ELECTRIC POWER RESEARCH INSTITUTE

Power Harvesting for Sensors in Electric Power Utility Applications

State-of-the-Science Review and Test Bed Development

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Technical Update, December 2011

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Southwest Research Institute

This is an EPRI Technical Update report. A Technical Update report is intended as an informal report of continuing research, a meeting, or a topical study. It is not a final EPRI technical report.

NOTE

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ABSTRACT

The value of wireless sensor networks in remote locations or at high-voltage applications depends on the networks' reliable operation for extended period of times without human intervention. Therefore, a major consideration when using wireless sensors is the problem of providing power to the sensors. Presently, wireless sensor nodes are commonly powered by batteries. This situation presents a substantial roadblock to the widespread deployment of wireless sensors due to battery lifetimes and other issues because the replacement of batteries is cost prohibitive. Reducing these power requirements and harvesting power from sources available in the environment immediately surrounding the sensor are the keys to resolving this issue.

Alternatives have recently been explored to supplement or even move away from batteries by harvesting power from the variety of energy sources in the sensor node's environment. The idea is that a sensor node would convert unused energy from its environment into electricity for use by the electronics. If the ambient energy can be captured and used, this energy could prolong the life of the battery or, ideally, provide power for the lifespan of the sensor node. This opportunity will allow the sensor node to be placed in any inaccessible location to provide vital information on structural, environmental, or operational conditions.

Currently, the Electric Power Research Institute (EPRI) is evaluating available power harvesting technologies and, in some cases, new solutions are being developed. The work includes the investigation of energy harvesting from a range of sources, including solar, vibration, magnetic and electric fields, thermal differences, and radio frequency energy. As part of the project, several harvesting technologies have been implemented in sensor technologies and deployed in the field.

EPRI's objective is to establish a test bed and protocol to evaluate power harvesting technologies so that the best existing technology can be identified for immediate consideration and new technologies can be comparison tested as they become available. The features of the test bed and protocol will be selected to best match the electric power sensor applications that are known and envisioned. The test system will be designed to be as flexible and capable as practical and with consideration for keeping it straightforward to use.

Keywords

Energy harvesting
Magnetic field
Radio frequency
Solar
Thermal energy
Vibration

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1 INTRODUCTION

Background

The value of wireless sensor networks in remote locations or at high-voltage applications depends on the networks' reliable operation for extended period of times without human intervention. Therefore, a major consideration when using wireless sensors is the problem of providing power to the sensors. Presently, wireless sensor nodes are commonly powered by batteries. This situation presents a substantial roadblock to the widespread deployment of wireless sensors due to battery lifetimes and other issues because the replacement of batteries is cost prohibitive. Reducing these power requirements and harvesting power from sources available in the environment immediately surrounding the sensor are the keys to resolving this issue.

Alternatives have recently been explored to supplement or even move away from batteries by harvesting power from the variety of energy sources in the sensor node's environment. The idea is that a sensor node would convert unused energy from its environment into electricity for use by the electronics. If the ambient energy can be captured and used, this captured energy could prolong the life of the battery or, ideally, provide power for the lifespan of the sensor node. This opportunity will allow the sensor node to be placed in any inaccessible location to provide vital information on structural, environmental, or operational conditions.

Currently, EPRI is evaluating available power harvesting technologies and, in some cases, new solutions are being developed. The work includes the investigation of energy harvesting from a range of sources including:

- Solar
- Vibration
- Magnetic and electric fields
- Thermal differences
- Radio frequency (RF) energy

As part of the project, a number of harvesting technologies have been implemented in sensor technologies and deployed in the field. However, many of these types of energy sources that are harvested, including solar, are intermittent. This requires the energy to be stored for use when the energy source is not available or if the instantaneous power does not meet the sensor's needs. The challenges of using rechargeable batteries for this purpose include their life expectancy and their ability to charge in low-temperature conditions. In order to jump these hurdles, various approaches are being investigated, including the use of supercapacitors combined with lithium batteries in a hybrid approach.

Project Objectives

EPRI's objective is to establish a test bed and protocol to evaluate power harvesting technologies so that the best existing technology can be identified for immediate consideration and new technologies can be comparison tested as they become available. The features of the test bed and protocol will be selected to best match the electric power sensor applications that are known and envisioned. The test system will be designed to be as flexible and capable as practical and with consideration for keeping it straight forward to use.

Report Structure

The remainder of this document is organized as follow:

- Chapter 2 presents a review of power harvesting methods and energy sources including possible power utility applications, advantages, and disadvantages.
- Chapter 3 presents some examples of power harvesting technologies that EPRI has incorporated into sensors field trials and demonstrations.
- Chapter 4 presents the efforts towards the development of a power harvesting test bed for evaluation and understanding of emerging power harvesting technologies.
- Chapter 5 presents the references used during the creation of this document.
- Finally, Appendix A presents a list of companies/organizations engaged in developing or researching power harvesting technologies. The intention is to give the readers an idea of who is doing work, what products could be evaluated, and possible organizations to collaborate with.

2
POWER HARVESTING METHODS AND SOURCES

Introduction

There are many alternative energy sources to conventional batteries. This section focuses on energy sources that have some foreseeable viability for wireless sensor system components in electric power applications. A review of potential power harvesting methods sources are shown in Table 2-1 and Table 2-2. Any of these energy sources or a hybrid combination may be worth pursuit depending on the site environment and power requirements. Other energy sources exist such as radioisotopes, hand cranks, hydroelectricity, etc., but are discounted for the envisioned applications and therefore not addressed herein.

The information in the tables are derived from a combination of publish studies, theory, and information that is available in textbooks. The sources of information for each technique are given in the last column of Table 2-1. While this comparison is by no means exhaustive, it does provide a broad cross section of potential methods for harvesting power. Other potential sources were also considered but deemed to be outside the applicable conditions under consideration. It is important to mention that no alternative exists that will solve the problem for all, or even the majority of cases. However, many attractive and creative solutions do exist that can be considered on an application by application basis. This chapter will describe briefly each method presented on Table 2-1 and Table 2-2.

Table 2-1
Power Harvesting Technologies

Harvested Source		Avg. Performance	Commercially Available	References
Solar (Ambient Light)	Outdoor	15 mW/cm^3 (direct)	Yes	[1],[2],[3]
		150 $\mu W/cm^3$ (cloudy)		
	Indoor	6 $\mu W/cm^3$		
Vibrations	Electromagnetic	10 - 15 $\mu W/cm^3$	Yes	[4],[5]
	Electrostatic	50 $\mu W/cm^3$		[4],[5]
	Piezoelectric	250 $\mu W/cm^3$		[4],[5]
	Magnetostrictive	600 $\mu W/cm^3$		[6],[7]
Ambient Airflow		380 $\mu W/cm^3$	No	[1],[2],[8]
Temperature Gradient (Thermoelectric)		40 $\mu W/cm^3$	Yes	[1],[9],[10]
Ambient RF		$< 1 \mu W/cm^2$	Yes	[1],[12]
Magnetic Field Power		--	No	[13]
Electric Field Power		--	No	[14]

Table 2-2
Comparison of Power Harvesting Technologies

Harvested Source		Advantages	Disadvantages
Solar (Ambient Light)	Outdoor	Useful in recharging batteries at remote locations	Limited by availability of direct light, fragility; unequal at different points
	Indoor		
Vibrations	Electromagnetic	No need of smart material, no external voltage needed	Bulky size, max. voltage of 0.1V, difficult to integrate with electronics
	Electrostatic	No need of smart material, voltage of 2~10V, easy to integrate with electronics	External voltage needed, mechanical constraints needed, capacitive
	Piezoelectric	No external source needed, voltage of 2~10V, compact configuration	Depolarization, brittleness, charge leakage, high output impedance, poor coupling
	Magnetostrictive	No depolarization problem, high flexibility, suited for high freq. vibration	Non-linear effect, pick-up coil, may need bias magnets
Ambient Airflow			Unequal at different points, no airflow no power, large wind mills average only 20% efficiency
Temperature Gradient (Thermoelectric)		Can store extra energy produced, output compatible with micro-systems	Power output varies with temperature conditions
Ambient RF		Can penetrate buildings, can be converted into electricity easily	Not practical for dense networks, power can be limited by FCC regulations
Magnetic Field Power			Must be close to the current carrying conductor, amount of power harvested is dependent on obtaining sufficient voltage from the coil
Electric Field Power		Voltage is constant under load conditions, components are simple to construct	Amount of power harvested is very sensitive to the load

Solar Energy

While a wide variety of harvesting modalities are now feasible, solar energy is a mature technology for large scale energy generation. Photovoltaic systems are found from the Megawatt to the milliwatt range producing electricity for a wide range of applications: from wristwatch to grid-connected PV systems. Solar energy harvesting through photovoltaic conversion provides the highest power density, which makes it the modality of choice to power electronics that consume several mW using a reasonably small harvesting module. Solar energy is abundant outdoors during the daytime. In direct sunlight at midday, the power density of solar radiation on the earth's surface is approximately 100 mW/cm^3. As seen in Table 2-1, the power available falls off by a factor of about 100 on overcast days.

Electric Utility Application

Solar energy may be a viable power source for electric utility sensor applications since installation sites are typically outdoor environments with sky exposure. Solar panels (aka solar arrays or modules, or photovoltaic panels, arrays, or modules) convert incident solar energy into DC electrical power using a photovoltaic process. Solar panels are typically made up of several p-n junction cells in a series-parallel configuration to boost voltage (series) and current (parallel) output levels.

Mature technologies such as silicon solar cells with single crystal silicon cells are better suited to light conditions and the spectrum of light available outdoors. Single crystal silicon solar cells present efficiencies ranging from 12% to 25% under light conditions as one would find outdoors. Thin film amorphous silicon or cadmium telluride cells are also commercially available and offer better efficiency indoors because their spectral response more closely matches that of artificial indoor lighting. Thin film amorphous silicon or cadmium telluride cells cost less than single crystal silicon, but also have a lower efficiency of approximately 10%. Therefore, the power available from photovoltaics ranges from about 15 mW/cm^2 outdoors to 10 $\mu W/cm^3$ indoors.

Advantages

The advantages of solar panels are that the technology is mature and field proven, and there are many commercial products available. The power directly scales with panel area, so once a design is characterized it can be readily extrapolated with high confidence to similar applications based on the power requirement.

Disadvantages

The disadvantage of solar panels is the need to accommodate day/night cycles and output power variation due to geographic location, season, cloud cover, physical obstructions (buildings, mountains, etc.), and pollution/debris. This is done with battery storage for the day/night cycles, and design "overkill" to cover the worst case low end of the variation range.

Vibration Energy

Harvesting power from vibration is promising and one of the most effective approaches. Energy generation from mechanical vibration usually uses ambient vibration around the energy harvesting device as an energy source and then converts it into useful electrical energy. Low level mechanical vibrations are present in many environments. Table 2-3 shows measurements on several different vibrations sources including power transformers [11]. It can be noticed that the primary frequency of all sources is between 60 and 240 Hz. Acceleration amplitudes range from about 0.1 to 10 m/s^2. A combination of theory and experiment showed that in general approximately 200 $\mu W/cm^3$ could be generated from vibrations that might be found in certain environments.

Because vibration based power generators are almost always having fairly low damping, it is essential that the resonant frequency of the converter match the dominant frequency of the input vibrations. In many applications the vibration spectrum is known beforehand and the system can be designed to resonate at the appropriate frequency. However, in other applications the frequency of the input vibrations is either unknown or changes with time. Therefore, self-tuning generators would be necessary in these situations.

