs could alternatively comprise FETs **212, 214** of FIG. **2** or other types of FETs. The present solution will be described below in relation to the pair of FETs **300**. This description is sufficient for understanding the present solution in relation to FETs **212, 214** of FIG. **2** or other types of FETs.

[0035] FIG. **4** provides an illustration of a circuit **400** comprising shoot-through protection for the pair of FETs **300**. The shoot-through protection is provided by the inclusion of a transistor **402** that is configured to prevent a voltage at gate **218** of the upper switch **208** from being positive with respect to the source **216** of the upper switch **208** when gate **224** of the lower switch **210** is positive with respect to the source **222** of the lower switch **210**.

[0036] Transistor **402** includes a FET of an N-channel type (as shown in FIG. **4**) or a P-channel

type (as shown in FIG. 8). FET **402** may comprise a MOSFET. The MOSFET may be an enhancement mode MOSFET. FET **402** can include, but is not limited to, a gallium nitride FET. FET **402** has three (3) terminals respectively defined as a source, a gate and a drain. With regard to FET **402**, the source, gate and drain terminals are respectively identified with reference numbers **404**, **406** and **408**. Source **404** is connected to the source **222** of FET **210**. Gate **406** is connected to the drive line **282** extending from an output of the gate driver circuit **272** and the gate of lower FET **210** of the pair **400**. Drain **408** is connected to the drive line **280** extending from an output of the gate driver circuit **270** and the gate **218** of the upper FET **208** of the pair **400**. Optional resistors **410**, **412** may be provided between the drain **408** of FET **402** and the gate **218** of FET **208** to limit or regulate the flow of current.

[0037] During operation, a high drive signal is provided from the gate driver circuit **270** to the gate **218** of upper FET **208** in the series pair and a low drive signal is provided from the gate driver circuit **272** to the gate **224** of the lower FET **210** in the series pair. Accordingly, the upper FET **208** is in an “on” state while the lower FET **210** is in an “off” state. It should be noted that the low drive signal is also provided from the gate driver circuit **272** to the gate **406** of the shoot-through protection FET **402**. As such, the shoot-through protection FET **402** is in the “off” state while the upper FET **208** is in the “on” state and the lower FET **210** is in the “off” state.

[0038] If an event occurs (e.g., noise or a high radiation event) that causes the gate driver circuit **272** to provide a high drive signal to the gate **224** of the lower FET **210**, then FET **210** transitions from the “off” state to the “on” state whereby a shoot-through condition occurs since both series FETs **208**, **210** are in the “on” state at the same time.

[0039] Notably, the high drive signal is also provided from the gate driver circuit **272** to the gate **406** of the shoot-through protection FET **402**. Responsive to the high drive signal, the shoot-through protection FET **402** transitions to the “on” state. At this time, the shoot-through protection FET **402** pulls down the drive signal being supplied to the gate **218** of the upper FET **208**. In effect, a low drive signal is now provided to the gate **218** of the upper FET **208** despite the gate driver circuit **270** still being configured to continue output of a high drive signal on drive line **280**. The low drive signal at gate **218** causes the upper FET **208** to transition to the “off” state while the lower FET **210** remains in the “on” state. This prevents any potential damage to the upper and lower FETs **208**, **210** by actively removing, discontinuing or preventing the shoot-through condition.

[0040] In another scenario, a high drive signal is provided from the gate driver circuit **272** to the gate **224** of the lower FET **210** and a low drive signal is provided from the gate driver circuit **270** to the gate **218** of the upper FET **208**. At this time, the lower FET **210** is in the “on” state while the upper FET **208** is in the “off” state. Notably, the high drive signal is also being provided from the gate driver circuit **272** to the gate **406** of the shoot-through protection FET **402**. The shoot-through protection FET **402** is in the “on” state thereby preventing a high drive signal from being provided at the gate **218** of the upper FET **208**. Stated differently, the shoot-through protection FET **402** prevents the upper FET **208** from being turned “on” while the lower FET **210** is in the “on” state.

[0041] As evident from the above discussion, the shoot-through protection FET **402** guarantees that a low drive signal is always provided to the gate **218** of the upper FET **208** whenever the lower FET **210** is in the “on” state. This is achieved by pulling the gate **218** of the upper FET **208** down to a level of the source **222** of the lower FET **210** whenever the lower FET **210** is in the “on” state. This feature of the shoot-through protection FET **402** reduces or eliminate the probability that the series FETs **208**, **210** will be damaged during operation of the circuit **400**.

