Current Protection

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***Abstract*—This paper defines different variations of current protection, and their usefulness. The main purpose is to eliminate current protectors that use large amounts of power, and to simplify the circuit to aid in the robotic hand's functionality without damage to the system.**

Keywords-LtSpice; current protection; voltage protection; DC motor; diode; npn transistor; pnp transistor; kick-back current

I. Introduction

Currently there are more than 2 million Americans that have lost a limb. This is going over 185,000 people a year [1]. With this rapid grow in people with a need of a prosthetic Idaho State University is working researching technologies that will help reduce the cost of robotic hand.

The robotic hand is similar to the normal human hand in that it has four working fingers and a thumb. Each of the four fingers and thumb has motors attached to them. This provides the movability that is needed for a hand to function normally. The embedded system that is being used is Arduino microcontroller. The robotic hand and embedded processor is connected to a bread board which has various components on it; this also will be simplified after its initial prototype phase.

The components that are currently connected onto the board have simple surge protection but a more robust protection will be need for the final design. Like most DC motors there is an H-bridge attached to each of the motors for the system, however this protection is limited in most servo motors packaging. In most DC motors there is some kick-back current that occurs, which is where the H-bridge provides protection. It is possible to have enough back electromotive force (emf) destroy the H-bridge as well as some addition components which were attached to the DC motor. There are many different ways to protect a circuit from overvoltage and overcurrent, but this paper address a new design that will provide back emf protection with lower power consumptions than typical protection circuits. This design will be used to protect the microcontroller, various components on the hand, and possibly the wearer of the final design.

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II. Background and History

There have been many designs and projects that have required protected from overvoltage and overcurrent. Many of the protections are very simple such as a fuse. A fuse can be placed into a circuit to protect it from over current. In the case of a simple fuse there is a small wire inside of it of varying sizes (depending on the amperage that is needed for protection), and when too much current is being drawn it will simply break the wire that is inside of it. This causes an open circuit and all of the components will be saved. One of the down sides to use a fuse is that once it has been tripped it has to be replaced. Another design is a breaker, which is similar to a fuse in that it tripped when there is too much current being drawn. The advantage of a breaker over a fuse is that it doesn't need to be replaced. When the breaker is tripped all that needs to be done is to reset the breaker. The design for a breaker is a useful one, but when working on a smaller scale it isn't very useful since its design is intended for a system with large voltage and current. Also if a person doesn't know how to reset the breaker problem may occur.

A smaller protection setup that does not require users' involvement is a circuit a diode. A diode is a passive component the only allow current to flow in only one direction. If the current in the circuit attempts to flow in the opposite direction the current will be stopped, and the circuit will behave as if there is an open within it. The advantage in using a diode over a fuse or a breaker is that there is no need to replace or reset the device once it has been set off. One of the disadvantages of a diode is that it will absorb some is the voltage, so there will be addition losses in the system. There are many different types of diode that can have smaller losses than other diode, but there is always some loss found. In cases this might not be an issue but if the device is battery operated this is a problem.

A switch is a useful device that is used in circuit design. When the switch is positioned in the on state there is a connection with the circuit and current will begin to flow, and when the switch is positioned in the off state the current is stopped. The design of a switch has some advantages over a diode, but there is a need for an outside source to control the switch. For this problem designers came up with a transistor that uses semiconductor technology. A transistor is basically a switch that is self-activating, so there is no need for addition outside help as seen with the switch. When current starts to flow in a circuit the transistor will either turn on or off depending on the type to transistor that is placed into the circuit. In many transistors there is a built in diode that allows current to flow and thereby activating the transistor to turn on or off. By placing a transistor into the circuit current will flow in the direction that is desired and when the current attempt to flow in the opposite direction the transistor will shut off. There are two main types of transistors some are controlled by voltage like the MOFET (metal oxide semiconductor field effect transistor) and others are controlled by current like the BJT (bipolar junction transistor).

