The Freescale Black Widow $10,000 Design Challenge

Prototype Entry by:

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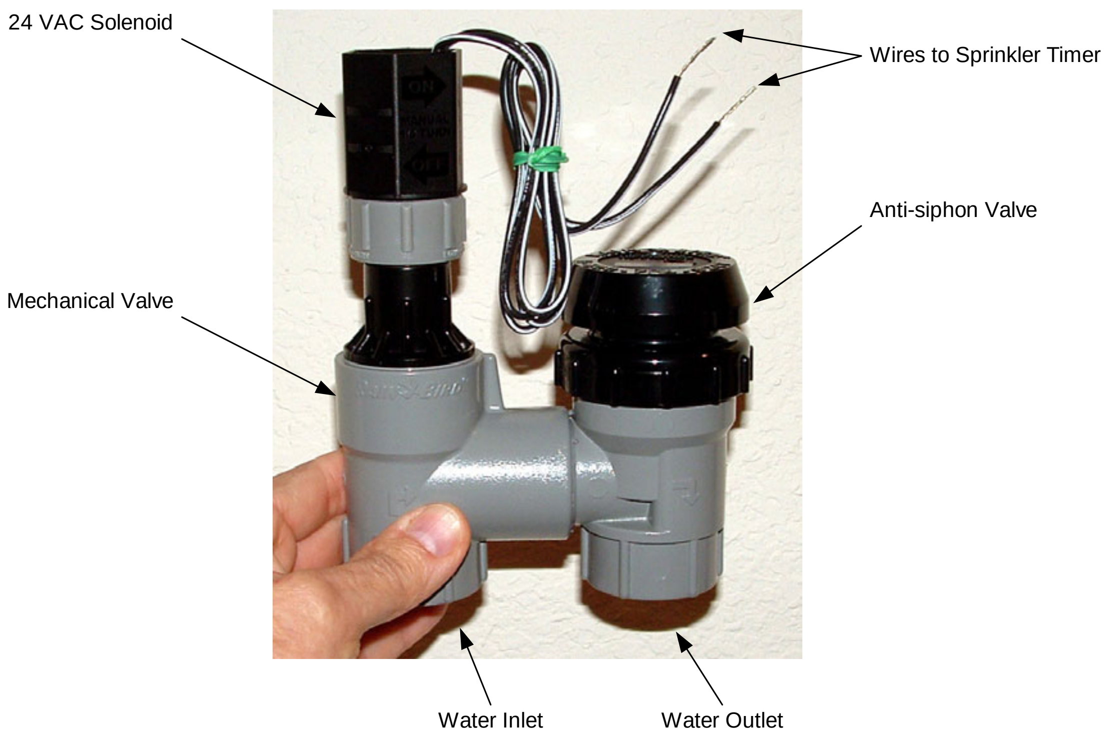
"SprinklerLink" for Networked Control of Irrigation Valve Solenoids

Executive Summary
The Freescale MC9S08QD is a highly integrated, low cost, low power, small size microcontroller which allows it to be literally embedded within the solenoid used to control automatic irrigation valves. This allows each solenoid to be uniquely addressable and controllable using a bidirectional protocol over a common two wire interface for the entire irrigation network. The two wire interface provides both power and data for each solenoid and provides major benefits such as lower installed cost, simplification of installation, future expansion, backwards compatibility, and diagnostics capabilities. A typical home irrigation installation contains six or more valves which provides a significant market opportunity for the MC9S08QD microcontroller.

Existing Irrigation Valve Technology

Figure 1 shows a typical automatic irrigation valve available today from retail home improvement stores (reference 1). The basic design of the type of valve has remained nearly the same for more than 30 years, is universally used and is low cost. It consists of a 24 VAC electrical solenoid that drives a mechanical valve to enable the flow of water under pressure to irrigation sprinklers. The solenoid wires are individually wired with a common return line to the sprinkler timer which is typically located within the home.

Figure 1 Typical Automatic Irrigation Valve



Irrigation Valve Control System - Existing Technology

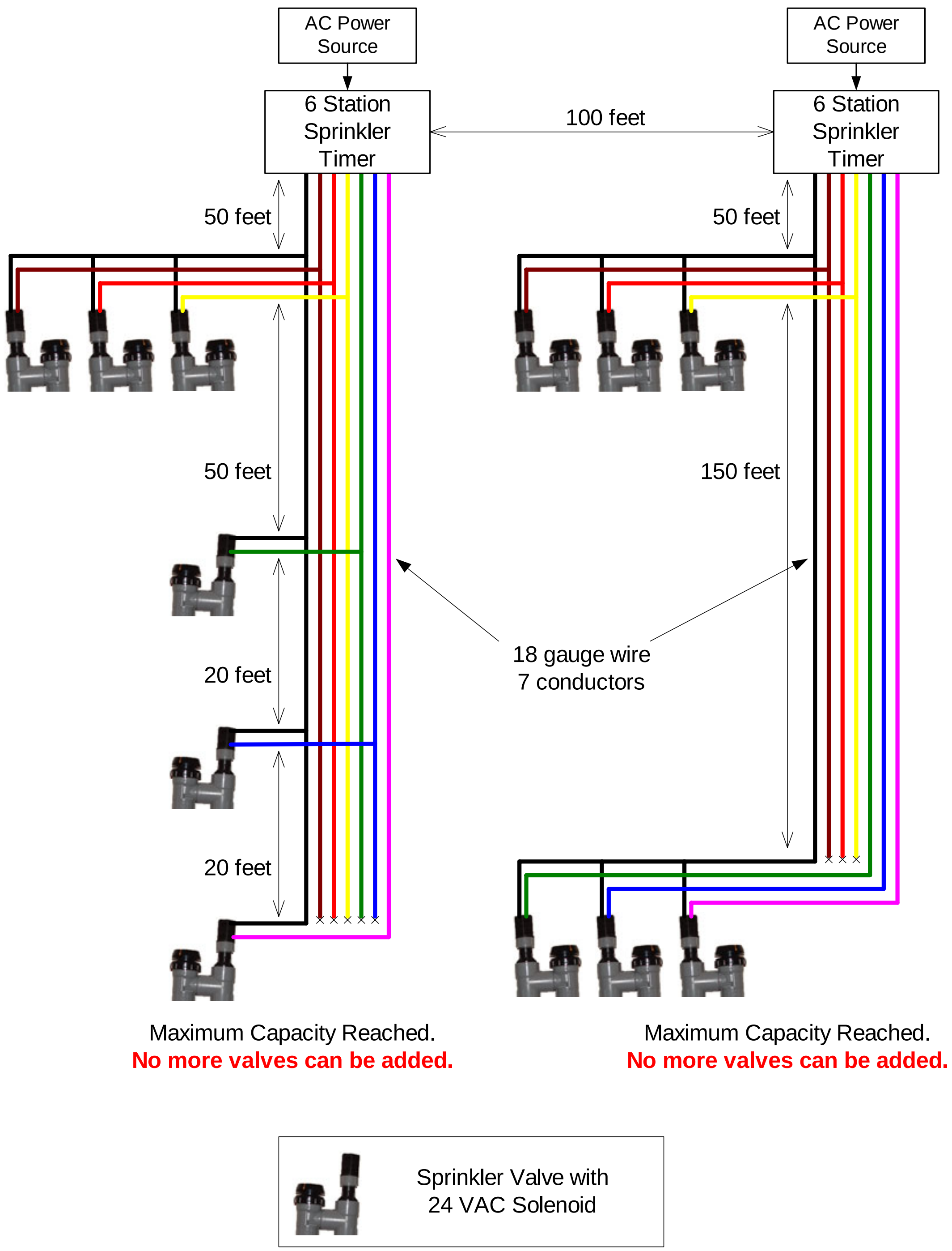
Figure 2 shows a typical irrigation valve control system using existing technology which is readily available from retail home improvement stores. The system consists of two independent irrigation / sprinkler timers which can each control six individual valves. Each sprinkler timer requires a source of AC power. Control of each valve is through individual wires that are connected from the timer to each valve, with a common return wire (black wire). The sprinkler timer activates only one valve at any time. Although it is possible to enable two valves simultaneously with the two independent timers, this is typically not practiced because of possible low water pressure issues.

The standard sprinkler wire is direct burial multiconductor 18 gauge class 2 UL rated wire (reference 2). The figure shows 7 conductor cable. The irrigation system is classified by the National Electric Code (NEC) as a Class 2 Remote-Control, Signaling, and Power Limited Circuit (reference 3). This classification places limitations on maximum voltage and current, in this case maximum voltage is 30 VAC (reference 4). The maximum distance between the timer and valve is determined by the total resistance of the wire and the minimum pull-in current of the solenoid.