Table 2-3
Summary of Several Vibration Sources

Vibration Source	Peak Acceleration	Frequency
Power Transformer	0.3 – 0.8 m/s^2	100 – 120 Hz
Base of 3-axis machine tool	10 m/s^2	70 Hz
Kitchen blender	6.4 m/s^2	121 Hz
Cloth dryer	3.5 m/s^2	121 Hz
Small microwave oven	2.3 m/s^2	121 Hz
Washing machine	0.5 m/s^2	60 Hz
Refrigerator	0.1 m/s^2	240 Hz
HVAC vents in office building	0.2 – 1.5 m/s^2	60 Hz
Notebook computer while CD is read	0.6 m/s^2	75 Hz
External window (2ft x 3ft) next to busy street	0.7 m/s^2	100 Hz

Electric Utility Application

Vibration energy may be a viable power source for electric utility sensor applications since the power lines are known to exhibit low-frequency Aeolian vibration due to wind. Insulators provide mechanical support between the power lines and the tower structures and couple some of this vibration energy as well. Consequently sensors mounted on a tower structure or on any of the system components may be able to harvest vibration energy. In substations, additional vibration energy sources exist. For example, transformers, compressors or motors (for example, for cooling fans) vibrate at the power line frequency (50-60 Hz) and/or harmonics (100-120 Hz).

Unlike solar and wind energy, large historic databases are not readily available to estimate the amount of vibration energy that is available at electric power utility sites. Based on EPRI's 1979 Transmission Line Reference Book "Wind-Induced Conductor Motion", vibration displacement amplitudes in the frequency range of 17-35 Hz are typically on the order of 5-12% of the conductor diameter with one vibration damper on the line, and 3-8% of the conductor diameter with two vibration dampers. The response peak is at approximately 19 Hz in either case. For a Drake size conductor (diameter of 1.108"), the estimated vibration displacement is from 0.033" to 0.133". This corresponds to peak acceleration levels from 0.5g to 2.5g, or RMS levels from 0.35g to 1.8g (based on sinusoidal excitation). While these levels are significant and indicate that vibration energy may be possible for some wireless sensor applications, the average time profile of vibration energy must be investigated so that suitable sensor design requirements can be targeted.

The amount of vibration energy available at potential sensor locations on the insulator and tower structure is expected to be less than that on the conductor and is expected to vary greatly depending on the mechanical configuration. This will need to be researched in order to make a proper assessment. It is postulated that a vibration harvester in the load bearing insulator linkage may be effective for power harvesting.

In substations, candidate transformer and motor locations are loosely identified at this point in the research. Interviews with site personnel and subject matter experts are planned to pinpoint the best candidates. Site data collection will likely be required to quantify the energy levels that are available including the time profile. Unlike wind-induced conductor vibrations, transformer and motor vibration profiles are expected to be much steadier levels that closely track with system loading.

Advantages

The advantages of vibration harvesting are similar in a way to wind energy, at least for conductor Aeolian vibrations, because they are due to the wind. In that sense, Aeolian line vibration energy is a good complement to solar energy in a hybrid power scheme. Wind is available at night, and, in general, when solar energy is below average (winter, cloudy), winds are more likely to be above average; and when winds are below average (summer, no clouds), solar energy is more likely to be above average. The advantage of vibration harvesting from transformers and motors is that the levels are steadier which simplifies the power management design (conversion, storage, etc.).

Disadvantages

The disadvantage of vibration harvesting is that there are only a few products available, so a custom design approach is most likely needed to optimize for the electric power applications. Custom approaches may be effective, but each application design (power line, insulator, tower, transformer, motor) will likely require characterization of the temporal profile (frequency response and amplitude) and then frequency tuning to optimize performance; this amounts to additional work that must be budgeted into the development.

Types of Vibration Harversting Devices

Several researchers have developed devices to scavenge power from vibrations. These devices can be classified into four categories: electromagnetic (inductive), electrostatic (capacitive), piezoelectric, and magnetostrictive. A brief discussion of these devices will follow.

Electromagnetic

Electromagnetic power conversion results from the relative motion of an electrical conductor in a magnetic field. Typically the conductor is wound in a coil to make an inductor and the relative motion between the coil and magnetic field cause a current to flow in the coil. The amount of electricity generated depends upon the strength of the magnetic field, the velocity of the relative motion and the number of turns of the coil.

Electrostatic

Electrostatic generation consists of two conductors separated by a dielectric (that is, a capacitor), which move relative to one another. As the conductors move the energy stored in the capacitor changes, thus providing the mechanism for mechanical to electrical energy conversion. If the charge on the capacitor is constrained, the voltage will increase as the capacitance decreases. If the voltage across the capacitor is constrained, charge will move from the capacitor as the capacitance decreases.

Piezoelectric

Piezoelectric materials are materials that physically deform in the presence of an electric field, or conversely, produce an electrical charge when mechanically deformed. This effect is due to the spontaneous separation of charge within certain crystal structures under the right conditions producing an electric dipole. When a piezoelectric material is placed under a mechanical stress, an open circuit voltage appears across the material. Likewise, if a voltage is put across the material, a mechanical stress or strain depending on how the material is constrained develops in the material.

Magnetostrictive

Magnetostrictive materials also possess suitable characteristics. These materials deform when placed in a magnetic field and conversely if strained can induce changes in a magnetic field. Magnetostrictive materials can be used independently but have more typically been employed in piezoelectric-magnetostrictive composites. Such composites were originally intended for use in magnetic field sensors but have more recently been evaluated for use in energy-harvesting applications.

Wind Energy

Wind power has been used on a large scale as a power source for centuries. Large windmills are still common today. However, the authors are unaware of any commercially available devices to generate power at a very small scale from air flow.

Large scale windmills can operate at efficiencies of up to approximately 40%. This efficiency is dependent on wind velocity, resulting on average operating efficiencies of usually about 20%. Windmills are generally designed such that maximum efficiency occurs at wind velocities around 8 m/s (or about 18 mph). Therefore, at low air velocity, efficiency can be significantly lower than 20%. However, even at efficiencies lower than 20%, power densities from air velocity can be quite promising. As there are many possible applications in which a fairly constant air flow of a few meters per second exists, it seems that research leading to the development of devices to convert air flow to electrical power at small scales is expected.

Electric Utility Application

Wind energy may be a viable power source for electric utility sensor applications since installation sites are typically outdoor environments with open air exposure. Wind turbines typically have two or three propeller blades that comprise the rotor. The blades are propelled by the wind and turn the rotor. The rotor speed is typically increased using a gearbox in order to drive the generator fast enough to produce electricity. There is a minimum wind speed threshold that must be met in order for the turbine to produce electric power. According to the American Wind Energy Association website (http://www.awea.org/), wind power is a function of air density, blade area, the wind speed cubed, the coefficient of performance, generator efficiency, and gearbox/bearings efficiency. Note the high sensitivity to wind speed (velocity) as it is raised to the 3rd power.

The National Renewable Energy Laboratory (NREL) publishes maps of the United States on its website (http://www.nrel.gov) that illustrate average wind speed levels based on many years of data collection. It is clear from these maps that wind energy is much more “spotty” than solar energy. In other words, solar coverage across the states is generally consistent whereas wind coverage is consistently strong in some regions (for example, the Midwest plains) but falls off to marginal levels just about everywhere else. This is important because of the start-up threshold.

Advantages

The advantage of wind turbine technology is that it's mature and field-proven. Wind energy is also a good complement to solar energy in a hybrid power scheme. Wind is available at night, and, in general, when solar energy is below average (winter, cloudy), winds are more likely to be above average; and when winds are below average (summer, no clouds), solar energy is more likely to be above average.

Disadvantages

There are several disadvantages with wind turbine technology that make it challenging to implement in electric power sensor applications, especially as a standalone power source. First, wind power varies greatly with location; oftentimes even within a small geographical area. Wind power also varies greatly over time and is unpredictable. Wind turbines generally need to be installed many feet above structures to avoid turbulence and capture the most energy. Moving mechanical parts in turbines generally leads to greater complexity (that is, reflects higher cost), and lower reliability. The products that exist, even the ones that are advertised as small, are physically much larger than desired, and produce much greater power than is needed. Micro turbine designs of size suitable for wireless sensors are primarily academic research, not proven products.

Thermal Energy

The use of thermoelectric generators to capitalize on naturally occurring temperature variations can also provide a means by which power can be scavenged from the environment. Thermoelectric generators use the Seebeck effect, which describes the current generated when the junction of two dissimilar metals experiences a temperature difference. Using this principle, numerous p-type and n-type junctions are arranged electrically in series and thermally in parallel to construct thermoelectric generators. Thus, when a thermal gradient is applied to the device, it will generate an electrical current (thermal energy is directly converted to DC electricity) that can be utilized to power electronics. These techniques are mature and have been used to convert the heat from radioisotopes to electric power in many spacecraft applications.

The maximum efficiency of power conversion from a temperature difference is equal to the Carnot efficiency. However, available thermoelectric energy conversion devices achieve only a small fraction of Carnot efficiency since the transport properties of available materials are insufficient. Moreover, it has been demonstrated experimentally that a thermoelectric micro-device can be capable of converting 15 $\mu W/cm^3$ from a 10°C temperature gradient [9,10]. While this is promising, situations in which there is a static 10°C temperature difference within 1 cm^3 are very rare. Alternatively, the natural temperature variation over a 24 hour period might be used to generate electricity. It can be shown with fairly simple calculations that an enclosed volume containing an ideal gas could generate an average of 10 $\mu W/cm^3$ [9,10]. This is assuming no losses in the conversion of the power to electricity.

Electric Utility Application

Thermal energy may be a viable power source for electric utility sensor applications since surfaces and components may be heated from solar radiation or power dissipation (I^2R in conductors; inefficiency in motors, etc).

The amount of thermal energy available for harvesting at electric utility sensor sites will need to be investigated. If suitable "hot spots" significantly greater than 10 ºC above ambient are identified, then this approach may have merit. For a location to be suitable, it will need to have a surface area that the harvesting device can be mounted to with a low thermal resistance. A thermal paste or gasket material may be needed depending on the surface texture.

Advantages

The advantage of thermal harvesting from devices like transformers and motors is that thermal dissipation may be much steadier than weather-based energy sources like solar, wind, and wind-driven vibration. Thermal harvesters have the advantage of no moving parts which make them highly reliable. They generate DC which simplifies conversion and avoids rectifier losses and tuning optimization that are inherent to AC vibration harvesters. Also, there is potential to drive thermal harvester cost very low using semiconductor mass manufacturing techniques if there is sufficient volume demand.

Disadvantages

The disadvantage of thermal harvesting is the need to identify, verify, and approve candidate hot spots to which the device can be attached. Also, the need for an effective heat sink and suitable mounting method likely drives a custom packaging development for each unique application. Additionally, the level of power output is still substantially lower than other possible methods (<5%). Furthermore, the fabrication cost is high, and the volume and weight are still too large for microscale sensing systems. Products do not appear readily available off the shelf although evaluation kits appear to be offered.

Radio Frequency Energy

Another way of supplying power to sensor networks is that of wireless energy transmission. In this case, power is generated elsewhere and transmitted to a sensor node by some form of electromagnetic wave or radio frequency radiation. This concept can utilize two different RF energy sources, ambient or controlled RF sources.