DC motors are small device that are being placed into the robotic hand, so that the robotic hand can have some functionality. From the microcontroller there is a signal that is sent to the DC motor so that it can begin the rotate. As long as the DC motor is being supplied with current it will continue to rotor, and when the current stops being supplied to the DC motor it will stop moving. After the DC motor has been supplied with current for a period of time and then stops it will still have some energy that is stored within it. This is where the kick-back current comes from, and sometimes there is a lot of kick-back current and other times there isn't as much. The current that is kicked-back has to go somewhere and many times it goes back and damages the components that are attached to it; in this case the embedded processor and other various components in the system.

When designing a circuit that has need for protection using the above mentioned components are a good way to start.

III. Background

The basic setup that is used in this paper consists of a voltage source and a load which is a DC motor in the system. The setup as it is now runs efficiently with no problems as long as there is no kick-back current from the DC motor, but when there is kick-back current it has the potential to damage the microcontroller and the other components that are connected to it. To prevent damage a fuse can be installed into the system, however when there is kick-back current the fuse would not open to prevent the current because of the short duration of the back emf. Also for a robotic hand to run efficiently there needs to be as little maintain as possible; this makes a fuse an inadequate choice.

The next option is to place a diode into the circuit's design. This will ensure that the current flows in the direction that is desired. There are some limitations with a diode being placed into the circuit's design. First off when calculating the voltage (V), current (I), and resistance (R) use the Ohm's Law:

$$V = I * R \tag{1}$$

An example of the equation would be a system that has a voltage of 10 volts and a resistor that is 1k ohms, using Equation (1) the current is found to be 0.01 amps. The example would be using ideal conditions; since the setup would be ideal with no losses it would be perfect. In order to model real world condition losses need to be included in the model's setup.

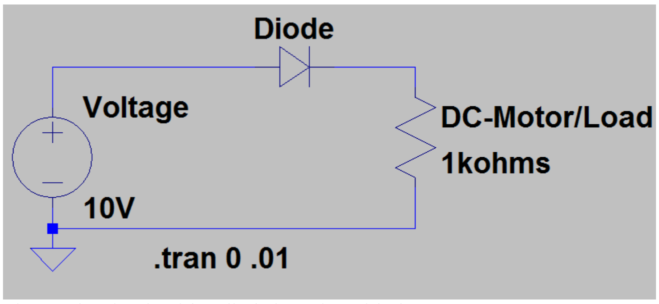

Fig. 1. The circuit with a diode in series with the DC motor.

The basic circuit displayed in Fig. 1 shows the setup circuit design with a diode in the circuit. The diode only allows current to flow in the desired direction, and stops the current from flowing in the wrong way by creating an open circuit. In an ideal condition the setup here would be the same as the previous example. However losses in the circuit need to be accounted for. The most common models for a diode are a 0.7 volts drop across the diode. To find the power lost (P_W) in the system across the diode multiple the voltage drop (V_D) across the diode by the current (I) as shown in the following equation:

$$P_W = V_D * I \tag{2}$$

When using the Equation (2) to find the power losses across diode and the numbers from the example the losses are calculated to be 0.007 watts. The losses may not seem to be a lot, but in the application that it is being designed for the power loss across the diode is too high. One of the solutions is to get a different type of diode, but each diode has a different forward voltage drop and there is a reverse leakage current that needs to be taken into account. In this application the objective is to protect and prevent all current from going back into the system. With the DC motor there are times when the kick-back current is high enough to leak through the diode and damage the microcontroller and the other various components used in the system. When this happens the diode is usually gets damaged to the point that it needs to be replaced, which goes against the objective of the circuit application that it is designed for.