The irrigation valves are typically grouped together but may also be individually spread out as shown. Because the sprinkler wire is available as a multiconductor cable, there will typically be wasted conductor lengths because all conductors in the cable are routed to each valve or group of valves.

The system depicted is at maximum capacity (12 valves) and adding an additional valve is not possible without significant changes including the addition of a sprinkler timer or changing the sprinkler timer to one with more stations. Additional wire would have to be laid for the entire length from the timer to the valve being added.

Figure 2 Typical Irrigation Valve Control System - Existing Technology



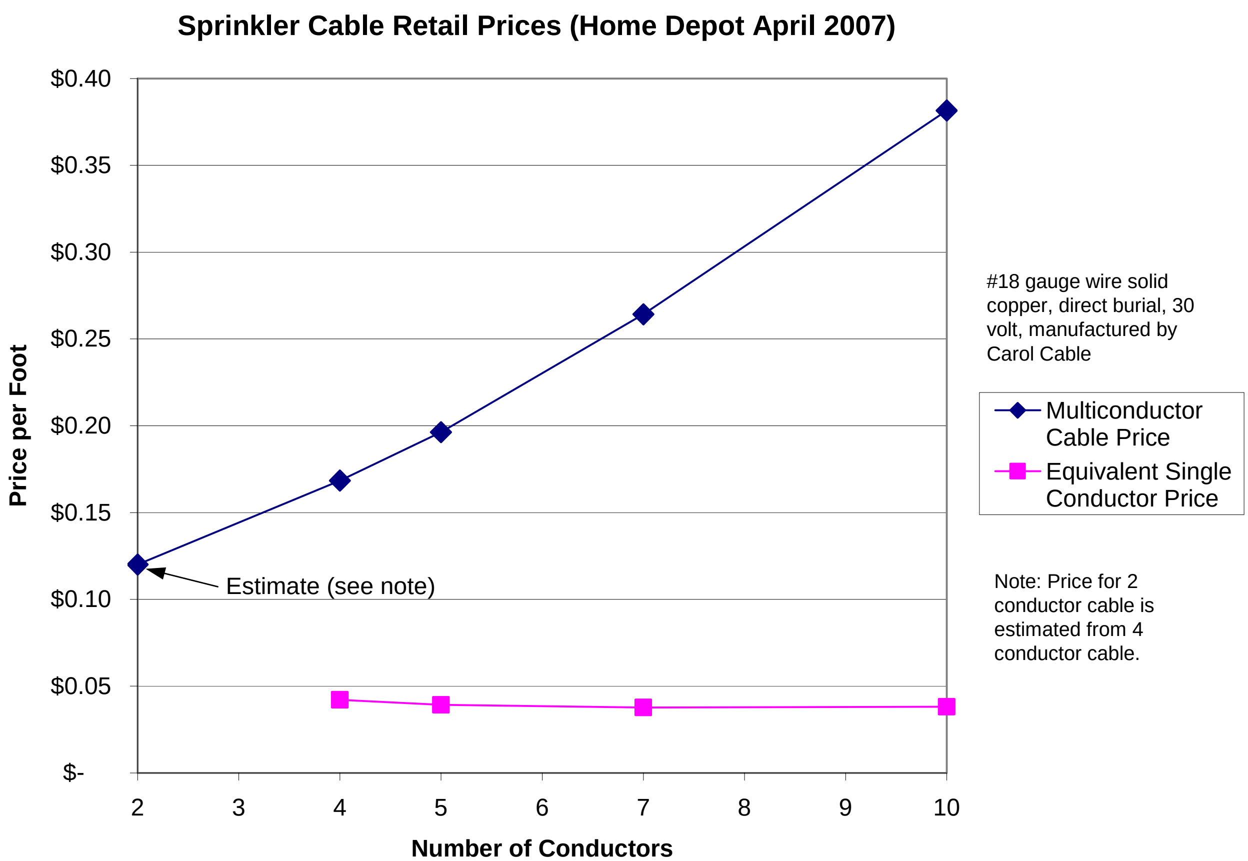
Cost Implications of Existing Technology

Figure 3 shows the copper metal price quote in US dollars per pound for the last 5 years. Over the 5 year period, the price has increased by a factor of 4 and in the last 18 months it has nearly doubled. This has a direct impact on the price of the multi-conductor sprinkler cable in use today.

Figure 3 Copper Metal Price Quote ($US/pound) - Last 5 Years

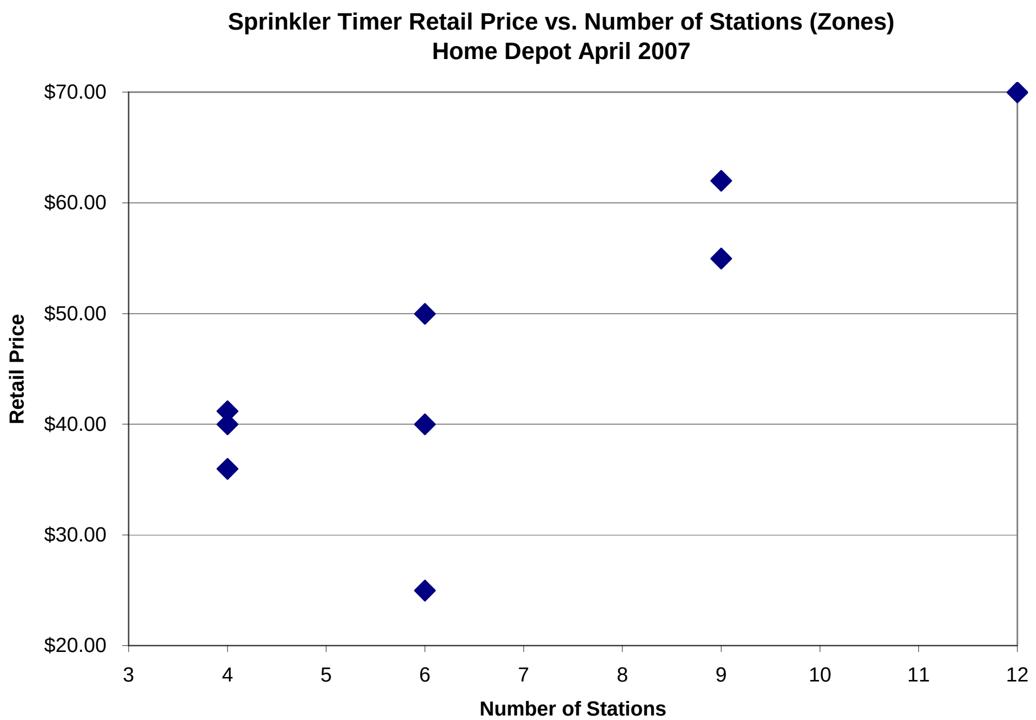
Figure 4 shows the retail price of multi-conductor sprinkler cable as sold by Home Depot in April 2007. The top line shows that the price per foot increases nearly linearly as the number of conductors increases. The bottom line shows the equivalent single conductor price which is nearly constant. The price for two conductor cable was estimated by interpolating from the other data points. The obvious conclusion is that cost savings can be realized by reducing the number of conductors required. This is one of the benefits of the SprinklerLink technology.

Figure 4 Multi-conductor Sprinkler Cable Prices



Another opportunity for cost savings targets the traditional sprinkler time / controller. Figure 5 shows the price of sprinkler timers as sold by Home Depot in April 2007. The price is correlated with the number of individual stations (zones) that can be controlled. The SprinklerLink technology eliminates this price dependency as a single timer can control 100 or more valves with minimal cost impact to the timer itself.

