Design of a Phantom Load Controller for Entertainment Centers

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Abstract

A phantom load is a device that consumes power while it is off or in standby mode. Phantom loads consume a large amount of wasted energy in the United States. Some research has shown that typical household phantom loads draw about 65 W, or 569 kWh per year, which amounts to an estimated 5-10% of a household's expected energy usage[1]. Several of the highest energy offenders are located in centralized areas in a home including the home office, kitchen, and entertainment centers. An entertainment center can consist of, but is not limited to, a plasma television, VCR, DVD player, CD player, stereo receiver, and numerous gaming consoles. This centralized hub presents an opportunity to eliminate or minimize a significant number of phantom loads with minimal cost of inconvenience for the end user. The authors have designed a phantom load controller that can activate a series of outlets feeding the entire entertainment center by intercepting any infrared power-on request. Furthermore, the controller automatically senses when the components of the entertainment center are all in standby mode and turns them completely off. The controller itself consumes less than one watt.

Introduction and Problem

Phantom loads use electricity while an appliance is not performing its main function. Table 1 outlines the different kinds of phantom loads. The International Energy Agency (IEA) reports that 5-10% of a residential home's power usage and 1% of global carbon dioxide emissions are attributable to phantom loads[1].

Table 1. Kinds and Descriptions of Phantom Loads[2]

Category	**Description**
Passive Standby	Appliance is off, but can be powered on remotely
Active Standby	Appliance is on but not providing a primary function
Sleep	Mode entered after a period of inactivity
Off	Appliance is off and offers no operations

Standby power amounts to 480 TWh per year globally, or more than the entire electricity usage of France[3]. Several of the highest energy offenders are located in centralized areas in a home including the home office, kitchen, and entertainment centers. Table 2 outlines the phantom loads of several common devices in an entertainment center.

Table 2. Phantom Loads of Common Entertainment Appliances[4,5,6]

Device	Average Phantom Load (W)
TV	5
VCR	6
DVD Player	4
Cable Box	11
Satellite System	13
DVR	25
Stereo	9.5
Nintendo Wii	1.3
Playstation 3	1.9
Xbox 360	2.5

Currently, most devices receive remote control commands via an infrared carrier modulated near 44 kHz both for power switching and functional purposes. Thus, power-on requests can be exploited as initial signals for a load demand.

Current Solutions and Research

Policies

In 2000, the IEA initiated the "1-Watt Plan" which seeks to reduce standby power per device to one watt. Regulation has been adopted in Japan and California, and under consideration in the rest of the United States, Canada, EU, Australia, Korea, and China[3]. The plan has three parts:

1. Participating countries would seek to lower standby power draws to below one watt in all products by 2010.
2. Each country would use measures and policies appropriate to its own circumstances, including legislation, financial incentives and voluntary programs.
3. All countries would adopt the same definition and test procedure[1].

Energy Star has been a successful voluntary program. Manufacturers can place "Energy Star" labels on their products to entice energy conscious consumers[3]. Executive Order 13221 requires that any federal agency must purchase devices with a standby power of one watt or less[7]. Stricter regulation has been recommended for TV's, which consume 4% of U.S. power in the on-state and need closer monitoring during the off state[6]. In 2005, 90% of U.S. households were subscribed to cable or satellite services; the set top boxes that come with these services often take the same amount of power in the on and off states, so stricter regulation has been recommended[6].

Hardware

Inefficient power supplies are often the culprits of standby power drain. Traditional linear power supplies are based on transformer technology, which are inefficient at low power draws, such as standby mode. Switched-mode power supplies can reduce the energy wasted by up to 90%[8]. These switched-mode power supplies have been so successful in the cell phone industry, that no further regulations have been imposed or recommended for cell phone chargers[6]. A simple solution would be to require the use of switched mode power supplies rather than transformers wherever possible. The phantom load controller designed by the authors employs one of these power supplies. Several circuits have been proposed[9,10,11] that adapt a linear supply with additional components to increase efficiency. Two other approaches propose integrating outlet monitoring in a home to a centralized location to track and control outlet and appliance activities[12,13]. Two designs that are similar to the phantom load controller designed by the authors are the design by Mozar[14] and "Smart Strips" by Bits Ltd.[15].

Mozar's design utilizes an IR detector to receive power-on commands, but leaves it on all the time and needs a rechargeable battery instead of using a small draw to keep the microcontroller running. The authors rejected this design because the use of a battery does not reduce the unit's power draw per se (batteries actually increase the power demand slightly because of their inherent inefficiencies) and also to eliminate the environmental footprint of a battery. The unit is only switched by particular on/off RC-5 IR codes, limiting the adaptability to one remote.