[0042] FIG. 5 provides an illustration of a circuit **500** comprising shoot-through protection for the pair of FETs **300**. The shoot-through protection is provided by the inclusion of a transistor **402** that is configured to prevent a voltage at gate **218** of the upper switch **208** from being positive with respect to the source **216** of the upper switch **208** when gate **224** of the lower switch **210** is positive with respect to the source **222** of the lower switch **210**. Circuit **500** is similar to circuit **400** except

for the inclusion of an additional optional diode **502**. Diode **502** may include, but is not limited to, a Schottky diode. Diode **502** is provided to limit the negative voltage at the gate **218** of the upper FET **208** with respect to the source **216** of the upper FET **208**.

[0043] Diode **502** may be provided based on the relative speed of “on/off” state transitions by the FETs **208**, **210**, **402**. For example, if FET **402** is relatively fast and transistors **208**, **210** are relatively slow, then it may cause an undesirable condition in which the gate **218** of the upper FET **208** is pulled low but the source **216** is still high. The diode **502** prevents such an undesirable condition by ensuring that the gate **218** and source **216** are concurrently pulled low by the transistor **402**.

[0044] FIG. **6** provides an illustration of a bridge converter **600** implementing the present solution. The bridge converter **600** comprises a transistor active bridge circuit electrically coupled to a transformer **602** having a primary winding **604** connected to the output lines **264**, **266** thereof. The transistor active bridge circuit may comprise transistor active bridge circuit **200** of FIG. **2** which has been modified to comprise the shoot through protection circuits of FIG. **4** and/or FIG. **5**. In this regard, each branch **620**, **622** of the transistor active bridge circuit comprises a pair of series transistors **208/210** or **212/214** and at least a shoot-through protection transistor **402**. Thus, branch **620** includes circuit **400** of FIG. **4** or circuit **500** of FIG. **5**. Branch **622** includes either (i) circuit **400'** which is similar to or the same as circuit **400** except for the replacement of series transistors **208**, **210** with series transistors **212**, **214** or (ii) circuit **500'** which is similar to or the same as circuit **500** except for the replacement of series transistors **208**, **210** with series transistors **212**, **214**.

[0045] During operation, the two series pairs of FETs **208/210**, **212/214** are used to drive the transformer's primary winding **604** symmetrically. FET **208** and FET **214** conduct in a first switching period and the other FETs **210**, **212** conduct during the next switching period. As one set of FETs (e.g., FETs **208**, **214**) conducts, the other set of FETs (e.g., FETs **210**, **212**) remains in the “off” state. The output voltage $V_s(t)$ is determined by the transistor duty cycle, the transformer's turn ratio, and the input voltage V_g .

[0046] FIG. **7** provides a flow diagram of an illustrative method **700** for operating a circuit. Method **700** begins with **702** and continues with **704** where a first high drive signal is provided from a first gate driver circuit (e.g., gate driver circuit **270** or **274** of FIG. **2**) to a gate (e.g., gate **218** or **230** of FIG. **2**) of a first transistor (e.g., transistor **208** or **212** of FIG. **2**). A first low drive signal is provided from a second gate driver circuit (e.g., gate driver circuit **272** or **276** of FIG. **2**) to a gate (e.g., gate **406** of FIGS. **4-5**) of a third transistor and a gate of a second transistor (e.g., gate **224** or **236** of FIG. **2**), as shown by block **706**. The first and second gate driver circuits may comprise sub-circuits of a gate driver circuit. The second transistor is connected in series with the first transistor across first and second input lines (e.g., input lines **204**, **206** of FIG. **2**). The first transistor is transitioned to its on state in block **704** and the second and third transistors are transitioned to their off states in block **706**. The operations of blocks **704**, **706** may occur simultaneously or concurrently rather than serially as shown in FIG. **7**. The first, second and/or third transistors may include, but are not limited to, gallium nitride field effect transistors.

[0047] In next block **708**, a second high drive signal is provided from a second gate driver circuit (e.g., gate driver circuit **272** or **276** of FIG. **2**) concurrently to the gates (e.g., gate **406** of FIG. **4** and gate **224** or **236** of FIG. **2**) of the second and third transistors (e.g., transistor **402** of FIG. **4** and transistor **210** or **214** of FIG. **2**). The second high drive signal may be provided from the second driver circuit responsive to a radiation or noise event in a surrounding environment. The second high drive signal causes the second and third transistors to transition from the off states to on states while the first transistor is still in the on state.