Figure 5 Sprinkler Timer Prices



Irrigation Valve Control System - SprinklerLink Technology

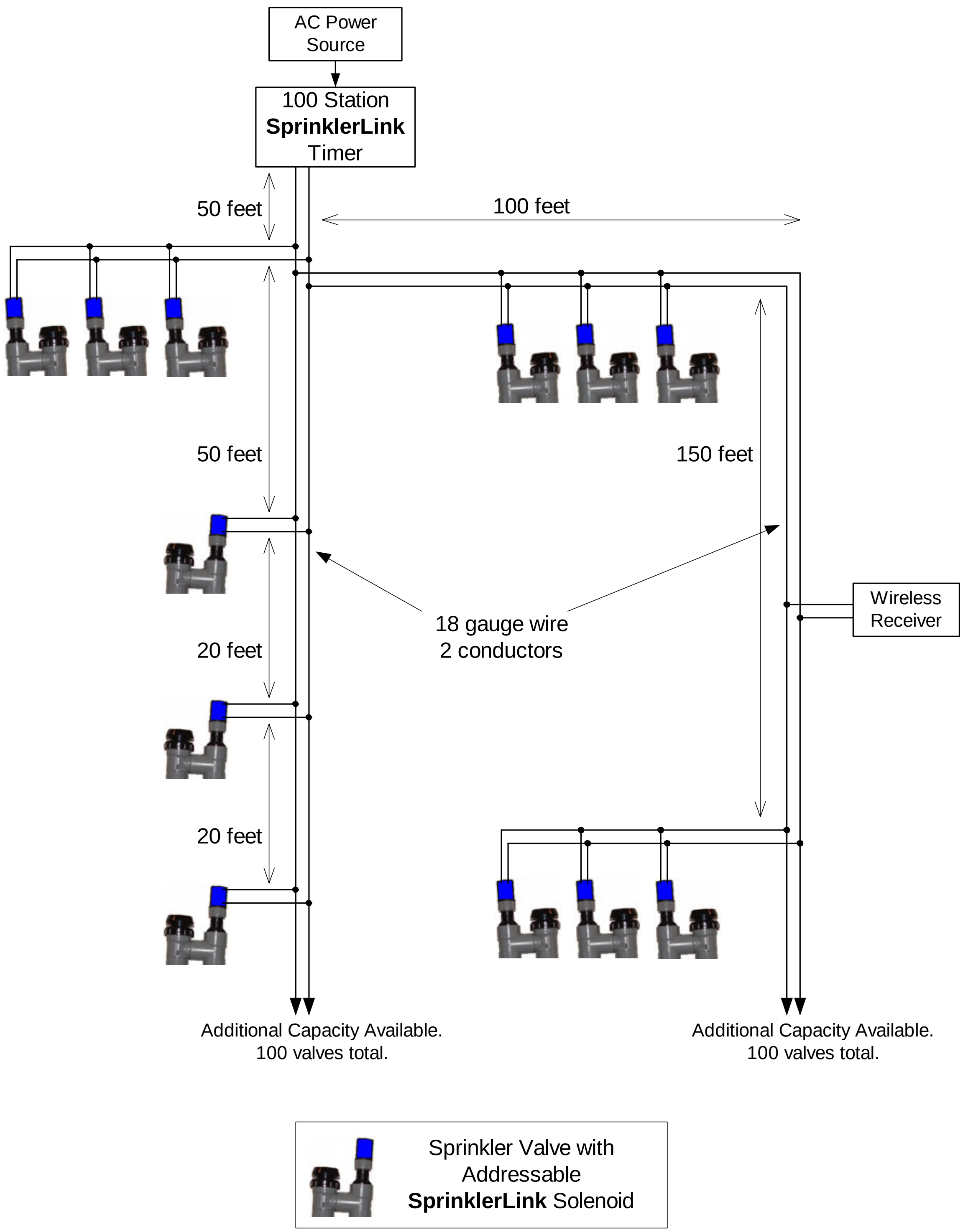
Figure 6 shows the same irrigation valve system as Figure 2 but in this case the irrigation valves and irrigation timer include the SprinklerLink interface. The benefits of this change are immediately realized:

- The entire system is controlled by a single timer. Only one timer needs to be accessed when making changes to the irrigating schedules.
- Significant wire reduction and cost savings because only two wires are required.
- Simplified installation: All valves wired in parallel with no regard for polarity which results in no wiring errors. Fewer connections are required when wiring valve groups which improves connection reliability.
- A single timer can control up to 100 valves making expansion simply a matter of connecting additional valves in parallel with existing wires and no additional timers are required.
- A wireless receiver may be placed anywhere along the cable and can be centrally located for best reception from a wireless transmitter used for in field irrigation testing.

Additional benefits include:

- Bidirectional communication allows early identification of faults such as shorted solenoid, open solenoid, and open cable.
- Diagnostics can include remote temperature sensing to identify possible freezing conditions.
- New irrigation valves embedded with SprinklerLink operate the same as tradition valves when 24 VAC is applied. This backward compatible allows a single SKU to be installed in old or new irrigation systems.

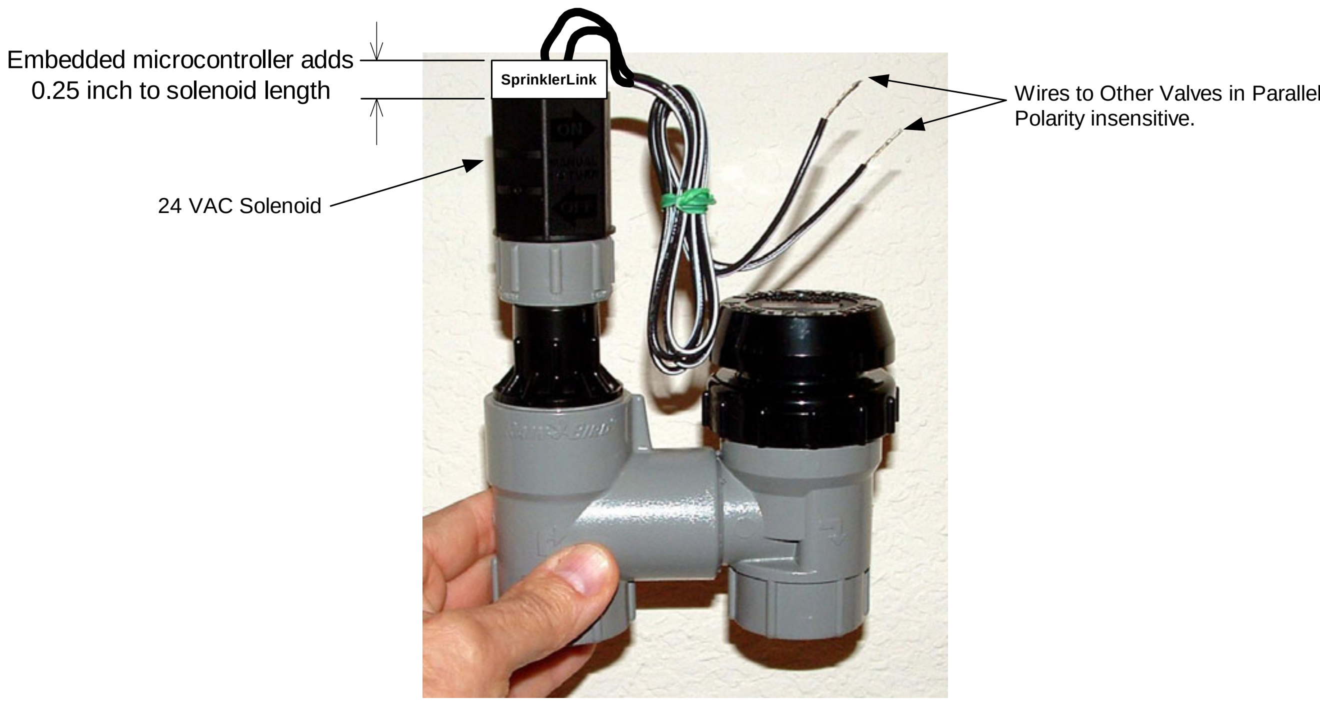
Figure 6 Typical Irrigation Valve Control System - SprinklerLink Technology



Irrigation Valve with Addressable Control Interface

Figure 7 shows the same irrigation valve as Figure 1 with the addition of the SprinklerLink interface which allows the solenoid to be uniquely addressable and controlled by a common two wire interface. The major component of the SprinklerLink interface is Freescale MC9S08QD4 microcontroller. Because of the high integration of the MC9S08QD4, few additional components are required which allows the size to remain small. The proposal includes a circuit board design that fits within the outline dimensions of the solenoid and adds about 0.25 inch of height. This allows the circuit board assembly to be encapsulated (potted) within the same housing as the solenoid resulting in a water proof unit. The SprinklerLink interface is transparent to the user.