Smart Strips® switch several outlets based on one "control" outlet that the unit monitors for a standby current. However, the unit still allows phantom loads on the control outlet, and will only switch the balance of outlets on or off based the draw of the control load. The author's design overcomes this limitation.

Phantom Load Controller

Overview

The front and back of the phantom load controller is shown in Figure 1.

Figure 1. Front and Back of Phantom Load Controller

The prototype unit consists of two boxes – one containing the microcontroller and power control components, and the other the IR sensor tethered by a RJ25 telephone cord. Power enters through an IEC 320 receptacle on the back, and a 5-15R power outlet on the front allows a power strip to be plugged in to provide power to the entertainment center. A small fraction of the A.C. input current is converted to low-power 5 V_{DC} for component use through a switched mode power supply and the rest passes through a switched relay and current sensor, and then through the unit's power outlet. The IR sensor can receive any remote control signal from about 15 feet to turn power on.

The PWR/STORE button on the front allows the user to manually switch power on and off by pressing the button once. If the power is on and the user presses and holds the button for three seconds, the magnitude of the A.C. current through the power outlet at that moment is stored to non-volatile memory. The user can store the A.C. current draw to memory while all devices are in their standby mode. This provides a threshold against which A.C. current is compared in the future, to know whether the entire system is in standby mode. When the load is equal or below this threshold within a certain interval for five minutes, power is turned completely off.

A green LED is on when the load is switched on, and blinks to inform of other operations. When the user presses and holds the PWR/STORE button, the LED will blink slowly and go solid then begin blinking rapidly representing that it has begun sampling the current, then conclude with four blinks to show the store process is complete. The LED will also rapidly blink about every 15 seconds to represent that it is monitoring the current. A second RJ25 jack is for In Circuit Serial Programming (ICSP) to update microcontroller software but will not be present on future versions. The two additional buttons on the back will also not be present, and are for ICSP programming release and master reset.

Specifications

Prior to design, specifications were laid out. These specifications articulated that the device shall:

1. Act as a load control device that is capable of switching 120 V_{AC} 60 Hz power to multiple devices.
2. Power-on in two ways:
    a. Manual button press.
    b. Modulated IR signal (30-60 kHz).
3. Measure standby load current draw so that user can program standby current into non-volatile memory.
4. Draw a load of less than one watt itself.
5. Show the following indicators:
    a. Green LED to show power on.
    b. Blink to inform of non-volatile memory programming.
6. Perform the following sequence of functions:
    a. Upon receiving a valid IR signal or manual button press:
        1. Green LED will turn on.
        2. Relay will close 120 V_{AC} circuit.
    b. Upon receiving a "Store Load" button press:
        1. Green LED will blink until the end of three seconds.

2. After three seconds, the value from the power sensor will be stored in non-volatile memory.

c. Load monitoring:

1. Every minute the A.C. current draw will be compared to the value in memory:
   1. If it is less than or equal to this value:
      a. Relay opens circuit.
      b. Green LED turns off.
      c. Microcontroller awaits the next event.
   2. If it is greater than this value:
      a. The clock starts over and no change occurs.

Designing Hardware

The hardware specifications were constrained by power, cost, and adaptability.

Power

The power available to the system must be limited to less than one watt while the load is disconnected. To reach this constraint, only devices that need to be on should receive power. During standby, the unit waits for either a button press or modulated infrared signal; therefore, only the microcontroller and IR sensor are powered, along with the operational amplifier. Following a power-on request, the IR sensor is no longer needed and is switched off while the relays, LED, and current sensor are turned on to begin monitoring. Table 3 outlines the power draw of the components in the phantom load controller.

Table 3. Operating Current Draw of Phantom Load Controller Components

Component	**Operating Current Draw (mA_{DC})**	**Operating Power (mW_{DC})**	**Operating Power Including A.C. Conversion (mW_{AC})**
Power Relay (NO)	46.0	230	410.7
Current sensor	10.0	50	89.3
Photo-Relay	2.3	11.5	20.5
LED	2.0	10	17.9
Microcontroller	**1.3**	**6.5**	**11.6**
Operational Amplifier	**0.9**	**4.5**	**8.0**
IR sensor	**0.4**	**2**	**3.6**
ON State	62.5	312.5	558.0
STANDBY State	**2.6**	**13**	**23.2**

Table 3 shows the power draw before and after the power supply conversion according to manufacturer specifications. The switching power supply operates at 56% efficiency when converting from 120 V_{AC} so the standby-state power draw was expected to be about 23.2 mW. This value represents the expected maximum current draw while the actual is different (see the testing and results section).

Cost

The energy saved by the phantom load controller is a small amount, but over time accumulates to significant savings. To realize these savings more rapidly, a lower initial cost must be present to motivate commercial production. The design trade-offs with biggest impact involved the switching power supply and current sensor; see Table 4.