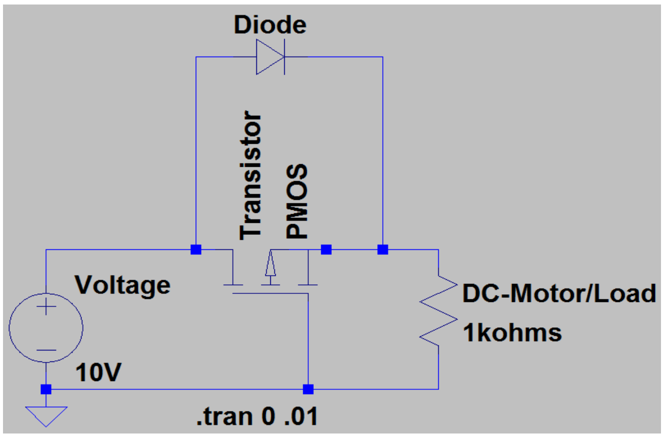

Fig. 2. The circuit with a diode in parallel with a PMOS Transistor which is connected to the DC motor.

In Fig. 2 it shows the circuit design with a transistor in it to control the current flow. Also in Fig. 2 it shows a diode in parallel with a transistor; the diode is in the transistor, so when implementing the circuit design the diode isn't needed since it is built into the transistor's design. The diode is in Fig. 2 because the model used in LtSpice needs to have it included for it to be simulated.

For this circuit's design in Fig. 2 a PMOS transistor is used; in it there is the gate voltage (V_G) which is the wire in the middle, the source voltage (V_S) which is the wire connecting on the left, and the drain voltage (V_D) which is the wire connection on the right. To find out if the PMOS transistor is turned on or off use the following equation:

$$(V_G - V_S) = V_{GS} \tag{3}$$

The average PMOS transistor will turn on at -4 volts or less at the V_{GS}. There are many different types of PMOS transistors with different features, however the one used in the example is at a -4 volts or less V_{GS} to turn on. When doing the calculations to see if the PMOS transistor will turn on, the drop across the diode needs to first be taken into account. When the PMOS transistor first turns on the diode that is inside of it activates, so that current can start to flow. If the diode wasn't in the PMOS transistor the circuit would never work, since the PMOS transistor would never be turned on. The diode inside the PMOS transistor only stays on for a small amount of time and once the PMOS transistor is on the diode turns off and there isn't a drop across it. The calculations for the PMOS transistor to be turned on need to take the voltage drop off the diode into account. In the example there is a 1 volt drop across the diode, which makes the V_S equal to 9 volts, and the V_G is equal to 0 volts because it is connected to the ground. Then using Equation (3) the V_{GS} becomes -9 volts, and since -9 volts is less than or equal to -4 volts the PMOS transistor will turn on. When the source voltage is turned off the V_S equal to 0 volts and the V_G is equal to 0 volts, and using Equation (3) the V_{GS} is greater than -4 volts so the PMOS transistor will be off.

In the PMOS transistor there is a resistance ($R_{DS(on)}$) value that is attached to it. The resistance value can change depending on the PMOS transistor used as well as the V_G and the temperature that it is at, and the desired resistance values is to be as low as possible. Just as seen in the previous section there is going to be some losses in the system and this is found using the following equation where power loss (P_W) is equal to current (I) square multiplied by the PMOS transistor's resistance ($R_{DS(on)}$):

$$P_W = I^2 * R_{DS(on)} \tag{4}$$

PMOS transistors have varying types of internal resistance, but for this example the internal resistance is 0.034 ohms. Using Equation (4) the power loss in the PMOS transistor is 3.4 microwatts. When comparing the losses from the previous example at 7 milliwatts to 3.4 microwatts it is about 2000 times better, this shows that there is a lot less energy being wasted. The design here is a very good one and it is one of the most commonly used designs. This design has very low power loss and using the PMOS transistor it is able to turn on and off without any outside assistance, but if there is a large enough kick-back current from the DC motor there is still the possibility that some or all of the components could be damaged. To solve this problem there need to be a path for the current to go.

IV. Proposed Design

Based on the previous designs a more robust circuit was desired to protect the embedded process from motors and other circuit failures. To accomplish this, this paper looks at developing another type of over current protection circuit. The current protections that are used current ensure that the current does not flow in the wrong direction. Though there are times when the back flow of current in great enough to damage the component that are used to protect the circuit, and in extreme cases the back flow of current can damage components that the protection part to the circuit's design was intended to protect.