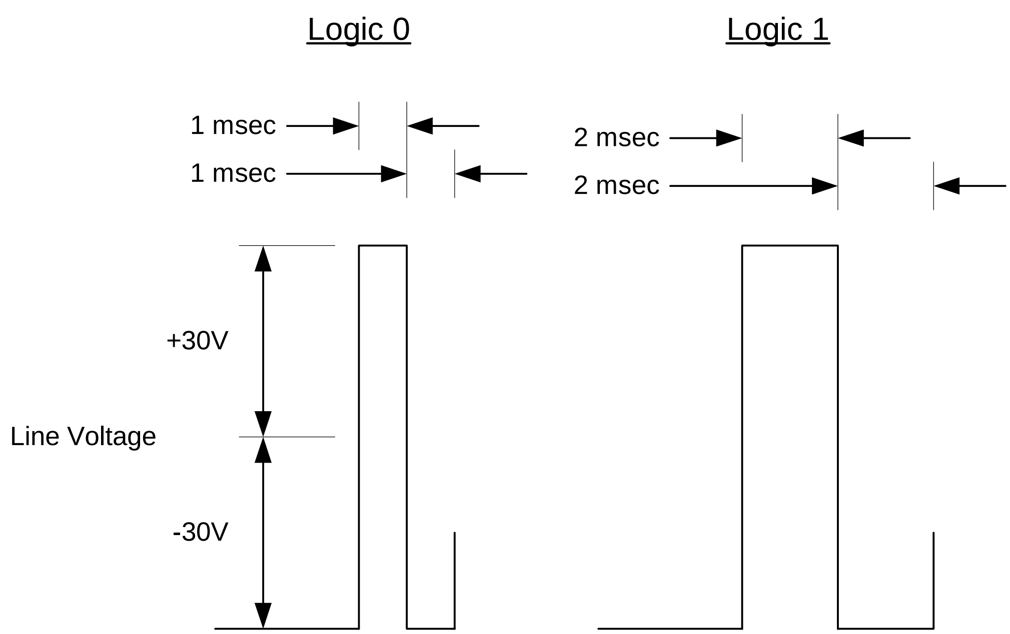
Figure 7 Irrigation Valve with Addressable Control Interface



SprinklerLink Electrical Interface - Master to Slave (Physical Layer)
The two wire interface between the sprinkler timer (master) and the irrigation valves (slaves) is completed with two wires which carry both power and data. The nominal line voltage should be as high as possible to overcome wire resistive losses and maximize distance, but still be low enough so that inexpensive (low voltage) wire can be used. The maximum voltage is chosen to be 30V. The polarity is alternated at a slow rate (1 Hz maximum) so that the average DC voltage is zero which helps to prevent corrosion by electrolysis in wet locations.

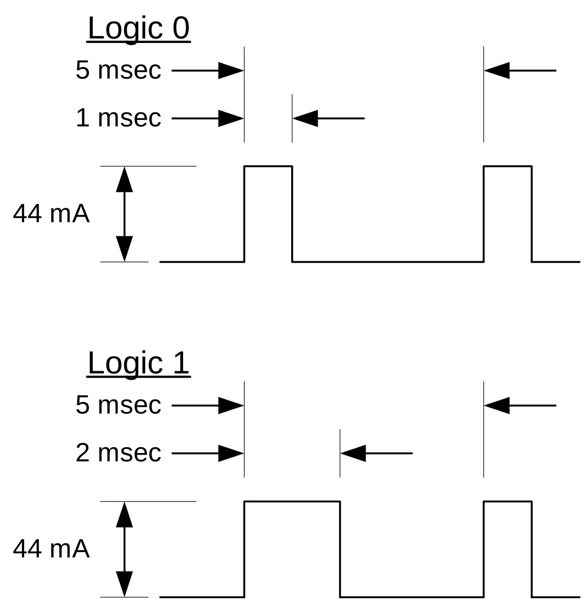
In order to transmit data from the master to slave units, the line voltage polarity is alternated at a fast rate with unique pulse widths to indicate logic 0 and logic 1 values. Figure 8 shows the details of the logic 0 and logic 1 waveforms. The master unit must be able to drive the line with the waveform shown when the maximum specified load current is present. The average data rate, assuming equal numbers of logic 0 and logic 1 bits is 333 bits/sec.

Figure 8 Master to Slave Transmit Data Waveforms



SprinklerLink Electrical Interface - Slave to Master (Physical Layer)
Communication from an individual slave unit to the master unit is performed by the slave unit loading the line with a unique pulse width and constant current per pulse. The master unit contains a current monitor so that it can see the load changes no the line. Figure 9 shows the details of the logic 0 and logic 1 waveforms. The duty cycle of each bit is chosen to be low to minimize the average power dissipation in the slave unit. The duration of each pulse is chosen to be an order of magnitude longer than the period of the PWM driving the solenoid so that the line disturbances from the PWM can be filtered out by the master unit while still passing the received data bits. The average data rate, assuming equal numbers of logic 0 and logic 1 bits is 200 bits/sec.

Figure 9 Slave to Master Transmit Data Waveforms



Data Link Layer & Commands

The communication between master and slave units operates in half-duplex mode with the master initiating all responses from the slaves. Uninitiated transmissions from the slave units is not allowed and are ignored. Data is transferred msb (most significant bit) first in 8 bit bytes with no delays in between bytes. A sequence of bytes (message) is terminating by the absences of pulses on the line for more than 3 msec for master to slave communication and for more than 6 msec for slave to master communication.

A single message consists of an address length byte, address bytes, command length byte, command bytes, data length byte, data bytes, and checksum. The entire message is depicted in Figure 10. The address is unique to each manufactured SprinklerLink slave unit so that two slaves with the same address will never be present on the same line. A 6 byte or 8 byte address is proposed (similar to a MAC address). A fixed global address value is defined so that the master can command all slave units simultaneously, for example to power down all but one slave units. Commands are typically one byte in length, with or without corresponding data. Data will typical be one or two bytes.

Typical commands that must be supported by each slave unit include:

- Slave acknowledge.
- Slave power down.
- Slave ignore next global command.
- Slave diagnostic report-back (line voltage, solenoid current, temperature, etc).
- Solenoid ON for defined duration.
- Solenoid OFF.

Figure 10 Components of a Message

Address Length Byte	Address Bytes	Command Length Byte	Command Bytes	Data Length Byte	Data Bytes	Checksum

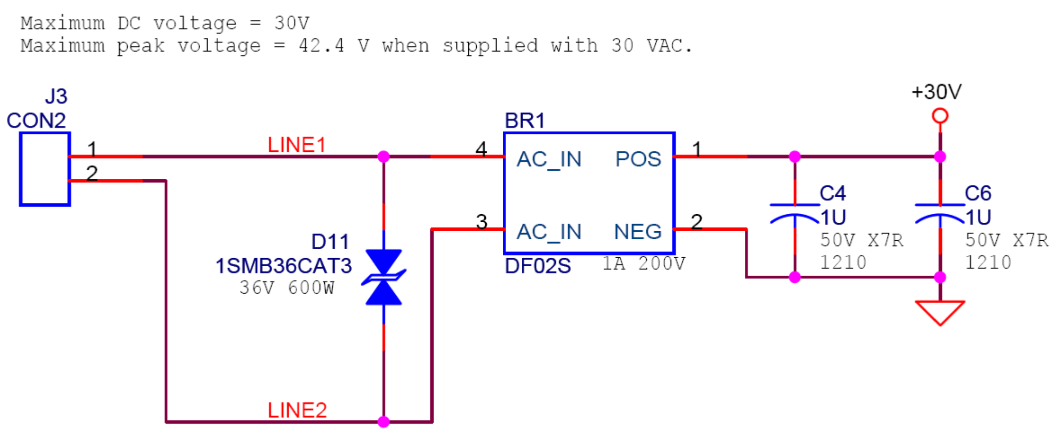
Addressable SprinklerLink Slave Solenoid Circuit

The circuit that implements the embedded controller for the irrigation valve solenoid is described below.

LINE1 and LINE2 shown in Figure 11 are the two input/output wire connections. To protect the circuit for voltage surges from nearby lightning strikes, a transient voltage suppressor (D11) is present that starts to conduct around 42V and clamps its rated power at 58V. For backwards compatibility with legacy sprinkler timers, the input must be able to operate with 30 VAC (42V peak) across the line.