Table 4. Several Cost Trade-Offs

Component	**Cost**	**Attribute**	**Cost of Alternative**	**Alternative Attribute**
Switching Power Supply	$3.83	Efficiency 56%	$22.64	Efficiency 70%
Current Sensor	$2.90	Range ±5 A	$26.03	Range ±3 A
Microcontroller	$1.55	6 I/O	$2.99	16 I/O

The increased power efficiency of 14% was not worth another $18.81. The current sensor needs to have a narrower range than ±5 A to allow for precise analog to digital conversion; however, this limitation was overcome with amplification to ±2 A and saved $23.13. The authors chose an inverting amplifier that narrowed the standby current measurement range from ±5 A to ±2 A and therefore increased the 10-bit analog to digital measurement precision from 102 bits/amp to 256 bits/amp.

Adaptability

The phantom load controller needs to be able to fit multiple users with different entertainment setups. Since the phantom load controller is primarily turned on by an infrared remote, the user may not always have their equipment directly in front of them as shown in Figure 2.

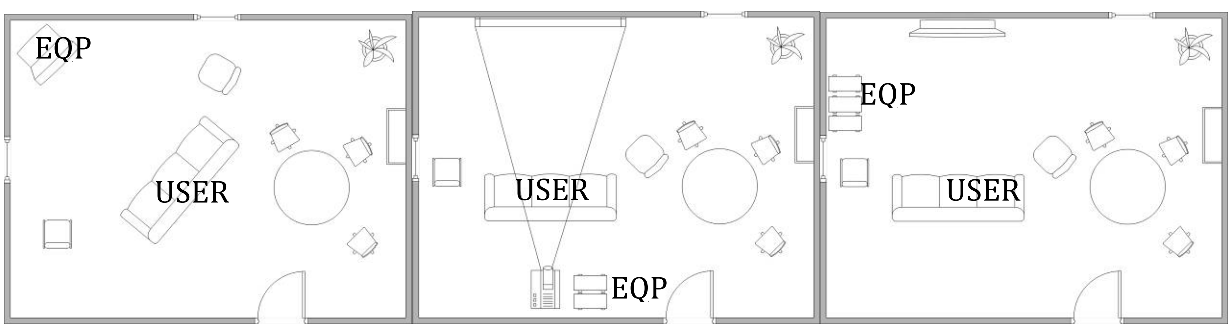

Figure 2. Entertainment equipment placed straight ahead, behind, and to the side of user.

This called for a level of adaptable modularity, so the IR sensor was placed in its own enclosure and pigtailed to the control box via a standard six position RJ25 jack. This allows the user to vary the length of cable to suit their specific need. The phantom load controller also can handle up to 14 A of entertainment power allowing numerous devices to be plugged into it. The phantom load threshold is also adaptable. Since the phantom load may change as the user expands or changes their entertainment center, the phantom power threshold can be reprogrammed with the press of a button. The IR sensor is also adaptable to various remote controls. The sensor does not decode specific power-on requests but rather uses any properly modulated IR signal to turn the unit on. Therefore, any button press on any IR remote control should result in a power-on.

Designing Software
The software map is shown in Figure 3.

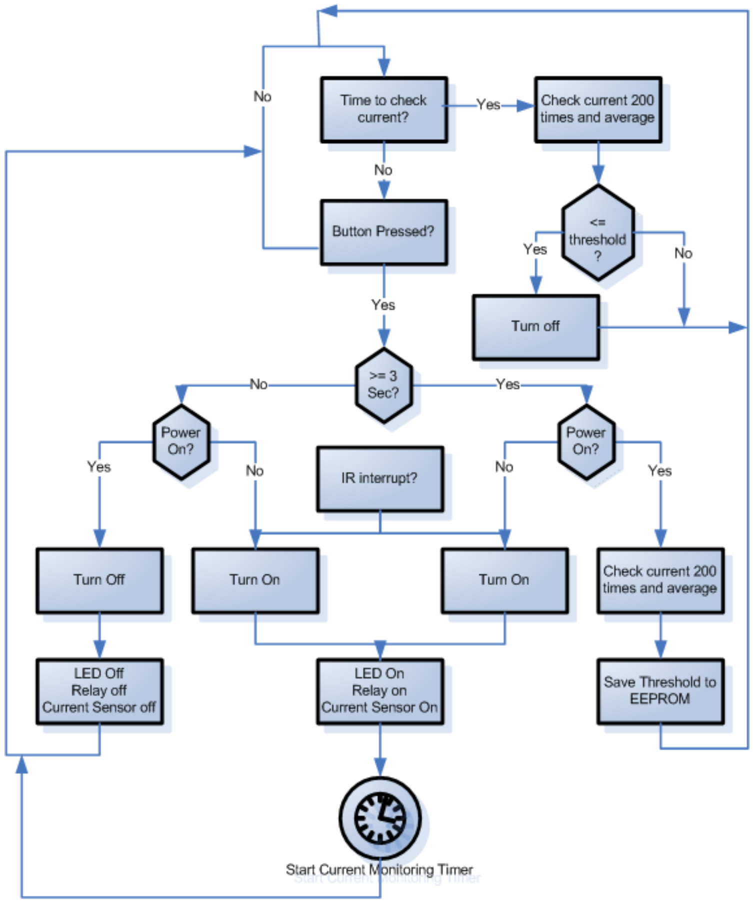

Figure 3. Phantom Load Controller Software Map

The software can be broken down into two main functions, the main program loop and the interrupts.