[0048] In blocks **710**, the third transistor is used to prevent a shoot-through condition. The third transistor operates to pull down a voltage of the first high drive signal being output from the first gate driver circuit to a level that causes the first transistor to transition from the on state to an off state while the second transistor is in the on state. The third transistor also operates in **712** to

prevent the first transistor from transitioning to the on state while the second transistor is in the on state.

[0049] In block **714**, a diode (e.g., diode **502** of FIG. 5) is optionally used to limit a negative voltage at the gate of the first transistor with respect to a source of the first transistor while the third transistor is being used to prevent the shoot-through condition. The diode may be selectively provided in the circuit based on relative state transition speeds of the first, second and third transistors.

[0050] In block **716**, the first and second gate driver circuits are operated to cause the second and third transistors to turn off. Thereafter, the first and second gate driver circuits may be operated in block **718** to cause the second transistor to transition to the on state while the first transistor is in the off state. The third transistor is used in **720** to prevent the first transistor from being transitioned from the off state to the on state, for example, when a radiation or noise event occurs in a surrounding environment which impacts operation of the first gate driver circuit. Subsequently, method **700** continues to block **722** where it ends or other operations are performed (e.g., return to block **702**).

[0051] In view of the forgoing, the present document concerns a circuit (e.g., circuit **400** of FIG. 4, **500** of FIG. 5 and/or **600** of FIG. 6) comprising: first and second transistors (e.g., transistors **208**, **210** or **212**, **214**) connected in series across first and second input lines (e.g., input lines **204**, **206**) of the circuit; a third transistor (e.g., transistor **402**) comprising a source (e.g., source **404**) connected to a source (e.g., source **222** or **236**) of the second transistor, a gate (e.g., gate **406**) connected to a gate (e.g., gate **224** or **234**) of the second transistor, and a drain (e.g., drain **408**) connected to a gate (e.g., gate **218** or **230**) of the first transistor; and a gate driver circuit (e.g., circuit **270/272** or **274/276**) connected to the gates of the first, second and third transistors and configured to provide (i) a first drive signal to the gate of the first transistor to cause the first transistor to transition between an on state and an off state and (ii) a second drive signal to the gates of the second and third transistors to cause the second and third transistors to transition between on states and off states. The third transistor is configured to prevent a shoot-through condition in the circuit by pulling the first drive signal down to a level of the source of the second transistor when the second transistor is in the on state. The third transistor is also configured to prevent the first transistor from transitioning from the off state to the on state while the third transistor is in the on state.

[0052] In some scenarios, the first transistor is in the on state when the first gate drive signal has a first voltage value and the second and third transistors are in the off states when the second gate drive signal has a second voltage value lower than the first voltage value. The gate drive circuit may be caused, by a radiation event occurring in a surrounding environment, to increase the second voltage value of the second gate drive signal. The third transistor prevents the shoot-through condition when the second gate drive signal has the increased second voltage value.

[0053] The circuit may further comprise a diode (e.g., diode **502**) configured to limit a negative voltage at the gate of the first transistor with respect to a source of the second transistor while the third transistor is being used to prevent the shoot-through condition. The diode may be selectively provided in the circuit based on relative state transition speeds of the first, second and third transistors.

[0054] In those or other scenarios, the gate driver circuits is operable to cause the third transistor to be in the on state while the first transistor is in the off state. The third transistor is configured to prevent the first transistor from being transitioned from the off state to the on state when a radiation event occurs in a surrounding environment which impacts operation of the gate driver circuit.

[0055] In those or other scenarios, the first, second and third transistors are bipolar junction transistors with emitters replacing sources, collectors replacing drains, and bases replacing gates. Alternatively, the first and second transistors are insulated-gate bipolar transistors with emitters replacing sources, collectors replacing drains, and the third transistor comprise a field effect

transistor.