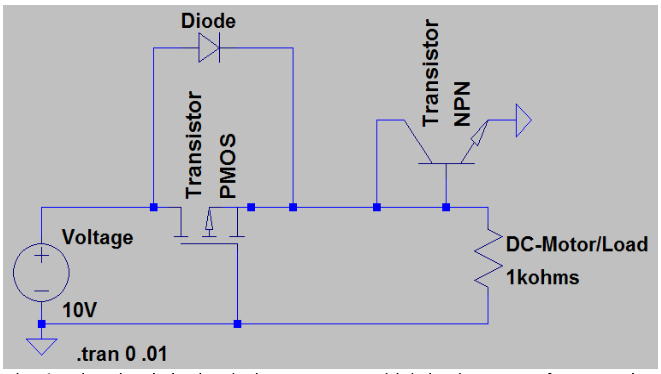

Fig. 3. The circuit is the design to prevent kick-back current from causing damage to any components.

In Fig. 3 it shows a circuit that is similar to the last one except that there is a BJT NPN transistor connected to it. The NPN BJT has the collector connected to the wire on the left, the base connected to the wire in the middle, and the emitter is connected to the ground which is on the right as shown in Fig. 3. The circuit functions in the same way as the circuit in the previous example, and the losses are similar as well. When the circuit is turned on the current will start to flow and activate the PMOS transistor turning it on. The current will then flow pass the NPN BJT without it affecting the circuit. When the voltage source is turned off after the DC motor has been running for a while the PMOS transistor will turn off preventing current from flowing back into the system. This is when the NPN BJT turns on, when there is any current that is being kicked-back the NPN BJT turns on. After the NPN BJT turns on the current flows from the collector to the emitter which is connected straight to ground. This allows there to be protection on the circuit in case of kick-back current. The current will flow in the direction that is desired and when the current is flowing in the wrong direction it will simply go straight to ground.

V. Experiment

After the accomplishment of the circuit design using simulation software an experiment was done to ensure that the circuit design would also work in hardware. The experiment was done at Idaho State University's Electrical Engineering Laboratory. A standard powered breadboard was used to place the circuits design onto along with the DC motor. The DC motor was just a simply motor similar to the one being used in the robotic hand. There was a PMOS transistor and a BJT NPN transistor used to complete the circuit design. The diode that is shown in Figure 3 wasn't needed for the experiment since there was a diode that was prebuilt into the PMOS transistor. With these various components in addition to the standard wires used that circuit was implemented into hardware in the same way as the circuits design describes.

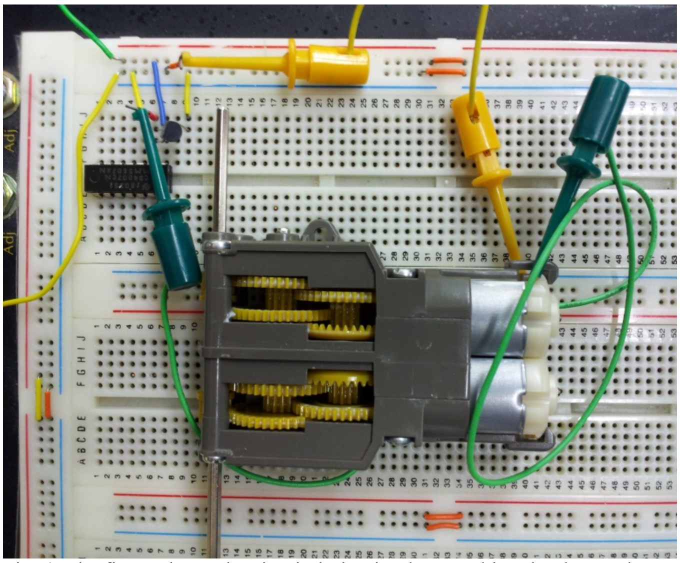

Fig. 4. The figure shows the circuit design implemented into hardware, then connected to a DC motor on a breadboard.

