A Minimally Intrusive, Low Cost System for Determining Indoor Air Flow Patterns

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***Abstract*— This paper describes an ozone-based tracer gas system that can be used to create models of indoor air flow. Ozone is generated via corona discharge using a parallel resonant DC-DC converter, and ozone concentration is monitored using a novel low-noise amplifier. Power-line carrier modems are used to coordinate the generation and detection of ozone. Intelligent digital control strategies for the generator are developed using the requirements of several different air flow tests.**

I. INTRODUCTION

In the aftermath of the oil shocks of the 1970s, building owners and operators became increasingly interested in reducing their energy costs [1], [2]. As a result, building engineers were called upon to develop methods to increase overall building energy efficiency. One of the ways in which engineers approached that task was to attempt to reduce the amount of air and heat exchanged between a building and its environment. Consequently, techniques were developed to measure the amount of air that escapes through a building envelope. These techniques, which make use of tracer gases such as SF_6, require highly expensive and elaborate equipment. Unfortunately, the cost and intrusiveness of tracer gas systems has prevented engineers from making widespread use of building leakage measurements.

In order to meet the need for a low cost, minimally intrusive air flow monitoring system, we are investigating a technique that uses ozone as a tracer gas. In the current system, high voltage DC power supplies are used to generate ozone via corona discharge. Several of these ozone generating power supplies as well as their corresponding ozone detectors are deployed at different points in a building. Accompanying each individual generator and detector unit is a power line carrier (PLC) modem module which is used to communicate with a centrally located personal computer. When it is desired to conduct a series of air flow tests, the central machine will issue appropriate commands to each generator and detector. At the end of an experiment, ozone generation is ceased and concentration measurements from the detectors are transferred to the central machine. The information returned from the remote detectors can then be used to create nearly real-time models of indoor air flows.

This paper discusses the individual components of the aforementioned tracer gas system, with particular emphasis placed upon how to control the high-voltage DC power supply to conduct several useful tracer gas measurements. Results of several initial experiments are presented.

II. SYSTEM OVERVIEW

From the perspective of a building engineer, a robust air flow monitoring system must be able to determine several different pieces of information about a building's air distribution system. Moreover, the monitor must be able to adapt to provide new information as conditions change. These considerations demand a flexible system in which units can both operate and communicate reliably.

A. Flexible Design Through Digital Control

The present design for the tracer gas system makes use of a network of remote stations all under the control of one master computer. Figure 1 shows the components of one of the individual remote stations. Note that each of these units is equipped with both the high voltage power electronics required for ozone generation and the low-level sensing circuitry required for ozone detection. Additionally, each station has a Pentium-class PC and a power line carrier modem which are used to relay control information sent from the central computer to the generation and detection circuitry.

The great flexibility derived from the use of a controlled network of integrated generation and detection units is that the the network can be configured as needed for different measurement situations. Prior to any given test, user supplied configuration files on the central computer are utilized to decide which units must generate ozone and which must detect it. Once that information has been read, the central computer sends information to all of the units on the network, informing each of its task during the impeding test.

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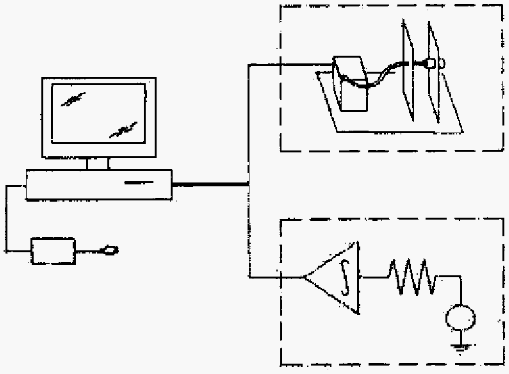

Fig. 1. A single ozone test station includes a PC, an ozone generator (top right), an ozone detector (bottom right), and a power line carrier modem module.

B. Reliable Communications

A critical issue in the operation of any distributed network such as this one is that of communications reliability. For this system, the building's internal electrical network was chosen as the broadcast medium and has been found to be reliable under various conditions.

From a communications standpoint, the characteristics of the AC power line often make it an undesirable choice for use as a reliable data transmission channel. In particular, attenuation in power networks varies significantly with the overall load and with time, making continuous and dependable communications extremely difficult [3].