[0056] This document also concerns a method for operating a circuit. The method comprises: providing a first high drive signal from a first gate driver circuit to a gate of a first transistor and a first low drive signal from a second gate driver circuit to a gate of a second transistor and a gate of a third transistor that is connected in series with the first transistor across first and second input lines, whereby the first transistor is transitioned to an on state and the second and third transistors are transitioned to off states; providing a second high drive signal from the second gate driver circuit concurrently to the gates of the second and third transistors to cause the second and third transistors to transition from the off states to on states while the first transistor is still in the on state; and using the second transistor to prevent a shoot-through condition by pulling down a voltage of the first high drive signal being output from the first gate driver circuit to a level that causes the first transistor to transition from the on state to an off state while the third transistor is in the on state. The second high drive signal may be provided from the second driver circuit responsive to a radiation event in a surrounding environment. The second transistor can include, but is not limited to, a gallium nitride field effect transistor. The method may also comprise preventing, by the second transistor, the first transistor from transitioning from the off state to the on state while the third transistor is in the on state.

[0057] The method may further comprise: selectively providing the diode in the circuit based on relative state transition speeds of the first, second and third transistors; and/or using the diode to limit a negative voltage at the gate of the first transistor with respect to a source of the third transistor while the second transistor is being used to prevent the shoot-through condition.

[0058] Additionally or alternatively, the method comprises: operating the first and second gate driver circuits to cause the third transistor to be in the on state while the first transistor is in the off state; and/or using the second transistor to prevent the first transistor from being transitioned from the off state to the on state when a radiation event occurs in a surrounding environment which impacts operation of the first gate driver circuit.

[0059] The present document also concerns a circuit, comprising: first and second transistors of a P-channel type connected in series; a third transistor comprising a source connected to a source of the second transistor, a gate connected to a gate of the second transistor, and a drain connected to a gate of the first transistor; and gate driver circuits connected to the gates of the first, second and third transistors and configured to provide (i) a first drive signal to the gate of the first transistor to cause the first transistor to transition between an on state and an off state and (ii) a second drive signal to the gates of the second and third transistors to cause the second and third transistors to transition between on states and off states. The third transistor also a P-channel type is configured to prevent a shoot-through condition in the circuit by pulling the first drive signal up to a level of the source of the second transistor when the second transistor is in the on state. In some scenarios, the first, second and third transistors may be bipolar junction transistors with emitters replacing sources, collectors replacing drains, and base replacing gates.

[0060] The described features, advantages and characteristics disclosed herein may be combined in any suitable manner. One skilled in the relevant art will recognize, in light of the description herein, that the disclosed systems and/or methods can be practiced without one or more of the specific features. In other instances, additional features and advantages may be recognized in certain scenarios that may not be present in all instances.

[0061] Although the systems and methods have been illustrated and described with respect to one or more implementations, equivalent alterations and modifications will occur to others skilled in the art upon the reading and understanding of this specification and the annexed drawings. In addition, while a particular feature may have been disclosed with respect to only one of several implementations, such feature may be combined with one or more other features of the other implementations as may be desired and advantageous for any given or particular application. Thus, the breadth and scope of the disclosure herein should not be limited by any of the above

descriptions. Rather, the scope of the invention should be defined in accordance with the following claims and their equivalents.