From the circuit design that is shown in figure 3 has a resistor just after the BJT NPN transistor this is replace with the DC motor in the hardware experiment. The circuit on the breadboard was connected to an oscilloscope. Several different levels of voltage were applied to the circuit in order in ensure that the circuits design would perform appropriately; however the voltages weren't greater than 15 voltages since the circuits design is only intended to work on a smaller scale.

VI. Results and Analysis

The circuit's design is to protect against kick-back current from a DC motor. In the simulation test it was found to be successful. Also when doing the experiment on the circuit implemented into hardware it was found to be effective. In both cases the voltage and kick-back current was changed to find if the circuit would hold up under more than just the basic values, and it was confirmed to work. The circuit's design has not been tested to work under high values of voltage and kick-back current, since the circuit design's main focus was to ensure that lower voltage and current wouldn't damage any of the components used. The results found from both the simulation and hardware testing showed that the current will flow around the circuit in the desired direction, and that the circuit preforms in the correct way under normal conditions. In the case of kick-back current the BJT NPN transistor turns on and gives the kick-back current a path to ground. The power performance is still that same as in the present design, aside from the fuse, diodes, and other method explained earlier. The main focus of this circuits design is to give the kick-back current a path to ground without causing any damage to the circuit's components. The present circuit protection designs ensure that current doesn't go in the wrong direction and damage any of the components, but with this new circuit design if the kick-back current regardless of the amount within reason will have a path to follow that goes straight to ground. This will ensure that all of the component will be protected. The PMOS transistor prevents the current from flowing in the wrong direction, and the NPN transistor gives the kick-back current a path to follow go ground. This gives the circuit two types of protection, and in doing so allows a stronger overall protection.

VII. Conclusion

There are many different ways of solving the protection problems in circuits. There are designs for voltage protection and current protection, and each of these designs has advantages and disadvantages. The design that was formed in the research is for a specific circuit. There are other ways of solving this problem. One of the reasons that this circuit is designed small and with only a couple of components is that it is going to be used in a robotic hand, and the design needs to be able to fit into each of the fingers and thumb. Also, with there being fewer components the cost of this project will be a lot less. In the design the microcontroller is going to be connected to the circuit design, so that there will be protection on it and there will be no damage done to the microcontroller. However the design as it is will only accept an in going signal. The design allows for there to be a signal or current to flow into the DC motor, but if there is a need for there to be a signal from the DC motor to the microcontroller it will be stopped. If there is a need for the DC motor the return current or a signal another circuit design may be of better use.

The objectives of this paper was to design a circuit that prevents the possibility of current going back into the system and damaging any of the components, and in this the designed circuit has been a success. Furthermore with the application that the circuit design was meant for their needed to be very little power loss among the components and the more components that are in a system the more losses are acquired. The only losses that have significances in the circuit are the PMOS transistor and the DC motor. The DC motor is meant to have the most power outputted, and the PMOS transistor has some power losses that were calculated, and there will be some losses in the wires. The NPN BJT does have losses with it, but the losses that it has will only have an effect on the kick-back current. Since the objective is to eliminate the kick-back current the losses in the NPN BJT are negligible since the current is designed to go straight to ground. The circuit design for the application that it is intended will work successful and with very little losses.

This will work was able to develop a protection circuit for embedded processor that stops back current.

VIII. FUTURE WORK

This study was done for the work that is being performed on the robotic hand that is currently located at Idaho State University. The work done is to provide protection for the circuits and user of the robotic hand being developed. The next step for the future would be to scale down the circuit's size to a more manageable size so that it will be able to fit into any circuit that has a need for current protection. Also the circuit's current design is used for protecting a circuit with low current and voltage, so future work needs to be done to improve on the circuit's design to include high levels of current and voltage. This will ensure that there will be protection to the circuits from any back flow of current at any desired value.

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