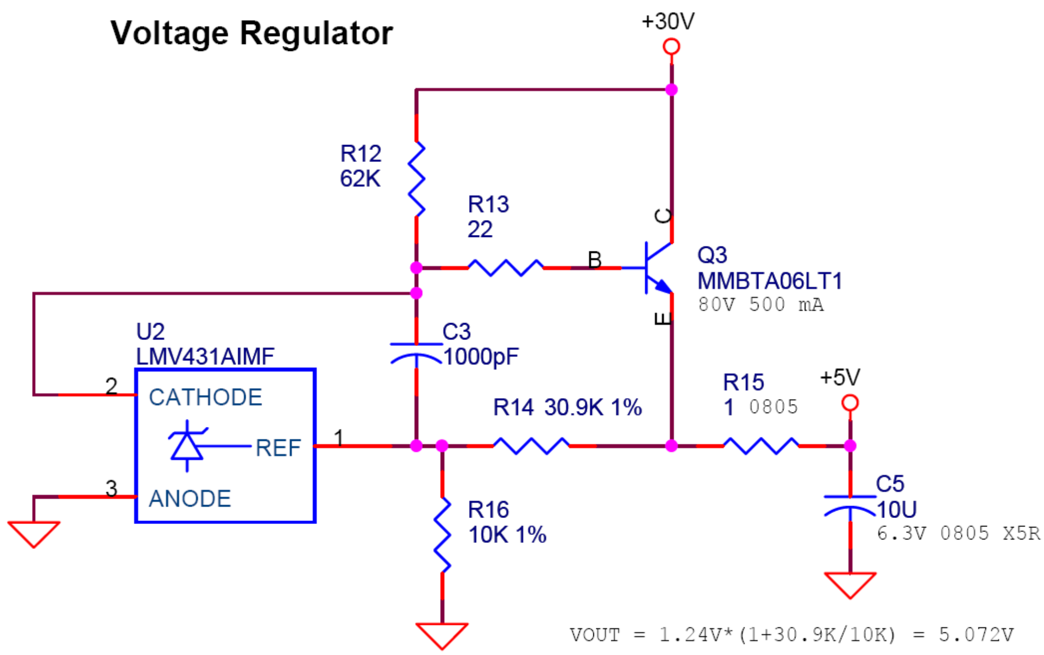
The bridge rectifier (BR1) allows the LINE1 and LINE2 wires to be reversed with no change in operation. This simplifies user installation as polarity is irrelevant. The nominal line voltage is 30 VDC and some bulk capacitance is provided by C4 and C6 to smooth out current transients on the line.

Figure 11 Line Input Transient Protection and Full Wave Bridge Rectifier



The extremely low current consumption of the MC9S08QD microcontroller allows the use of a simple and low cost discrete linear voltage regulator to generate 5 VDC nominal from the 30 VDC line input. See Figure 12. The circuit consists of a low cost pass transistor and low cost voltage reference IC.

Figure 12 Linear Voltage Regulator



The microcontroller and remaining circuitry are shown in Figure 13. The input line voltage is monitored through D8, divided down and filtered by R10, R11 and C2 and applied to one of the analog input pins of the microcontroller. The diode is required so that the monitored voltage polarity is always positive. The A/D converter is used to convert the analog voltage to a digital value and is processed to determine the steady state line voltage and also decodes the transmission pulses on the line.

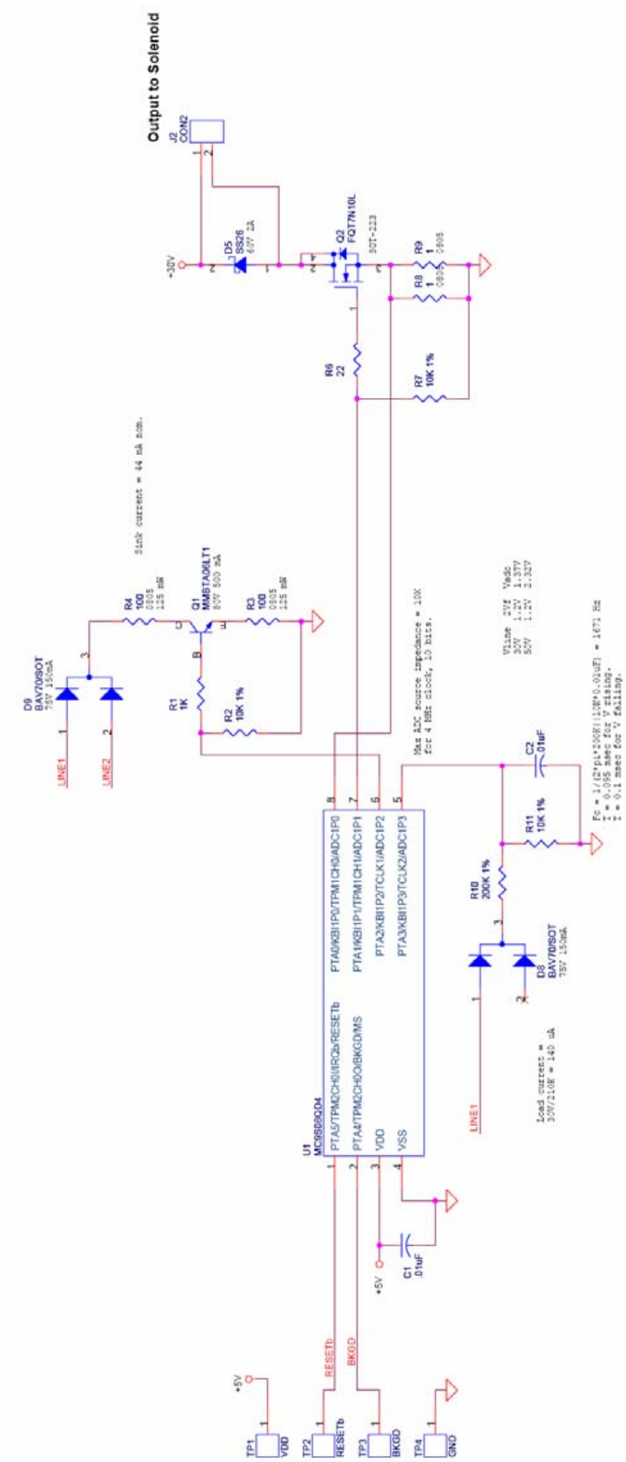
The solenoid is driven by and N-channel MOSFET (Q2) with pulse width modulation (PWM) so that only the required amount of average current flows through the solenoid. D5 is the freewheeling diode which conducts when Q2 turns off. When Q2 is on, the current through the solenoid passes through resistors R8 and R9 which generate a small voltage proportional to the amount of current. This voltage is applied to the microcontroller analog input which is used to monitor the current so that the correct average current is maintained by the PWM control.

The microcontroller sends data back to the master device by modulating the line current with a constant current sink (Q1 and R3). R4 shares the total power dissipation with Q1 and R3. The diode D9 is required so that the voltage applied to the current sink is always positive regardless of the line polarity.

For firmware development and debug, the standard background debug controller (BDC) signals, power and ground are provided on a four pin header.

Transient voltage protection of the solenoid output from nearby lightning strikes was not deemed necessary as the signal connections between the assembly and solenoid are very short so that the loop area is not considered to be significant.

Figure 13 Microcontroller, Line Monitor, Solenoid Driver



SprinklerLink Slave Bill of Material (BOM) Cost

The cost of all components including the printed circuit board is estimated at $1.63 (see below for details). The component prices listed are for high volumes (10K to 100K pieces). The low total cost is possible because of the low cost of the MC9S08QD microcontroller, its low power operation and its rich feature set that requires minimal external components for a complete solution.

Quantity	Reference	Part	Description	Manufacturer	Part Number	Unit Price	Total
1	BR1	DF02S	IC RECT BRIDGE 400V 1.5A 4SDIP	Fairchild	DF04S	$ 0.100	$ 0.100
2	C1,C2	.01uF	CAP CER .01UF 50V X7R 10% 0603	AVX	06035C103KAT2A	$ 0.010	$ 0.020
1	C3	1000pF	CAP CER 1000PF 50V NPO 5% 0603	Kemet	C0603C102J5GACTU	$ 0.010	$ 0.010
2	C4,C6	1U	CAP CER 1UF 50V X7R 10% 1206	TDK	C3216X7R1H105K	$ 0.020	$ 0.040
1	C5	10U	CAP CER 10UF 6.3V X5R 10% 0805	Taiyo Yuden	JMK212BJ106KD-T	$ 0.030	$ 0.030
1	D5	SS26	DIODE SCHOTTKY 2A 60V SMB	Fairchild	SS26	$ 0.080	$ 0.080
2	D8,D9	BAV70/SOT	DIODE ULTRAFAST HI COND SOT-23	Fairchild	BAV70	$ 0.020	$ 0.040
1	D11	1SMB36CAT3	TVS ZENER BIDIRECT 600W 36V SMB	On Semi	1SMB36CAT3G	$ 0.080	$ 0.080
2	Q1,Q3	MMBTA06LT1	TRANS DRIVER NPN 80V 500 MA SOT-23	On Semi	MMBTA06LT3G	$ 0.020	$ 0.040
1	Q2	FQT7N10L	MOSFET N-CHAN 100V 1.7A SOT223	Fairchild	FQT7N10LTF	$ 0.140	$ 0.140
1	R1	1K	0603 5%	Vishay/Dale	CRCW06031K00FKEA	$ 0.001	$ 0.001
4	R2,R7,R11,R16	10K 1%	0603 1%	Rohm	MCR03EZPFX1002	$ 0.001	$ 0.004
2	R3,R4	100	0805 5% 125 mW	Vishay/Dale	CRCW0805100RJNEA	$ 0.002	$ 0.004
3	R8,R9,R15	1	0805 5% 125 mW	Vishay/Dale	CRCW08051R00JNEA	$ 0.002	$ 0.006
1	R10	200K 1%	0603 1%	Rohm	MCR03EZPFX2003	$ 0.001	$ 0.001
1	R12	62K	0603 5%	Vishay/Dale	CRCW060362K0FKEA	$ 0.001	$ 0.001
2	R6,R13	22	0603 5%	Vishay/Dale	CRCW060322R0JNEA	$ 0.001	$ 0.002
1	R14	30.9K 1%	0603 1%	Vishay/Dale	CRCW060330K9FKEA	$ 0.002	$ 0.002
1	U1	MC9S08QD4	IC MCU 4K FLASH 8-SOIC	Freescale	MC9S08QD4CSC	$ 0.630	$ 0.630
1	U2	LMV431AIMF	IC LV ADJ PREC SHUNT REG SOT23-3	Texas Instr.	TLV431CDBZR	$ 0.100	$ 0.100
1	-	-	Printed Circuit Board	various	-	$ 0.30	$ 0.30
							$ 1.63