The conversion is based on a rectifying antenna, constructed with a Schottky diode located between the antenna dipoles to convert received radio power to a DC supply for the sensor electronics. The overall RF-to-DC power efficiency for wireless transmission is poor because the amount of power received at the sensor is miniscule and decreases as a function of the distance squared; but this may not be a factor if supply power is readily available at the radio transmitter and it can be positioned within a few meters of the sensors. Current research efforts in RF wireless energy transmission focus on improving the conversion efficiency and attempting to maximize the output power by designing efficient antennas and rectifying antennas.

The operating range is determined by the RF frequency, RF transmitter power, RF transmitter antenna gain, sensor receiving antenna gain, the RF-to-DC power conversion efficiency of the rectenna circuitry, and the sensor average DC power requirement.

Electric Utility Application

Radio Frequency (RF) energy may be a viable power source for electric utility sensor applications if it is possible to strategically position RF transmitters in locations that have access to power and are still in close proximity to the sensors.

It may be interesting to note that if perchance the sensor site is in close proximity to VHF/UHF television and/or FM broadcast transmitters, then it may be possible to harvest from 100 kW or MW power levels without needing to set up a special purpose transmitter on site; of course such a location is not anticipated.

Advantages

The motivation is that it may be cost effective to power smaller numbers of RF transmitters located in relatively safe and accessible locations, instead of having to periodically replace batteries in a larger number of individual sensors at potentially hazardous locations (high voltage, height, confined and/or restricted physical access).

Disadvantages

Some of the diasadvantages of RF energy is that the RF transmitters require power and the range to the sensors is limited. Also, the amount of power that can be harvested is relatively small compared to the other sources considered, even when the transmitter is positioned in relatively close proximity to the sensors.

Magnetic Field Energy

The 60-Hz magnetic field generated by current carrying conductors can be coupled using an inductive coil wrapped on a high permeability core to power sensor electronics. The amount of energy coupled to the sensor will be a function of several parameters, including the number of turns, core material, and length, as well as the radius of the coil itself. The inductive coil will have a mutual inductance as well as a self inductance. For this approach to be viable, the sensor must be attached to the conductor because the magnetic field strength falls off sharply with distance.

Maximum load power is achieved when the coil is oriented concentrically around the conductor for maximum magnetic flux through the coil. Magnetic field power harvesting in this manner works on the same principles as a transformer. In this case the primary is the conductor, and the secondary is the multi-turn coil.

Electric Utility Application

Magnetic field energy may be a viable power source for electric utility sensor applications since there may be large 60-Hz currents flowing through the power lines in close proximity to some of the sensors. Magnetic field power harvesting has been already implemented in EPRI sensors that are mounted on power lines to monitor line temperature and current.

Advantages

The advantage of magnetic field energy is that a harvester design has been implemented and proven to be effective in the EPRI conductor/splice sensor. The coil and electronics could be easily package within the sensor unit as it is mechanically simple. The coil just needs to be oriented perpendicular to the conductor, and preferably as close as possible. The component costs are relatively low and the board real estate requirement is relatively small. It is also advantageous that this design is not tied to the conductor voltage in any way; it is only a function of the current.

Disadvantages

The disadvantage of magnetic field energy is that the sensor needs to be attached to the conductor, and that may not be possible for many of the sensors applications. Another disadvantage is that conductor current typically fluctuates; therefore the design must accommodate the lowest possible level. When there is no current flowing, there is no magnetic field energy available to harvest, and power storage and/or a battery backup would be required for sensor operation.

Electric Field Power

High voltage power conductors generate a 60-Hz electric field from which power can be coupled using a capacitive plate to power the sensor electronics. A capacitive divider is formed between the plate and the line and the plate and ground (earth) where the capacitances are a function of the plate surface area. The output power is a function of plate dimensions/geometry as well as the load resistor. The electric field power harvesting approach is very sensitive to the load.

Electric Utility Application

Electric field energy may be a viable power source for electric utility sensor applications since there are normally large 60-Hz voltages whether it is from distribution lines of just a few kV or transmission lines of up to 765 kV. An electrically “floating” conductive object located between the high voltage lines and earth ground forms a capacitive voltage divider. The object is charged by the electric field (E-Field) to a voltage depending on the stray capacitance values (object to ground and object to line). The voltage across the object (either with respect to ground or the high voltage line) can be loaded to harvest power from the electric field. Analysis and experiments indicate that the source impedance is very high, but the amount of power available may be sufficient nonetheless. A cylindrical coupling plate surrounding a power line was investigated during past EPRI sensor developments, but many other physical realizations are possible [14]. A suitable E-Field "antenna" would need to be custom designed for each unique application, ideally integrated with the device package. Simple plate constructs may be effective; once a design is proven, it may be easy to extrapolate it to different applications.

Advantages

The advantage of using electric field energy, unlike all of the other ambient energy sources, is that the line voltage is fixed for each power delivery application. Consequently, a constant amount of power is continuously available to harvest with the actual magnitude dependent on the physical configuration/size of the "antenna" and its proximity with respect to the line voltages and earth. With a stable and suitable physical configuration, a design can be essentially guaranteed to operate whenever the line is energized.

Disadvantages

The disadvantage of using electric field energy is that commercial off the shelf products are not available; therefore custom designs need to be developed for the applications. A challenge will be producing a design in which the stray capacitances are dominated by the design and not easily influenced by surrounding objects. It may also be a challenge to efficiently match the relatively high voltage and high source impedance of the harvester to the wireless sensor load. Similar to H-Field harvesting, there are problems with E-Field harvesting when it comes to testing the sensors prior to installation at the utility site. For this reason power storage and/or a backup battery may be beneficial.

3
EXAMPLES OF POWER HARVESTING TECHNOLOGIES UNDER FIELD TRIAL

The value of wireless sensor networks in remote locations or at high voltages applications depends on their reliable operation for extended period of times without human intervention. So, a major consideration when using wireless sensors is the problem of providing power to the sensors. EPRI is evaluating available power harvesting technologies and in some cases new solutions are being developed. The work includes the investigation of power harvesting from a range of sources (see Figure 3-1). These ambient sources include:

- Solar
- Vibration
- Magnetic and Electric Fields
- Thermal Differences
- Radio Frequency (RF) Energy

As part of the project, a number of harvesting technologies have been implemented in sensor technologies and deployed in the field. The following sections describe some examples of various harvesting technologies implemented in sensor developments and demonstrations that are under way.

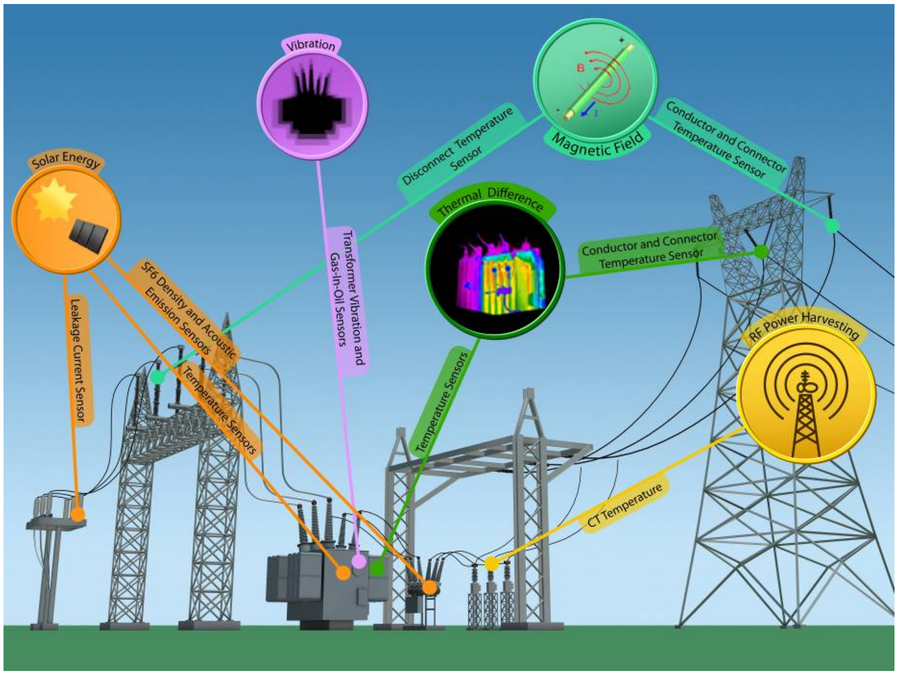

Figure 3-1
Range of Energy Sources for Which Power Harvesting Technologies are being Evaluated.

Solar Energy

EPRI has implemented several solar power harvesting technologies in sensors developments and demonstrations. Figure 3-2 shows an image of a solar-powered tank-top temperature sensor installed on the three phases of an oil circuit breaker. These sensors are used to monitor the difference in temperature between each phase.

In addition, Figure 3-3 shows an image of a solar-powered sensor that monitors and transmits the SF6 density signal at periodic intervals. This density sensor draw significant current compared to what can be harvested with a small solar cell, so challenging solutions had to be engineered.

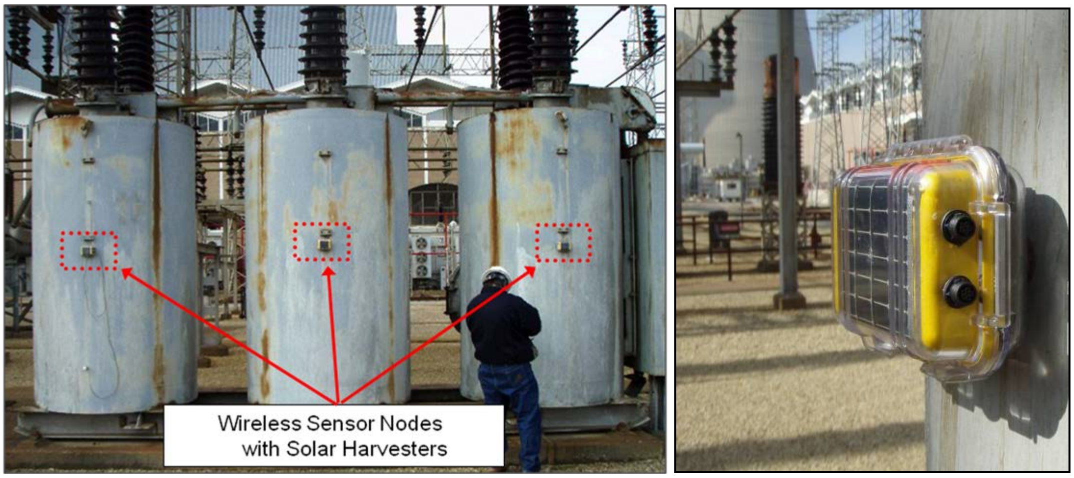

Figure 3-2
Solar-Powered Tank Temperature Sensors.

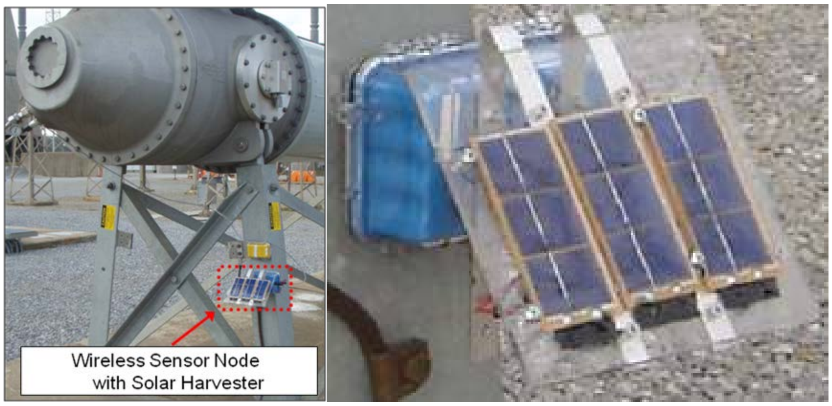

Figure 3-3
Solar Powered SF_6 Density Sensor Being Evaluated.