Main Loop
The main loop has a simple job, to monitor for a button press from a user and whether or not it is time to check the current. When a button press does take place, the program counts how long the button is held down to determine a power switch or threshold store. The loop also checks for a timer interrupt flag that starts the sampling of the current to compare to the saved threshold.

Interrupts
Five interrupts were necessary for the phantom load controller.
While the power is off, only the IR interrupt is on looking for a modulated IR signal. This interrupt is disabled once power is on.

A 15 second timer interrupt is necessary in order to know when to monitor the current. When the 15 seconds is done counting, a flag is thrown that the main loop catches to call the current checking function. When this function detects a current lower than the threshold 20 times, or 5 minutes, the power is switched off. This timer interrupt is only enabled when the load is powered.

When the user wishes to store a threshold A.C. current value, two interrupts are used. Current measurements may only be obtained over integer multiples of 60 Hz periods. Thus, one timer interrupt meters out time in 0.016667 second intervals. An analog-to-digital conversion interrupt was also utilized to indicate when each conversion was complete and to continue with the next sample. A.C. current is measured over 200 hundred periods and the values are averaged to increase precision. These interrupts are enabled only during the current capture function.

The non-volatile Electrically Erasable Programmable Read-Only Memory (EEPROM) utilizes the final interrupt when the threshold value is stored. This interrupt simply tells the microprocessor to wait until the write is complete. It is only enabled during the EEPROM writing function.

Results and Analysis

Testing and Results

The phantom load controller was found to only pull 2.2 mA during standby, which amounts to 0.026 W, this is only 2.8 mW higher than the designed standby load in Table 3. This device therefore meets the IEA's 1-Watt Plan for standby power. Three common devices in an entertainment center were used during testing: JVC 21" television, Sony DVD player, and Magnavox VCR in a setup shown in Figure 4.

Figure 4. Testing Scenario

Testing revealed that the equipment needed to be "warmed up" before storing the threshold value or else incorrect switching would take place. So after a five-minute warm-up period, each device was turned off and the threshold was stored. Following this step, each device was switched on and off ten times to make sure it fell above and below the threshold and switched properly. Table 5 outlines the results.

Table 5. Phantom Load Controller Testing Results

Device	Phantom Load (W)	Stayed On 10 Times	Switched Off 10 Times
JVC 21” TV	1.03	Yes	Yes
Sony DVD player	0.72	Yes	Yes
Magnavox VCR	11.0	Yes	Yes
All Three Together	12.27	Yes	Yes

These results indicate that the phantom load controller operates across a wide range of phantom loads from 11 W to less than 1 W, and maintains its precision even when numerous devices are powered together. When all three devices were together, turning off any one of them did not turn off the system but still required all three to be powered down.

Break-Even Analysis

The total cost of the prototype phantom load controller is about $68.16. Assuming mass production would result in a 75% cost reduction, the total production cost would be about $17.00. Assuming a 25% gross profit margin the sale price would be about $21.25. If the end user has five devices in their entertainment center averaging 5 W of phantom load per device, the total load would be 25 W. If these devices are not used 75% of a year, they are in standby for about 6,575 hours a year. This amounts to 164 kilowatt-hours. The average cost of residential electricity in 2008 was 11.21 cents/kilowatt-hour[16]. The total cost for this user per year is $18.38, showing a break even after 1.16 years. Any use of the phantom load controller beyond this point represents savings to the user.

Summary and Conclusions

The number of devices in a home that continue to use a significant amount of power in their standby mode is increasing. Up to 10% of a home’s energy use can be phantom loads. This leads to a large carbon footprint. Fortunately, however, the problem of phantom loads is relatively straightforward to address through policy and technology. The IEA has proposed the “1-Watt Plan” to encourage governments, users, and manufactures to only use devices that require less than one watt in standby. Home entertainment areas are centralized locations where many common phantom loads can be controlled in a convenient manner. The authors designed a phantom load controller that successfully turns on numerous loads with any remote control signal and turns them off when their power draw drops below a user-programmable threshold. The unit draws approximately 26 mW in standby mode and the user can financially break even shortly after a year.

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