SprinklerLink Slave Prototype Printed Circuit Board (PCB) Design

The SprinklerLink slave prototype design uses a two layer PCB with a rectangular form factor, 0.625 inches wide by 1.25 inches long (0.78 square inches). A production version PCB would be shaped to fit within the outline dimensions of a typical irrigation valve solenoid. This will allow the PCB to be mounted on top of the solenoid and encapsulated (potted) in the same manner as the standard solenoid. See Figure 14 and

Figure 15 for the top side and bottom side views of the prototype PCB. The small size of the MC9S08QD microcontroller and the minimal application circuitry allow it to easily fit within the constraints of the solenoid outline dimensions.

Figure 14 SprinklerLink Slave Prototype PCB - Top Side

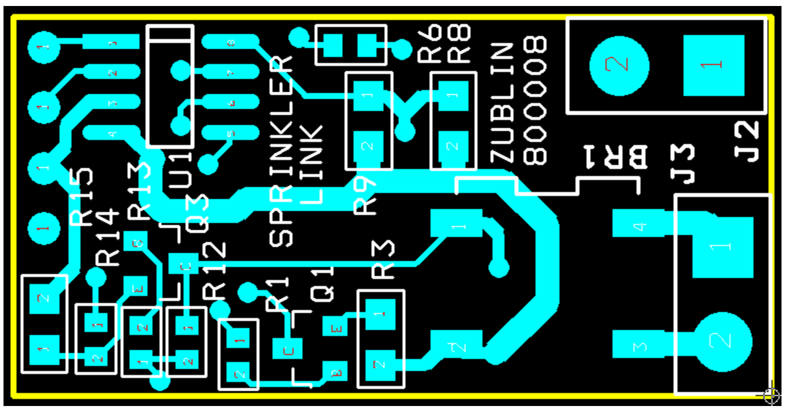
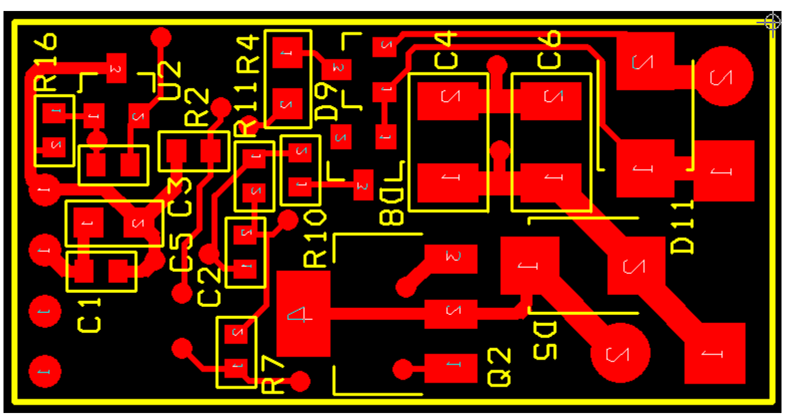


Figure 15 SprinklerLink Slave Prototype PCB - Bottom Side



Six prototype slave units were hand assembled by the author using a microscope, very small soldering iron and a steady hand.

Figure 16 SprinklerLink Slave Prototype PCB Assembly - Top Side

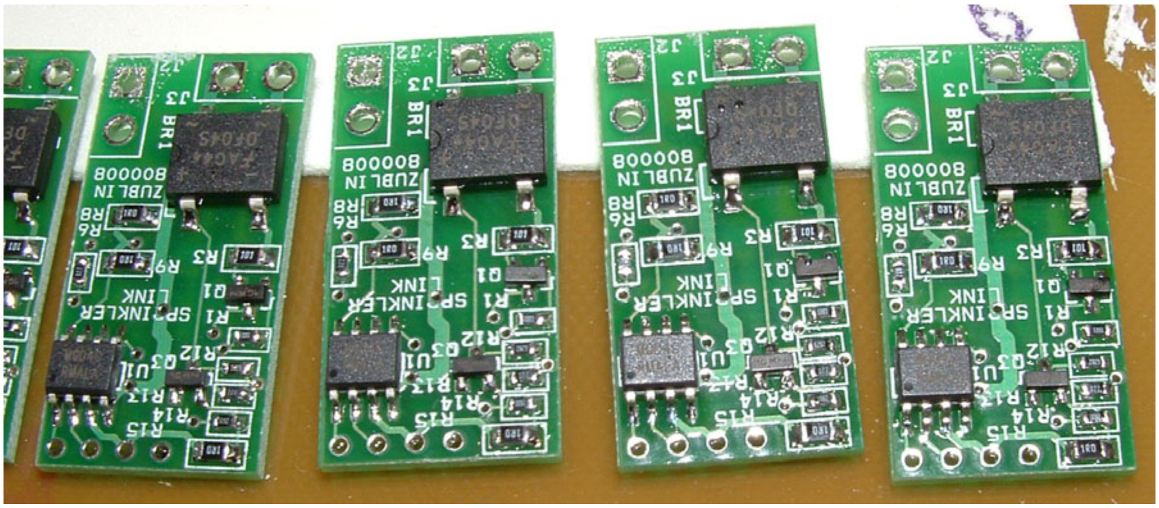
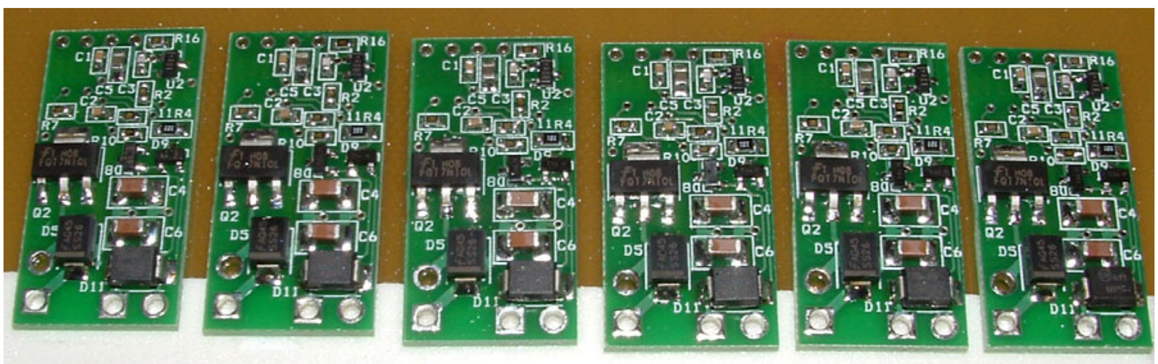
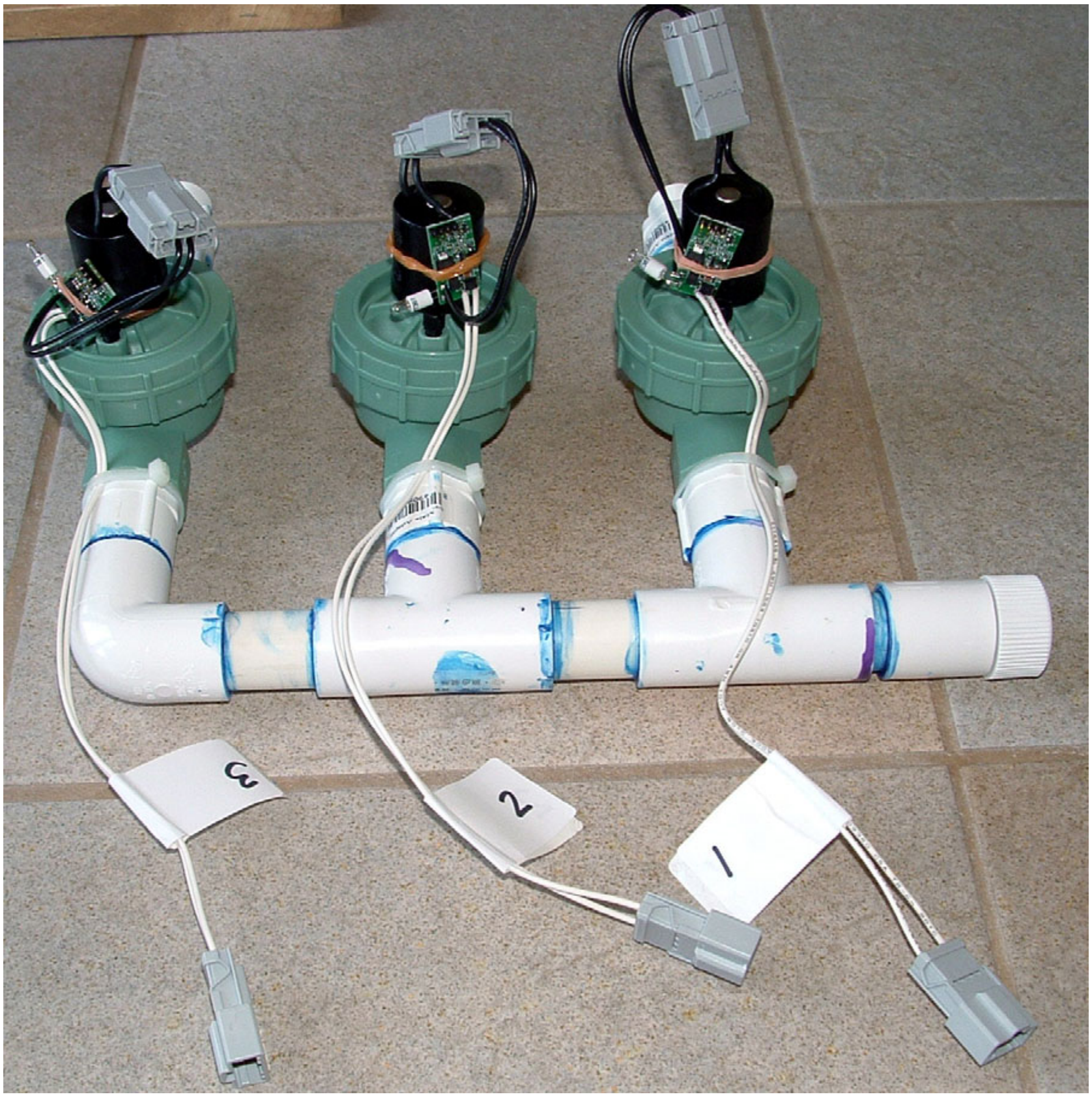