Vibration Energy

Vibration power harvesting is also currently being investigated for transformer monitoring. Figure 3-4 shows the vibration harvesters and a sample vibration profile of the available energy harvested from a 765-kV autotransformer over approximately 2-hour period. EPRI is using this information to develop power-harvesting sensors for transformers.

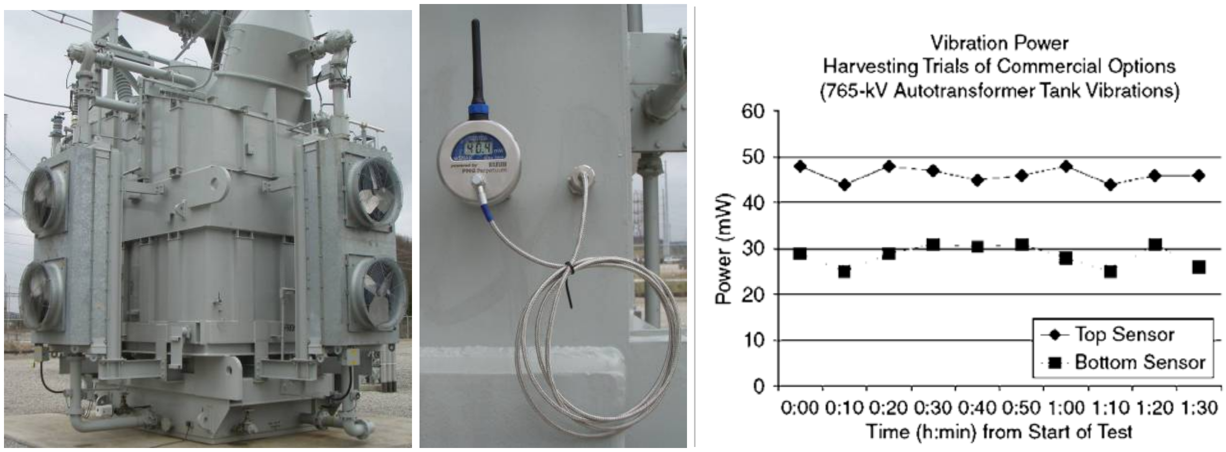

Figure 3-4
Vibration Harvester Module on 765-kV Autotransformer and Corresponding Power Harvested.

Thermal Energy

Thermal harvesting has been tested by EPRI for transformer monitoring. Figure 3-5 shows the thermal harvesters on a pad-mount distribution transformer. On the figure it can also be obseved the tank temprature and ambient temperature profiles. The approximately 4°C difference was enough to power a simple wireless temperature sensor. EPRI is using this information to develop power-harvesting sensors for transformers.

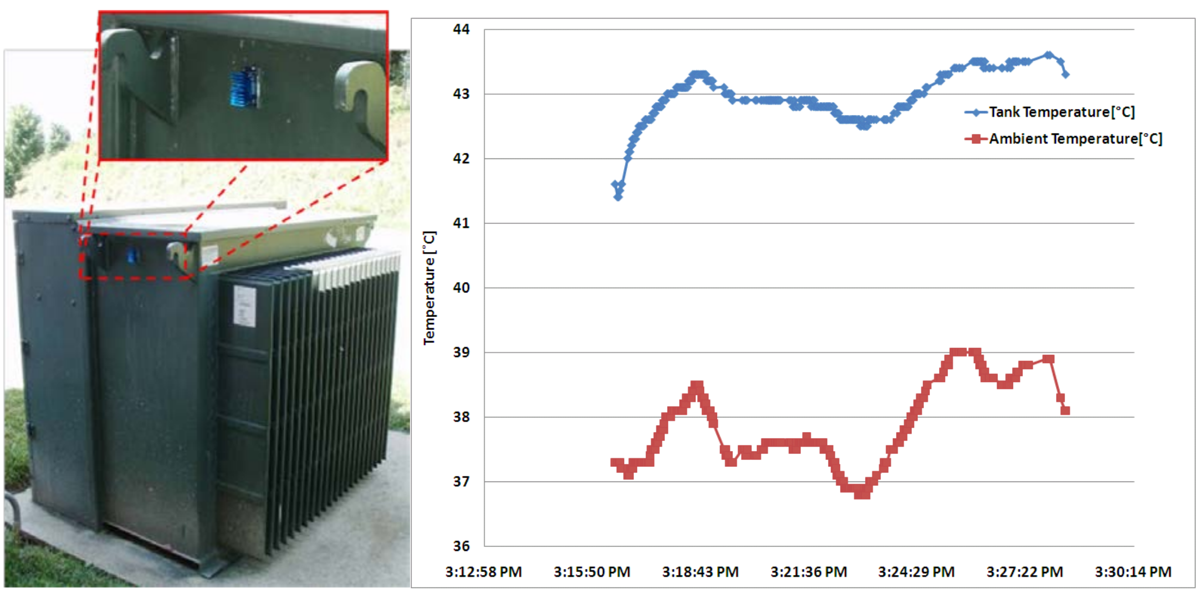

Figure 3-5
Temperature Sensor with Thermal Harvester Module on a Distribution Transformer.

Magnetic Field Energy

EPRI have implemented magnetic field power harvesting in EPRI sensors that are mounted on power lines to monitor line temperature and current. In this design a small coil wound on a high-permeability rod is used in conjunction with a voltage quadruple and rectifier circuit to self-power the sensor when the line current is approximately 50 Amps or greater. In this physical realization, the magnetic field at the coil with 50 Amps flowing through the line is approximately 3 Gauss. At currents below 50 A, the sensor may lose power; while at very high currents there is risk of overloading the power conversion circuitry. The design is sensitive to the distance from the power line, the orientation of the sensor with respect to the current path, the current magnitude, and the orientation and proximity of adjacent lines.

The magnetic field energy harvester design have been implemented and proven to be effective in EPRI conductor/splice sensors (see Figure 3-6).

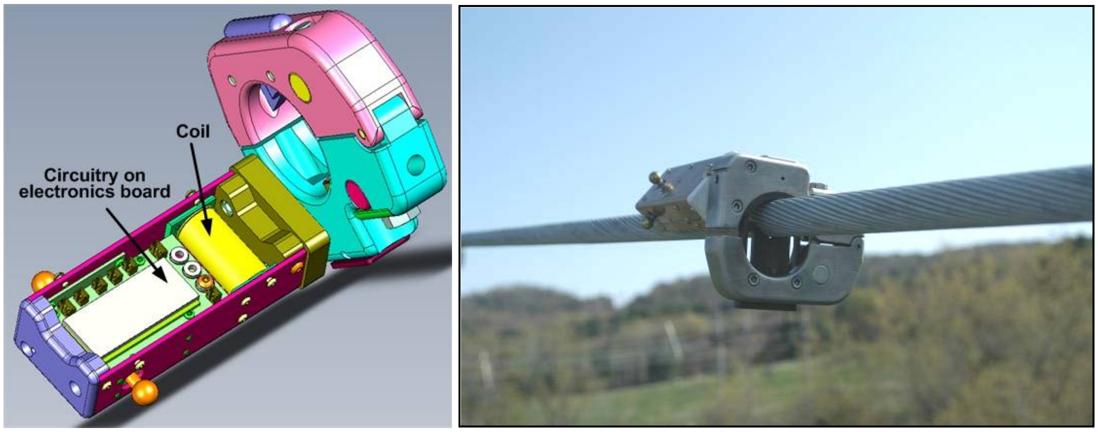

Figure 3-6
EPRI Conductor/Splice Sensor with Magnetic Field Power Harvesting

4
DEVELOPING A POWER HARVESTING TEST BED

Introduction

A test bed was designed for evaluation of emerging power harvesting products and technologies for wireless sensor applications. In consideration of the environmental energy sources that are most viable and equipment resources available at EPRI's Charlotte Sensor Laboratory, a test bed is proposed that combines a solar light simulation capability with a temperature chamber, a magnetic field simulator, and a vibration shaker. This test bed allows a test article (harvesting device) to be simultaneously illuminated, vibrated, and heated/cooled, with levels for each that can be independently varied under computer control. The test bed could be manually or computer controlled.

This section of the report presents the test bed design including requirements, background material regarding selection of a suitable light source, descriptions of the major components, and assembly including design rationale.

Test Bed Requirements

Although there are commercial solar simulator systems and combined environmental chambers available on the market, most of these systems are relatively large, bulky and expensive. Given that EPRI already owns a temperature chamber and vibration shaker, an emphasis was made to select or design a solar simulator to complement the existing capital equipment. The following requirements are proposed for the overall test bed:

- Temperature controllable from -40°C to +80°C
- Relative Humidity controllable from 20% to 100% non-condensing
- Light source irradiation meeting Class A Rating (goal) or Class B rating (threshold)
- Light source spectrum meeting Class A rating (goal) or Class B rating (threshold)
- Ability to control light source irradiation level
- Light source temporal response meeting Class A rating
- Test article sizes accommodated from 2x2 inches to 12x12 inches
- Equipment powered from standard 60 Hz 110 VAC/20 Amp outlet
- Ability to simultaneously stimulate test article using a vibration table
- A magnetic field test source controllable from 0-200 Amps
- Equipment programmable and controllable from a computer

Solar Simulator Design

Objective

The objective is to provide EPRI the capability to test and compare various power harvesting devices which relay on solar radiation for power generation. The development of a kilowatt class benchtop solar simulator is a key component to accomplishing the objective. Other laboratory components, including environmental test chamber and computer automation, are utilized to provide the capability to meet the objective. The benchtop solar simulator can be coupled with existing environmental chamber and the modular design provides the capability to add additional light sources should it become necessary to illuminate a larger area. The intermediate steps needed to complete the objectives were as follows:

- Design a light source which has the capability to simulate the spectral irradiance of solar radiation.
- The solar simulator device needs to provide the capability to meet or exceed ASTM standards for Class B spectral match, Class B uniformity, and Class A temporal stability over a 4-inch x 4-inch (approximately 6-inch diameter) test article and provide the capability to illuminate a 12-inch x 14-inch test article.
- Fabricate and assemble the device utilizing Commercial-Off-The Shelf (COTS) equipment modified only as necessary as a modular system.
- The device needs to have the capability to couple the light into EPRI's existing environmental chamber.

The development and testing of the solar simulator is documented in this section.

Approach

The approach involves the development of a modular benchtop light source capable of simulating solar radiation throughout the visible and Near InfraRed (NIR) region of the spectrum as illustrated in Figure 4-1. The key factors in the development of the light source are the spectral irradiance, uniformity, and stability. The spectral irradiance is the spectral distribution of the light and the light source should have the capability to produce a total irradiance of 1 Sun, equivalent to the amount of light produced, approximately 1000 W-m-2, when the Sun is directly overhead.