Claims

1. A circuit, comprising: first and second transistors connected in series; a third transistor comprising a source connected to a source of the second transistor, a gate connected to a gate of the second transistor, and a drain connected to a gate of the first transistor; and gate driver circuits connected to the gates of the first, second and third transistors and configured to provide (i) a first drive signal to the gate of the first transistor to cause the first transistor to transition between an on state and an off state and (ii) a second drive signal to the gates of the second and third transistors to cause the second and third transistors to transition between on states and off states; wherein the third transistor is configured to prevent a shoot-through condition in the circuit by pulling the first drive signal down to a level of the source of the second transistor when the second transistor is in the on state; wherein the gate driver circuits are operable to cause the third transistor to be in the on state while the first transistor is in the off state; and wherein the third transistor is configured to prevent the first transistor from being transitioned from the off state to the on state when a radiation or noise event occurs in a surrounding environment which impacts operation of the gate driver circuits.
2. The circuit according to claim 1, wherein the first transistor is in the on state when the first gate drive signal has a first voltage value and the second and third transistors are in the off states when the second gate drive signal has a second voltage value lower than the first voltage value.
3. The circuit according to claim 2, wherein the gate drive circuits are caused, by a radiation event occurring in a surrounding environment, to increase the second voltage value of the second gate drive signal.
4. The circuit according to claim 3, wherein the third transistor prevents the shoot-through condition when the second gate drive signal has an increased second voltage value.
5. The circuit according to claim 1, wherein at least the third transistor comprises a gallium nitride field effect transistor.
6. The circuit according to claim 1, wherein the third transistor is further configured to prevent the first transistor from transitioning from the off state to the on state while the third transistor is in the on state.
7. (canceled)
8. A circuit, comprising: first and second transistors connected in series; a third transistor comprising a source connected to a source of the second transistor, a gate connected to a gate of the second transistor, and a drain connected to a gate of the first transistor; and gate driver circuits connected to the gates of the first, second and third transistors and configured to provide (i) a first drive signal to the gate of the first transistor to cause the first transistor to transition between an on state and an off state and (ii) a second drive signal to the gates of the second and third transistors to cause the second and third transistors to transition between on states and off states; wherein the third transistor is configured to prevent a shoot-through condition in the circuit by pulling the first drive signal down to a level of the source of the second transistor when the second transistor is in the on state; a diode configured to limit a negative voltage at the gate of the first transistor with respect to a source of the second transistor while the third transistor is being used to prevent the shoot-through condition; wherein the diode is selectively provided in the circuit based on relative state transition speeds of the first, second and third transistors.
9. (canceled)
10. (canceled)
11. A method for operating a circuit, comprising: providing, by a gate driver circuit, a first high drive signal to a gate of a first transistor and a first low drive signal to a gate of a third transistor

and a gate of a second transistor that is connected in series with the first transistor, whereby the first transistor is transitioned to an on state and the second and third transistors are transitioned to off states; providing a second high drive signal from the gate driver circuit concurrently to the gates of the second and third transistors to cause the second and third transistors to transition from the off states to on states while the first transistor is still in the on state; and using the third transistor to prevent a shoot-through condition by pulling down a voltage of the first high drive signal being output from the gate driver circuit to a level that causes the first transistor to transition from the on state to an off state while the second and third transistor is in the on state; wherein the second high drive signal is provided from the gate driver circuit responsive to a radiation or noise event in a surrounding environment.

12. (canceled)

13. The method according to claim 11, wherein the second transistor comprises a gallium nitride field effect transistor.

14. The method according to claim 11, further comprising preventing, by the third transistor, the first transistor from transitioning from the off state to the on state while the second transistor is in the on state.

15. The method according to claim 11, further comprising using a diode to limit a negative voltage at the gate of the first transistor with respect to a source of the second transistor while the third transistor is being used to prevent the shoot-through condition.

16. The method according to claim 15, further comprising selectively providing the diode in the circuit based on relative state transition speeds of the first, second and third transistors.

17. The method according to claim 11, further comprising operating the gate driver circuit to cause the third transistor to be in the on state while the first transistor is in the off state.

18. The method according to claim 17, further comprising using the second transistor to prevent the first transistor from being transitioned from the off state to the on state when a radiation event occurs in a surrounding environment which impacts operation of the gate driver circuit.

19. A circuit, comprising: first and second transistors of a P-channel type connected in series; a third transistor comprising a source connected to a source of the second transistor, a gate connected to a gate of the second transistor, and a drain connected to a gate of the first transistor; and gate driver circuits connected to the gates of the first, second and third transistors and configured to provide (i) a first drive signal to the gate of the first transistor to cause the first transistor to transition between an on state and an off state and (ii) a second drive signal to the gates of the second and third transistors to cause the second and third transistors to transition between on states and off states; wherein the third transistor also a P-channel type is configured to prevent a shoot-through condition in the circuit by pulling the first drive signal up to a level of the source of the second transistor when the second transistor is in the on state; wherein the gate driver circuits are operable to cause the third transistor to be in the on state while the first transistor is in the off state; wherein the third transistor is further configured to prevent the first transistor from being transitioned from the off state to the on state when a radiation or noise event occurs in a surrounding environment which impacts operations of the gate driver circuits.

20. The circuit according to claim 1, where the first, second and third transistors are bipolar junction transistors with emitters replacing sources, collectors replacing drains, and bases replacing gates.

21. The circuit according to claim 19, where the first, second and third transistors are bipolar junction transistors with emitters replacing sources, collectors replacing drains, and base replacing gates.

22. The circuit according to claim 1, where the first and second transistors are insulated-gate bipolar transistors with emitters replacing sources, collectors replacing drains, and the third transistor comprises a field effect transistor.