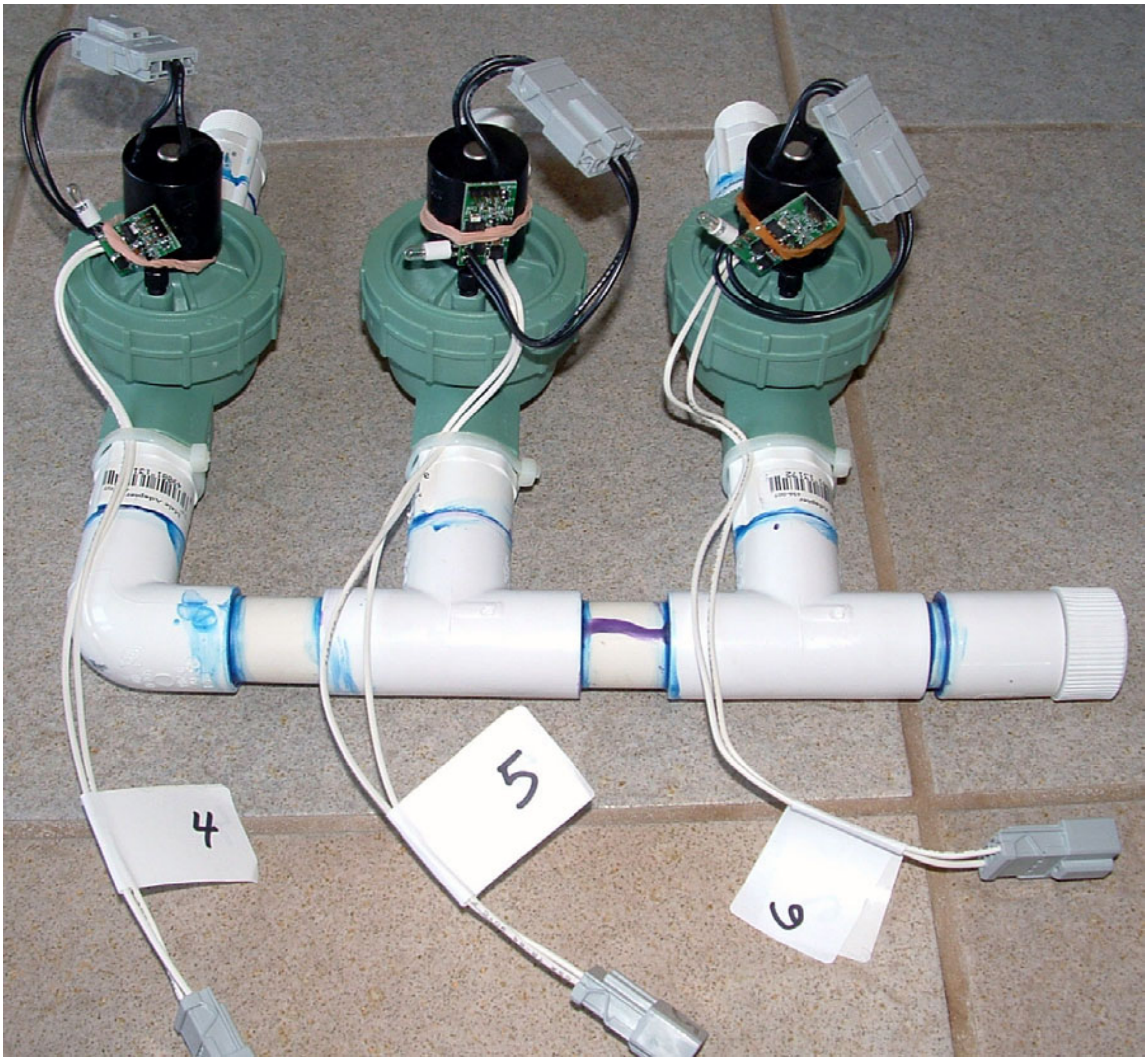
Figure 17 SprinklerLink Slave Prototype PCB Assembly - Bottom Side



SprinklerLink Slave Prototype Demonstration Units
The demonstration prototype units for the SprinklerLink slaves consist of the PCB assembly and sprinkler solenoids as shown below. Two sets of three valves each were assembled. The indicator lamps and solenoid connectors are included in the prototype and would not be present for the production version.