The sunlight reaching the ground through the Earth's atmosphere is generally classified as AM1.5D or AM1.5G, where the D indicates direct and the G indicates global. The global designation includes both direct and circumsolar light from the sun and is the classification that is used in the development of the light source. The light normal to the test article plane should be free of hot spots, or uniform, over the test article area. The light should also be continuous and temporally stable, free from noise. The specific ASTM specifications are provided in Table 4-1 and Table 4-2.

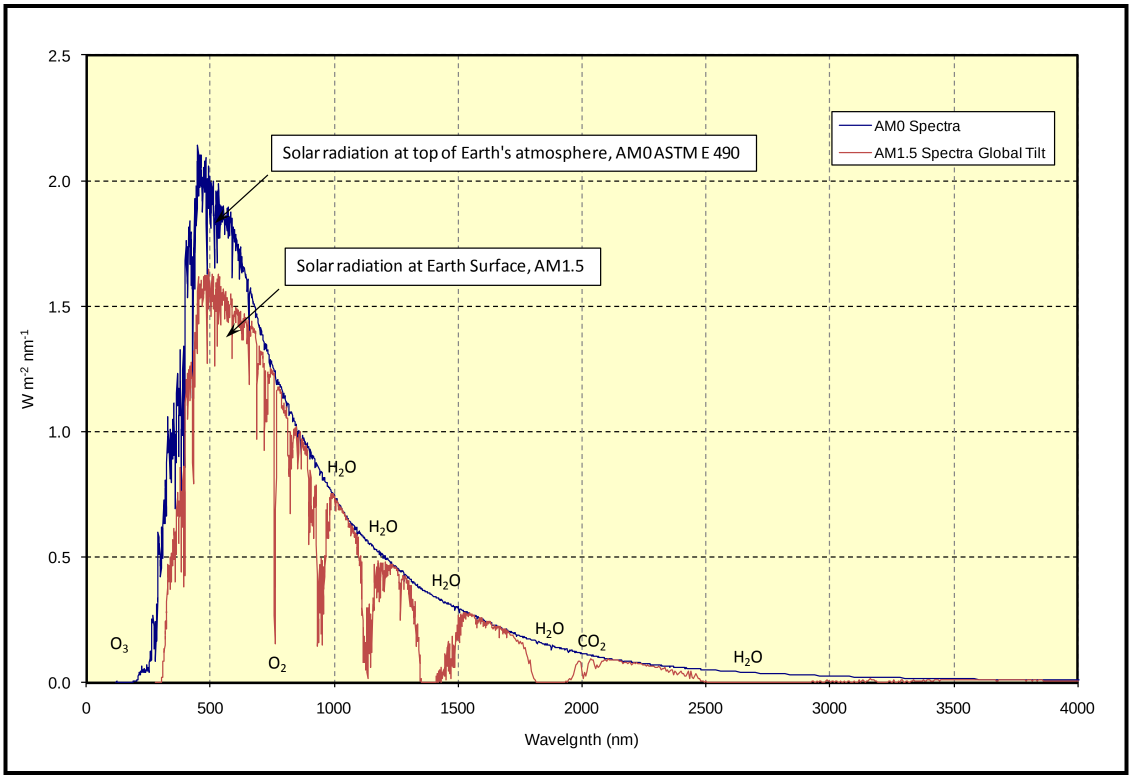

Figure 4-1
Solar Irradiance

Table 4-1
ASTM Class Specification

Classification	Spectral Match (each interval)	Irradiance Spacial Non-Uniformity	Irradiance Temporal Instability
Class A	0.75 - 1.25	2%	2%
Class B	0.6 - 1.4	5%	5%
Class C	0.4 - 2.0	10%	10%

Table 4-2
ASTM Spectral Irradiance

Wavelength Interval [nm]	AM1.5D	AM1.5G	AM0
300-400	no spec	no spec	8.0%
400-500	16.9%	18.4%	16.4%
500-600	19.7%	19.9%	16.3%
600-700	18.5%	18.4%	13.9%
700-800	15.2%	14.9%	11.2%
800-900	12.9%	12.5%	9.0%
900-1100	16.8%	15.9%	13.1%
1100-1400	no spec	no spec	12.2%

A solar simulator design concept was developed based on the objectives and ASTM solar simulator standards. The solar simulator system consists of a rollaway optical table, lamp and lamp housing, lamp power supply, power distribution, free space coupling optics, computer controlled variable Neutral Density (ND) filter wheel, and computer as illustrated in Figure 4-2. The solar simulator design utilizes a 1,000 Watt Xenon (Xe) arc lamp as the primary source and an AM1.5G filter is used to match the solar spectrum.

The rollaway optical table is designed to be placed next to the existing environmental chamber such that the free space optical system enters the chamber through the 2.72-inch side port. To remain within the ASTM standards, the test article should be place approximately 6-inches from the port illuminating an area approximately 7 to 8 inches in diameter. The computer controls a servo motor which turns the ND filter wheel causing the amount of light entering the chamber to increase or decrease without inducing a change in the optical spectrum or other optical properties. A photo-detector and spectrometer is coupled to the optical system via a lens tube cube connector. Back scattered light from the diffuser enters both detectors and may be monitored during testing.

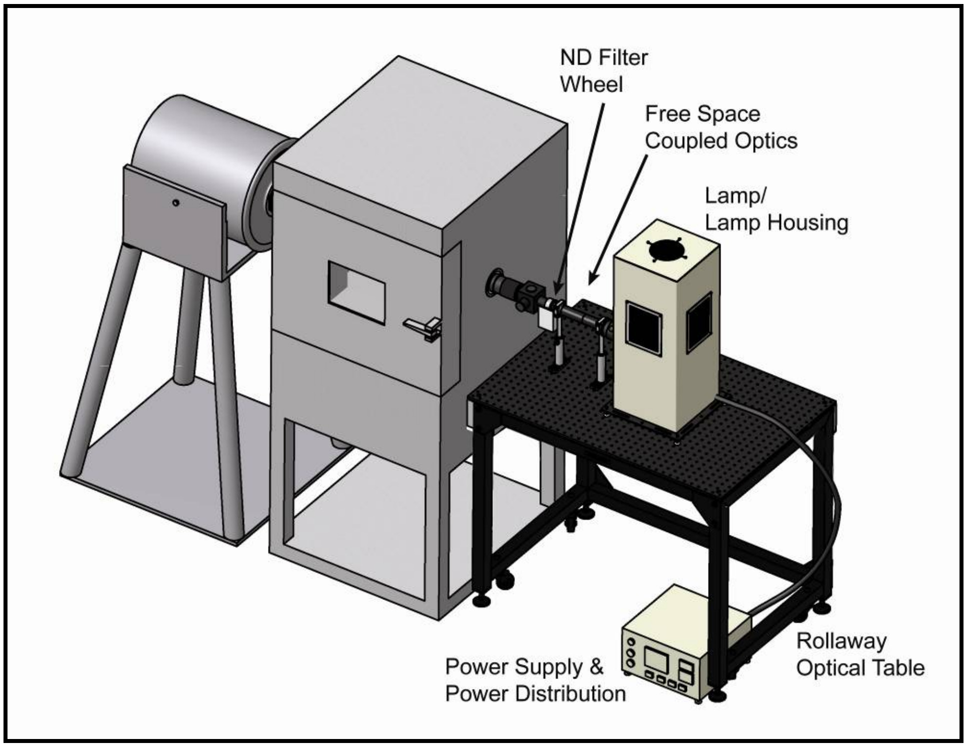

Figure 4-2
Solar Simulator Design Concept

Design Implementation

The design and fabrication of the benchtop solar simulator did not significantly differ from the original design concept as pictured in Figure 4-3. The benchtop solar simulator system is based on a custom Xe arc lamp housing, Sciencetech 201-1K, and 1 kW lamp power supply supplied by Sciencetech Inc. The lamp power supply was modified to include an hour meter for lamp elapsed time and to incorporate an external interlock loop for lamp thermal protection.

A power distribution box was developed to supply power to the lamp cooling fans, thermal controller, auxiliary power, and lamp power supply. The power distribution box is designed to couple the cooling fans to the main lamp power and provide thermal protection logic to prevent damage to the lamp and lamp housing. An electronic shutter system was provided by Sciencetech which has been incorporated into the system.

The shutter can either be controlled remotely via an RS-232 connection or manually via a switch on the shutter control box. The light from the lamp is propagated through a lens system to a computer controlled variable ND filter wheel which is used to adjust the amount of light passing through the system. The light is then propagated through a final set of lenses and a ground glass diffuser and is coupled into the environmental chamber. A fiber coupled spectrometer and a photo-detector provide the capability to monitor the light output from the lamp during testing or calibration. The whole system is securely mounted to a rollaway optical workbench for convenience and versatility.

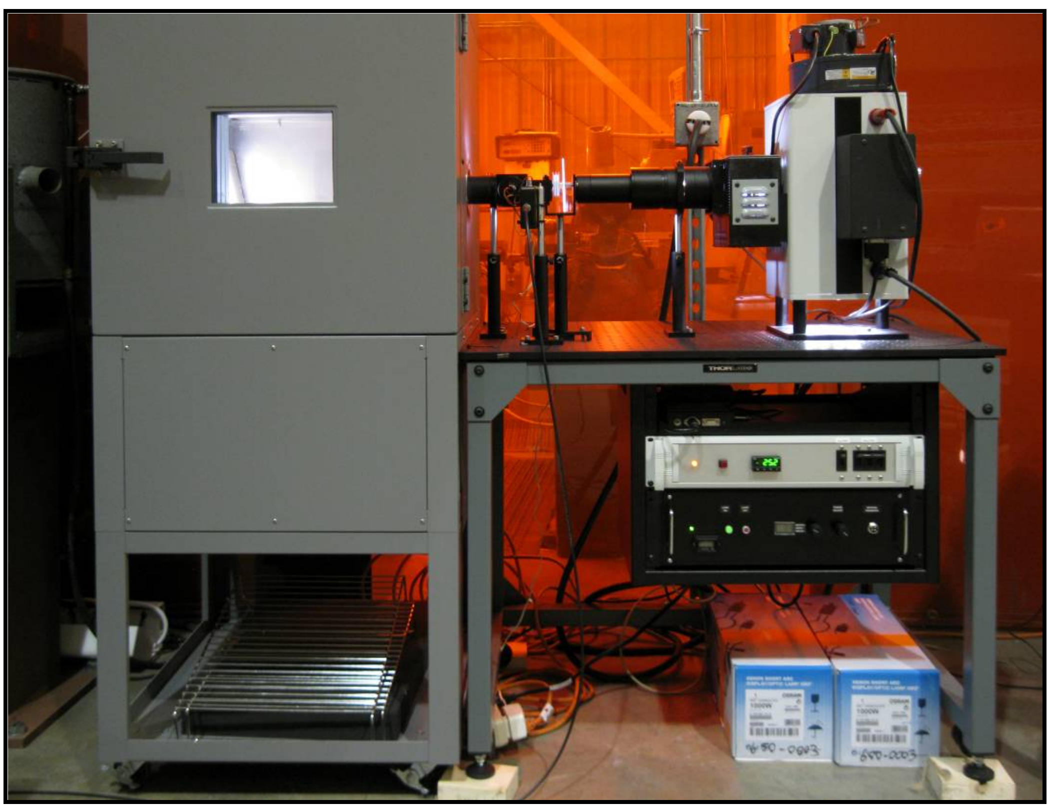

Figure 4-3
Contructed Benchtop Solar Simulator

Performance

The spectral performance of the lamp is consistent with that of an ASTM Class A solar simulator device. The Xe arc lamp spectrum was obtained with and without the AM1.5G filter. The spectral properties are illustrated in Figure 4-4.

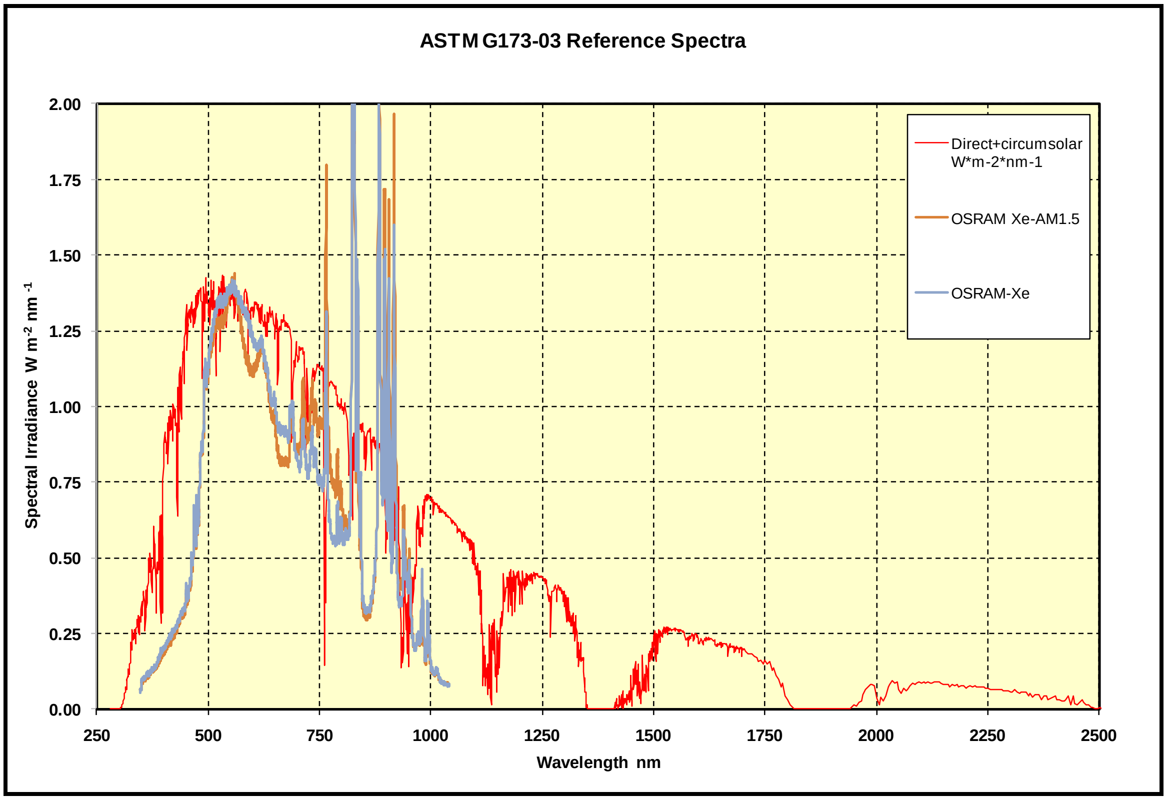

Figure 4-4
Lamp Spectrum

The irradiance of the benchtop solar simulator as measured at 514 nm without the diffuser is 0.96 Sun with a relatively uniform illuminated diameter of 6-inches. The irradiance of the solar simulator as measured at 514 nm with the diffuser is 0.74 Sun with a uniform illuminated diameter of 6-inches. Without the diffuser the non-uniformity is >10% which does not meet the ASTM standard for a Class B solar simulator. With the diffuser, the non-uniformity is within 5% which meets the ASTM standard for Class B simulator. However, as configured the simulator cannot produce 1 Sun. The lamp stability is well within 2% and meets the ASTM standard for a Class A solar simulator.

Control System

A simple control scheme for varying illumination intensity was proposed to provide flexibility for running different types of solar tests.

Figure 4-5 gives an overview of the control approach. The operator starts by selecting a desired radiation profile, which defines the intensity of the illumination at each moment in the test. The intensity level is then adjusted via the controller to match the specified level. This process is either pre-calibrated, such that it can work in an open loop fashion, or an indirect measurement of the light intensity can be used as feedback for closed loop control. The remaining tasks are to record relevant test and performance data for later analysis. Using this control scheme, short and long-duration testing can be carried out that simulates everything from short snapshots of solar irradiance to sequential day night cycles.

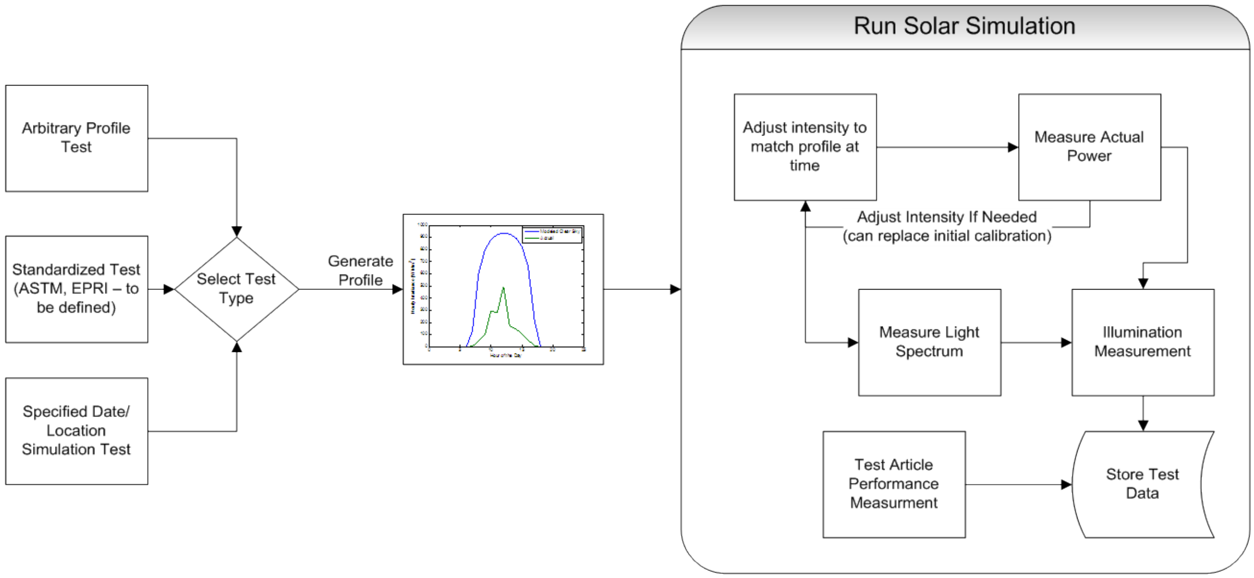

Figure 4-5
Solar Test Control and Data Acquisition Overview

Figure 4-6 illustrates some of the control hardware. The custom element to this design is the servo that controls the iris in order to vary the light intensity. A PC is used to provide a suitable user interface, which would allow the user to select (or define) a desired solar profile to test to, and communicate that profile to the real time controller. The control and data logging tasks can be carried out solely on the real time controller, or can be shared between the controller and the PC. For the purposes of this design, the responsibilities will be shared. In this case the PC will interface with the spectrometer and will control the shaker and the thermal chamber during combined solar/thermal/vibration tests. The real time controller would be responsible for the majority of the solar simulator control and data logging.

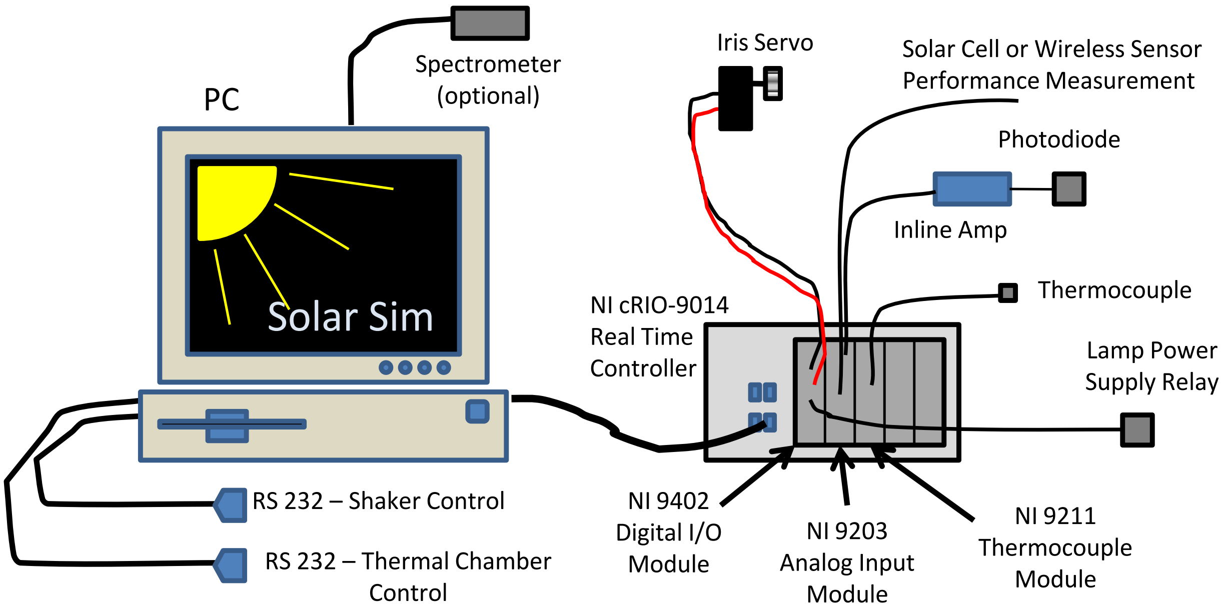

Figure 4-6
Control Hardware Schematic

Changes and Improvements

The original design concept utilized fiber coupling for transmitting the light to the target. However, it was determined that silica fibers were not a good choice for this application. After some research it looked as though a liquid light guide might have the capability of coupling the light to the target. There are several advantages to using fiber coupling in that it is compact and easy to move the light where you need it. However, the drawbacks are the coupling losses, non-uniformity, and aberrations which can occur. We experimented with the liquid light guide and the spectral properties performed well. On the other hand, the non-uniformity was an issue as was the coupling losses. The fiber losses were about what you would expect, but the non-uniformity requires the use of an integrating sphere which leads to further losses making this method impractical for this application.

The original design concept also included the use of a diffuse reflector made of Spectralon® within the lamp housing. The use of such a reflector will increase the light output as well as increase the uniformity of the light. However, at the moment it was not possible to incorporate the integrating cavity within the lamp housing. Instead, a spherical reflector was used to reflect a portion of the light into the light gathering optics. This leads to an increase in non-uniformity which must be addressed with the use of diffusing optics leading to reduced light output. Nevertheless, it appears that with a short spherical reflector the system will have the capability to develop 1 Sun over a 6-inch diameter area meeting ASTM Class B standards for uniformity.

The system, as implemented, utilizes a 2-inch diameter 100 mm focal length spherical reflector at the rear of the lamp to increase the light output by approximately 60%. As mentioned earlier the use of diffusers reduces the output power to 0.74 Sun. The light output can be increased significantly by using a short focal length spherical reflector. Therefore, a 2-inch diameter 17.5 mm focal length spherical reflector was obtained and will be incorporated directly into the lamp housing. This reflector should increase the light output by an additional 40%. The additional light should be enough to reach the 0.95 Sun or greater with the optical diffusers. This will provide the capability to run test at 1 Sun with ASTM Class A spectral match, greater than ASTM Class B uniformity, and ASTM Class A stability.