Figure 18 SprinklerLink Slave Demonstration Prototypes with Irrigation Valves

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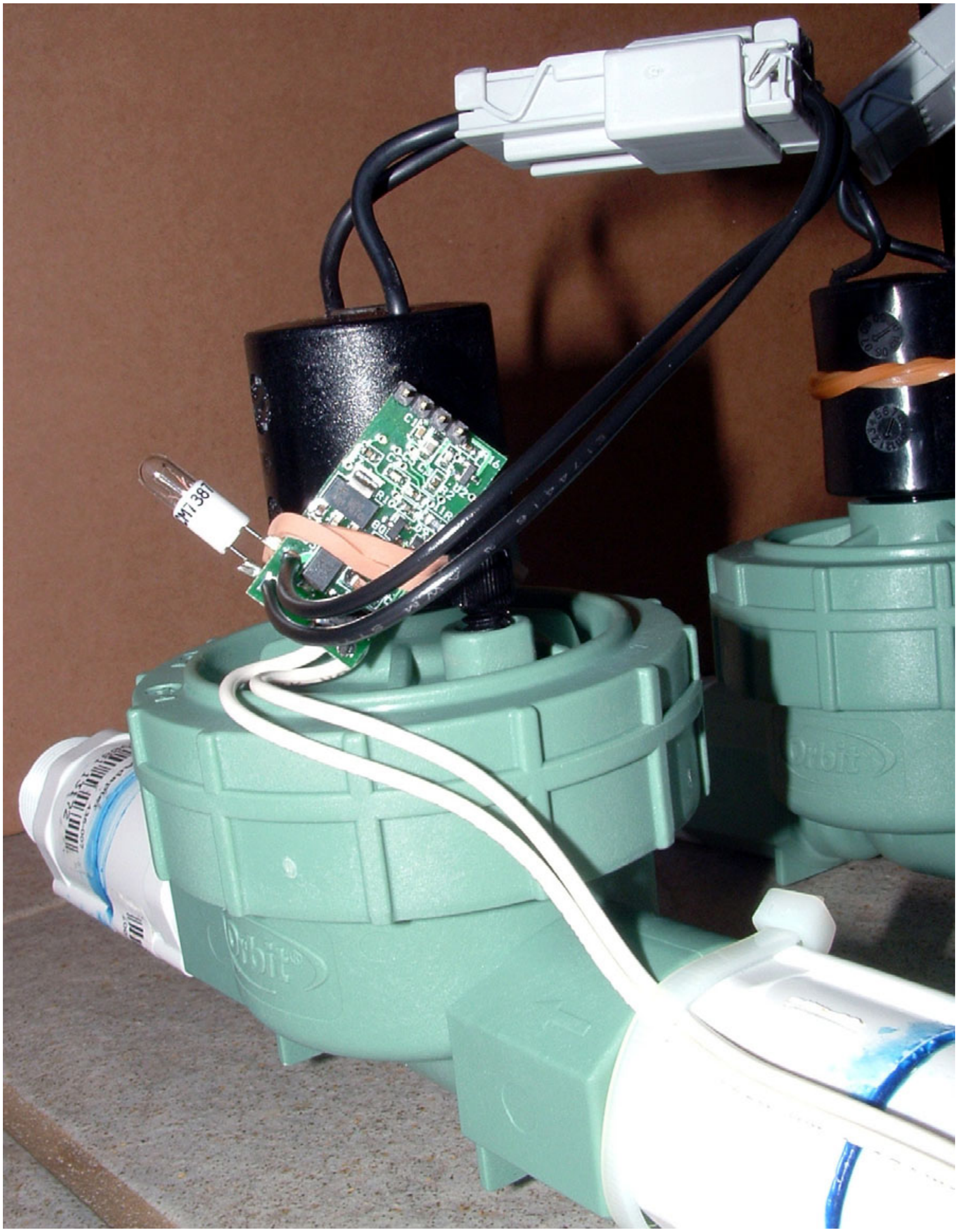


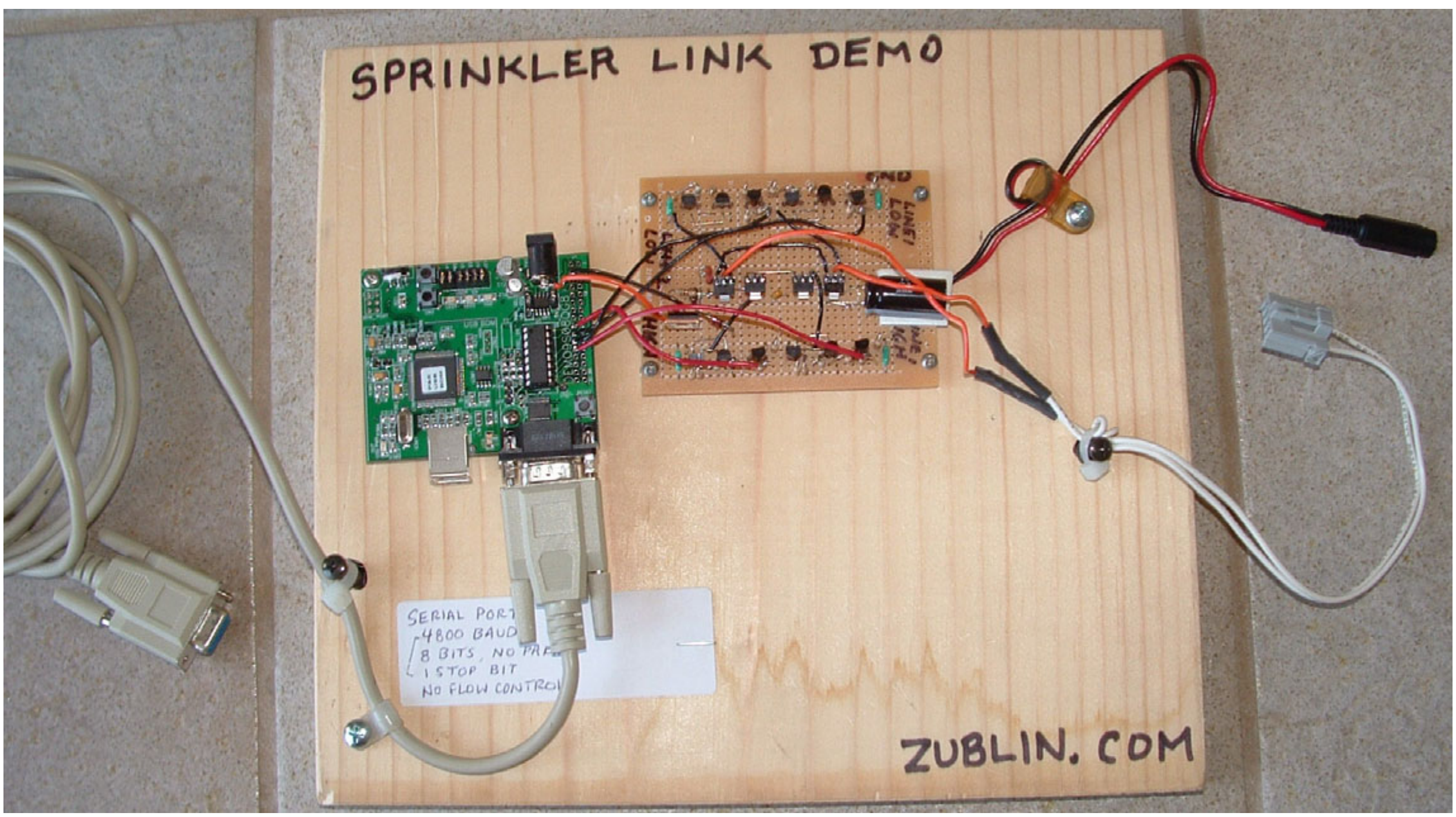
SprinklerLink Master Demonstration Prototype

The demonstration prototype for the SprinklerLink master unit consists of the Freescale MC9SQG8 demo board and power interface for driving the power and data onto the line. The power interface consists of four power MOSFET's connected in a full bridge (H bridge) configuration and associated gate drivers operating from an external power supply. The MOSFET gate drivers level shift the low voltage (3.3V) logic levels from the MC9SQG8 to the higher voltages required to drive the gates of the MOSFETs and also provide the high current drive required to switch the MOSFET's on and off quickly. Each of the four drivers consists of three small signal transistors ($0.02 each in high volume). The total BOM cost is less than $0.75. The voltage of the external power supply was chosen to be 24 VDC because a 30 VDC power supply was not readily available.

The current load is monitored by two 1 ohm resistors in parallel and the voltage across the resistors is filtered and applied to one of the A/D converter inputs of the MC9SQG8.

The demonstration prototype for the master unit is shown below. A serial connection is provided to interface with a PC running a terminal emulator.

Figure 19 SprinklerLink Master Demonstration Prototype



Sprinkler Link Demonstration Assembly and Operation
The remaining components of the SprinklerLink demonstration system consist of two lengths of two conductor wire (200 and 300 feet each) with connectors and a 24 VDC power supply. See below for photos.

Detailed assembly and operation instructions are shown in a video that can be downloaded from the web page listed below. The file is over 100 megabytes so it should be downloaded to your local PC and then viewed. The Teraterm terminal emulator software is also included at the address below as well as this document.

http://www.zublin.com/SprinklerLink.htm

Figure 20 Two Conductor Wire (200 & 300 feet each)

<u>References</u>

1. Rain Bird Automatic Anti-Siphon Sprinkler Valve, 1 inch, Model APAS-100.
2. General Cable / Carol Brand Low-Voltage Sprinkler Wire, 60 deg C, 30 Volts UL listed for outdoors applications and direct burial applications, size 18 AWG, 7 conductor, catalog number 23817-60-01.
3. National Electric Code (NEC) 2005 Handbook, Article 725, Class 1, Class 2, and Class 3 Remote-Control, Signaling, and Power Limited Circuits.
4. National Electric Code (NEC) 2005 Handbook, Chapter 9, Table 11(A) Class 2 and Class 3 Alternating-Current Power Source Limitations.