The light output is controlled by a variable ND filter which is driven by a servo motor connected to a computer. This system appears to work well, but the design of the filter holder allows the ND filter wheel to slip. If the filter wheel moves over time, it will no longer be calibrated. A new design has been developed which will ensure that the filter wheel stays calibrated over time.

Conclusions

A kilowatt class benchtop solar simulator was successfully developed. The system, as originally developed, is capable of performing comparative or absolute testing although several design improvements have been developed and fabricated. The system with the improvements installed will provide EPRI all of the capabilities outlined in the objectives and conceptual design. The spectral irradiance and stability meet ASTM Class A specifications for solar simulators. The uniformity of the system is within 5% meeting the ASTM Class B specification. Additional, testing is required to determine the exact uniformity of the system.

Magnetic Field Test Source

Objectives

The objective was to design a magnetic field test source for the Power Harvesting Test Bed at the EPRI Charlotte Sensor Lab. The sensor lab develops wireless sensors and instrumentation that are used in utility applications. Many of these devices harvest power for operation from the local environment, including the 60-Hz magnetic field that is generated from the large currents that flow through the utility power transmission system. Although currents on the transmission lines commonly exceed 1,000 Amps, the source for the test bed only needs to go up to about 200 Amps because the interest is in characterization of the sensor operating threshold, which is found at the worst case lower end of the range. The main requirement of the magnetic field test source for this application is that it should be controllable from 0-200 Amps through a computer interface in order to accommodate automated testing.

Approach

A motorized variac and step-down transformers were configured so that a standard 120V 60-Hz line input can drive a relatively high-current short-circuit loop. A current transformer in the loop provides an instrumented feedback signal for monitoring of the actual loop current. The equipment is mounted into a wheeled rack chassis. A switch and multi-turn potentiometer are provided to allow manual control of the current amplitude which is displayed on a panel meter. Alternatively with the switch in the “external” position, the current amplitude is controlled from a connector port with a DC voltage for example from a computer system. The panel meter monitor signal is also provided in parallel to the connector port so that closed loop feedback can be externally implemented. The concept diagram is presented in Figure 4-7.

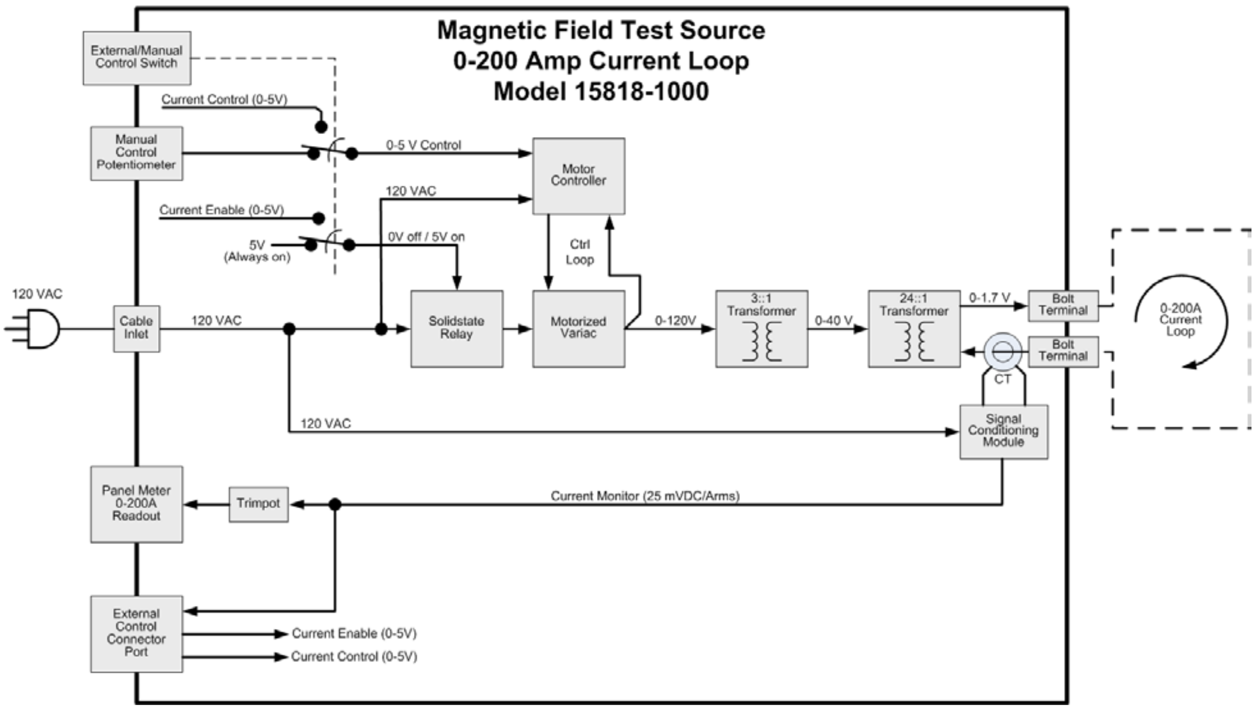

Figure 4-7
Design Concept of the Magnetic Field Test Source

Design Implementation

The magnetic field test source has been built and successfully verified. The source produces current up to 200A AC RMS from standard 120V AC 60-Hz wall power. The current is sourced through a short-circuit conductor loop external to the unit.

The current signal is produced using transformers to step down the 120 VAC nominal wall voltage to a maximum of approximately 1.7 VAC (that is, a factor of 69). The external loop resistance must therefore be less than approximately 8.5 milliohms to achieve 200 Amps. Large ½" brass bolt terminals on opposite sides of the chassis are used for the external current loop conductor connections.

The Magnetic Field Test Source current level can be controlled, either manually by the user, or automatically with external electronics. A front-panel switch allows the user to select either Manual or External (automatic control) mode. In Manual mode, the user controls a front-panel multi-turn potentiometer to set the current level, which is monitored internally and displayed on a front-panel meter. In External mode, the current level is set by voltages that are applied to a front-panel control port connector. The current monitor signal that drives the panel meter is also available at the front-panel control port connector for external closed loop feedback control. A computer program controls the current level from a computer that is equipped with National Instruments data acquisition peripherals.

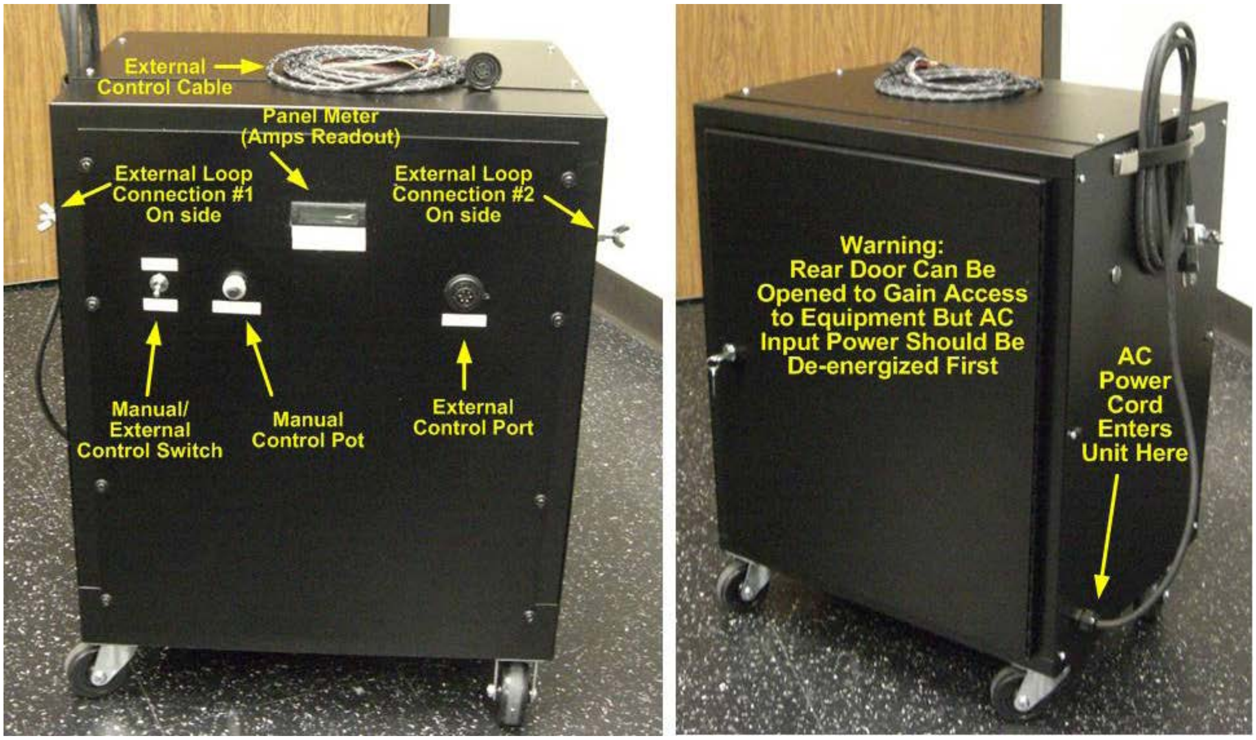

Figure 4-8
Magnetic Field Test Source Controls and Connections

Conclusions

The magnetic field test source was successfully built and integrated at the EPRI Charlotte Sensor Lab as part of the Power Harvesting Test Bed. It meets expectations and operates as designed. Three observations were noted that could be addressed in the future:

- The AC line is provided with an integral cord and there is no master power switch for the unit. This means that the unit is energized and consuming power if not unplugged or externally switched off. A master circuit-breaker switch could be added to the unit.
- Due to the way the motorized variac operates, full scale current magnitudes are temporarily produced when initially switching the solidstate relay on; however the unit automatically self corrects to the set point.
- The motor speed is relatively slow (60 seconds full scale), but higher speeds are available (up to 5 seconds full scale).

Test Bed Automation and Integration

Objectives

The primary objective of this task was to provide hardware and software interface to the power harvesting test bed components, such that a user could perform basic operation of the individual elements of the test bed. As the project evolved, the objective was expanded to include integration of the control of all of the components into a single user interface and to allow for flexibility in how each element is controlled. The control system was intended to control the following hardware:

- Electro-magnetic Shaker
- Thermal Chamber
- Solar simulator
- Magnetic field source

Approach

National Instruments hardware and Labview software were chosen for control of the test bed components. Initial preparation for the control system was carried out on an embedded real time controller, but since there was not a strong need for the control to be carried out on a stand-alone, embedded controller it was decided to shift to a controller which utilizes an attached PC to implement data processing and control routines.

Control Hardware

A controller with four slots available for I/O modules was used for the control system. The four slots available on this chassis accommodated all of the modules necessary for control and data acquisition for all test bed components, with the exception of the thermal chamber, which is connected directly to the host computer with a serial cable. The four modules used for I/O were:

- Accelerometer module
- Analog Voltage Input Module
- Analog Voltage Output Module
- Digital I/O module

The accelerometer input module is used to measure the motion of the shaker. This module allows for direct input of IEPE/ICP type accelerometers and provides the requisite sensor excitation voltage on-board without the need for an external power supply.

The analog input module is currently used to acquire analog voltage signals from the solar simulator and from the magnetic field source to provide feedback for controlling the respective devices. The photodetector signal from the solar simulator is acquired on one channel, and the loop current measurement from the magnetic field source is acquired on another. Two channels remain open and may potentially be used for measuring relevant voltage signals from test articles.

After the photodetector was brought online, it was discovered that there was significant noise in the signal when it was acquired using this module. A similar noise issue was discovered in relation to the current measurement signal from the magnetic field source during initial setup and testing. However, by connecting 100+kΩ resistors between the positive and negative terminals and COM, the noise was eliminated. A similar approach was attempted with the photodetector, but the noise remained. A software filter was implemented as a temporary solution to smooth the measurement instead, but the underlying noise issue still needs to be addressed.

The analog output module is currently used to control the EM shaker and the magnetic field source. The output from the module goes directly into the shaker amplifier to drive the shaker. During initial testing (with a loudspeaker), a passive, low-pass filter was added to the shaker channel to eliminate sampling noise. However, the filter was not used for the actual shaker implementation, because the sampling noise (10 kHz) is well above the maximum frequency that the shaker can output (~3 kHz). Note that a filter may be needed if the control frequency is ever reduced. The control signal for the magnetic field source adjusts the output voltage (which drives the current in a test loop).

The digital I/O module is used to control both the on/off relay of the magnetic field source as well as the servo motor that drives the filter wheel in the solar simulator. The servo motor requires a pulse-width modulated signal to control the angular position of the motor, which in turn requires that the channel on the I/O module be setup as a counter/pulse channel. Unfortunately, once a counter is implemented on one of the channels, all of the channels must be treated as counters. This means that instead of simply setting the channel for the magnetic field source relay high or low, a pulse width modulated signal must be used instead. Furthermore, neither a 0% nor a 100% duty cycle could be used, so a low, but non-zero duty cycle (~0.0001%) was used to turn the relay off, and a high, but not 100% duty cycle (~99.9999%) was used to turn the relay on. This resulted in very short duration, but measurable, pulses in the signal. Fortunately the relay responds slowly enough to be unaffected by the pulsed nature of the signal.

Implementation

The following sections describe the user-interface/front-end of the control system.

Overview of User Interface

At this stage in the development, all of the test bed devices must be setup and controlled somewhat independently, that is, there is no single means of configuring all of the systems (or a subset of the systems) to run a common test. Nevertheless, all of the elements have been integrated into a single computer program so that, if desired, they can all be run simultaneously. Configuration and setup must be performed for each test system separately. The interface elements for each of the control systems are grouped into separate tabs where all of the relevant controls and displays for a single device can be found on a single tab.

At the top of the interface are several buttons and indicators that remain visible regardless of the tab selected. These include the stop button, an elapsed time indicator, and “enable” checkboxes for each of the devices. The enable buttons allow the user to shut off a specific element from any tab. However, it should be noted that the enable button has a slightly different behavior for each element:

- For the shaker it sets the output signal to zero.
- For the magnetic field source it turns off the relay.
- For the thermal chamber the temperature is set to the current temperature (there appears to be no “off” command available).

Shaker Control

The control system allows for two modes of control of the shaker. The first is manual control of one or more excitation tones. The control system will measure the level of each tone in real-time and adjust the excitation amplitude by means of a PID controller to match the requested levels. The basic functionality of this mode of operation was proved-out by varying frequency and amplitude parameters and verifying that the control system maintained good stability while minimizing steady-state error.

However, the control system was not extensively tested and not all conceivable exceptions were addressed. It is recommended that low frequencies (less than 10Hz) and close frequency spacing (also less than 10Hz) be avoided. In both cases the accuracy of the amplitude measurements will tend to decrease and the control system’s stability may be affected, particularly for the closely spaced tones. Additionally, low excitation levels, less than 100 mG, may be difficult to control precisely.

The second mode is automatic control, which is intended to be used for long duration tests with varying excitation characteristics or for random vibration. In this mode the varying excitation is dictated by a comma separated variable (csv) file that contains a column for time and a column for the signal. This simple csv format is used for all of the automatic control implementations.

Magnetic Field Source Control

During both manual and automatic operation of the magnetic field source, the device can be switched on and off and the measured current and commanded current are displayed. The command signal sent to the device defines the set point output voltage that drives the current through the test loop. Because the load in the test loop can vary, particularly if the cables or connectors that make up the loop are changed out, the system cannot be driven reliably in an open loop fashion. Therefore a PID controller is used to control the current, using the actual measured current reported by the device as feedback.

The manual interface for controlling the magnetic field source allows the user to set the loop current to a desired value. Meanwhile, the interface for automatic mode of the magnetic field source uses a time based profile can be defined in a csv file, where time and current amplitude are specified.

Solar Simulator Control

At the moment this report was written, the solar simulator control system is not yet fully operational. Currently, it is possible to measure the uncalibrated intensity of the light, and manually control the filter wheel. The photodetector measurement is relatively noisy, so the control software uses a max level filter that appears to correspond closely to the equivalent noiseless output of the sensor. The sensor output still need to be calibrated in order to scale the measurement to equivalent intensity (in appropriate units) at the test article.

The manual control of the solar simulator lets the user control/turn the neutral density filter wheel. The exact values for precise 0-360 motion must still be calibrated, and the filter wheel must be adjusted to ensure that both extremes of the filter wheel are at opposite ends of the 360 degree motion. At this moment no automatic control mode has been implemented for the solar simulator.

Thermal Chamber Control

The basic functionality of the thermal chamber control includes the reporting of the current temperature in the chamber and the ability to choose between manual mode and automatic mode. Under manual control, the user simply selects the desired temperature set point and all of the actual temperature control is carried out by the controller inside the thermal chamber.

Similar to the automatic mode for the other test elements, the input for automatic control of the thermal chamber is provided to the system via a csv file. One consideration for the formatting of the temperature profile for the csv file is that very rapid changes in temperature are not possible, so profiles with high frequency changes in temperature cannot be tracked by the chamber.

Conclusions and Future Work

At this moment, not all of the control system desired capabilities were fully realized. In particular, the solar simulator can currently only be controlled in a manual mode with uncalibrated feedback. Nevertheless, most of the components were integrated successfully and basic control functionality was verified. The control of all of the devices was also integrated into a single user interface. Furthermore, with the exception of the solar simulator, all of the devices can be controlled in both a manual and automatic fashion allowing long duration tests to be carried out while the test bed is unattended. There is still considerable room to enhance the control capabilities for each of the devices and to simplify the process of setting up and running integrated tests that utilize multiple devices.

Future work that is underway on the control system includes:

- Finishing work on the solar simulator control (hardware and software) to close the loop for controlling the intensity as well as implementing an automatic mode that can be used to run through desired intensity profiles
- Further enhancing and integrating the control interface to make running a multi-device test (for example, Solar + Vibration + Temperature, or Magnetic Field + Temp) simpler
- Generating default, or standardized test profiles that can be easily selected and adjusted

- Incorporating the frequency response/transfer function of the shaker (measured during the current phase of development) into the control system to improve open loop control performance.
- Provide more control options for shaker (as needed) to better accommodate a wider range of excitation profiles.

5
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A
COMPANIES/ORGANIZATIONS ENGAGED IN POWER HARVESTING

Table A-1 lists the companies/organizations engaged in developing products or carrying out research related to power harvesting. The list is not exhaustive; however, it should be of good help in order to understand who is doing work, what product could be evaluated, and finding organizations to collaborate with.

Table A-1
Summary of Companies/Organizations Engaged in Power Harvesting

Company	Expertise	Website
BP Solar	Solar Panels	bp.com/
EPFL	Solar Energy Harvesting, Power Management	epfl.ch
MorningStar Corp	Solar Controllers	morningstarcorp.com/
Power Film	Solar Panel Material	powerfilmsolar.com/
Schott Solar	Solar Cells	schott.com/photovoltaic/english
Solarfun Power	Solar Cells	solarfun.com.cn
SunTech	Solar Panels	suntech-power.com/
Tyndall National Institute	Photovoltaics, Power Management, Characterization of energy harvesting devices	tyndall.ie
University of California, Los Angeles	Solar powered motes	nesl.ee.ucla.edu/projects/heliomote
University of Freiburg	MEMS and materials, including solar cells	imtek.de
University of Neuchâtel	MEMS, solar cells on rigid and flexible substrates, piezoelectric energy harvesting	unine.ch
University of South Carolina	Hybrid power systems with emphasis on ortable solar arrays	Vtb.engr.sc.edu/research/psl/
Adaptive Energy	Vibration Harvesting	adaptivenergy.com/
Advanced Cerametrics	Ceramic materials using PZT fibers	advancedcerametrics.com

Table A-1 (continued)
Summary of Companies/Organizations Engaged in Power Harvesting

Company	Expertise	Website
Arveni	Piezoelectric energy harvesters	arveni.fr
Cranfield University	Piezoelectric energy harvesters and modelling	cranfield.ac.uk/sas
EoPLEX	Piezoelectric energy harvesting, miniature fuel-cells	eoplex.com
Ferro Solutions	Piezoelectric and electromagnetic energy harvesting	ferrosi.com
Holst Centre	Vibration, thermal, and RF approaches with various prototypes	holstcentre.com
Imperial College London	Vibration and air-flow energy harvesting analysis and simulations	www3.imperial.ac.uk/electrical engineering
K. U. Lueven	Vibration and thermoelectric energy harvesting	mech.kuleuven.be
KCF Technologies	Piezoelectric vibration harvesting	kcftech.com
Lumedyne Technologies	Vibration energy harvesting	lumedynetechnologies.com/
LV Sensors	Piezoelectric powered tire pressure monitoring system	lvsensors.com
Microstrain	Piezoelectric strain energy harvesting	microstrain.com
Mide Technology	Piezoelectric energy harvesting	mide.com/
Penn State University	Piezoelectric energy harvesting, power management circuits	kirkof.psu.edu
Perpetuum Ltd.	Vibration electromagnetic harvesting	perpetuum.co.uk/
STEMiNC	Piezoelectric materials	steminc.com/
Tima	Piezoelectric energy harvesting, MEMS	tima.imag.fr
Univesity of Bristol	Vibration energy harvesting	bris.ac.uk/aerospace
University of California, Berkeley	Thin film piezoelectrics, MEMS	bsac.eecs.berkeley.edu
ETH Zürich	Thermoelectric generators	ethz.ch
IMEC	Thermoelectric energy harvesting	imec.be
Micropelt	Thermoelectric energy harvesting	micropelt.com/
Perpetua	Thermoelectric energy harvesting	perpetuapower.com/

Table A-1 (continued)
Summary of Companies/Organizations Engaged in Power Harvesting

Company	Expertise	Website
ThermoLife	Thermoelectric energy harvesting	thermolife.com/
Powercast	RF Harvesting	powercast.com/
University of Southhampton	Electromagnetic energy harvesting, multisource energy harvesting	ecs.soton.ac.uk
Univesity of Strathclyde	Magnetic and electric field energy harvesting	eee.strath.ac.uk
Ambient Micro	Multisource energy harvesting	ambient-micro.com
EnOcean	Range of energy harvesting, system on chip, wireless protocol	enocean.com/
Virginia Tech	Small scale windmills, energy harvesting materials and devices	me.vt.edu/people/faculty/priya.html
Advanced Linear Devices	Power management circuits	aldinc.com
TPL Inc	Power management circuits	tplinc.com/MicropowerDivision.html

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