The problems typically encountered when communicating over the power network in a single building have been overcome in this case through the use of HomePlug compliant products. HomePlug is a new industry standard developed by the member corporations of the HomePlug Powerline Alliance. HomePlug compliant devices, which transmit in the frequency band from 4.5MHz to 21MHz make use of several techniques in order to handle both the time-varying impedance of individual transmission channels and the interference caused by other devices on the network. Most importantly, in the event that the impedance on a particular channel begins to change, HomePlug devices are equipped with several functions which enable them to alter the overall data rate and continue communications. More information on these units can be found in [4].

III. THE OZONE GENERATOR: A HIGH VOLTAGE DC POWER SUPPLY

In the current system, trace amounts of ozone are generated using a high voltage version of a parallel resonant DC-to-DC converter. This type of supply is particularly useful in high voltage applications since the large leakage inductance and parasitic winding capacitance of the step-up transformer can be incorporated into the resonant tank network [5].

The converter used in initial experiments has the topology shown Figure 2. Note that this supply makes use of a series of Cockcroft-Walton voltage multipliers in order to lower both the required diode and capacitor ratings as well as the transformer turns ratio. In order to generate ozone, the voltage across the series combination of the capacitors C_{f2} and C_{f4} is applied to a pair of coaxial electrodes. Corona breakdown occurs at the central electrode which initiates a series of chemical reactions. One of the byproducts of these is ozone.

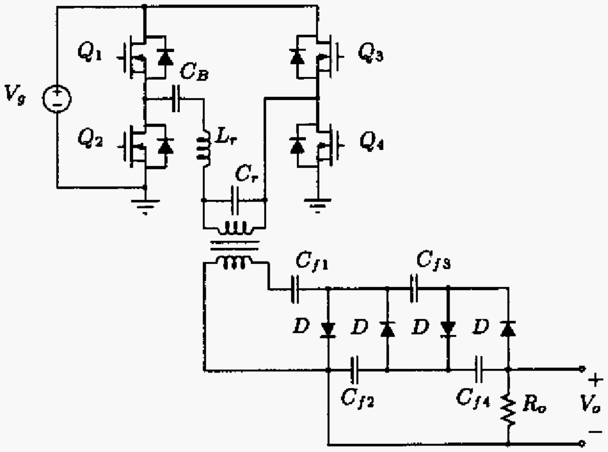

Fig. 2. A full-bridge implementation of the parallel resonant converter. Note that the diodes are arranged to produce a negative output voltage.

In the converter prototype, the resonant tank inductance is formed from a 25μH external inductor and the transformer leakage inductance; the resonant tank capacitance is provided by the secondary winding capacitance in parallel with an additional 10pF. The final converter is operated at a switching frequency of 67kHz. At this frequency, we are able to achieve an output voltage of approximately −6.6kV. A plot of the secondary voltage at the operating point is shown in Figure 3.

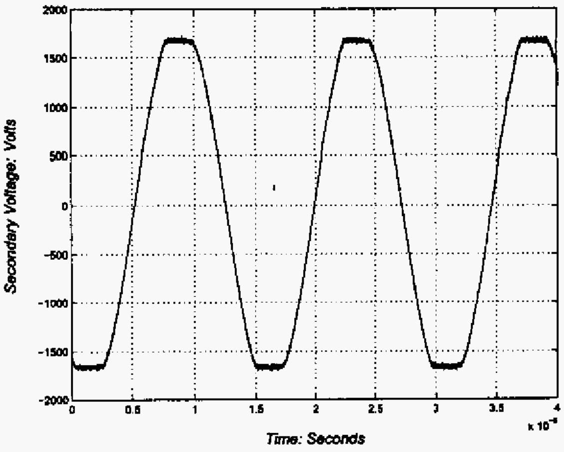

Fig. 3. Voltage across the secondary of the step-up transformer.

A. Control

For reasons which are discussed in greater detail in Section V, ozone is typically generated by creating a series of high voltage pulses which can last for minutes or even hours. Additionally, the length of a single pulse and the overall number of pulses varies from test to test. Thus, for purposes of overall coordination, ultimate control of the converter's output voltage must rest with the master computer. From a practical standpoint, this means that the master must send control instructions to the remote stations before each and every test.

For purposes of local control, each remote station is equipped with a PIC16F877A which generates the appropriate drive waveforms for the parallel resonant converter. Prior to the commencement of a new air flow experiment, a control program is created for each PIC by the master station and transferred over the power line to the computer at the remote station. This code is then uploaded to the PIC via an RS-232 data link. Figure 4 is a partial schematic which details how the PIC is used to drive one of the legs of the full-bridge inverter.

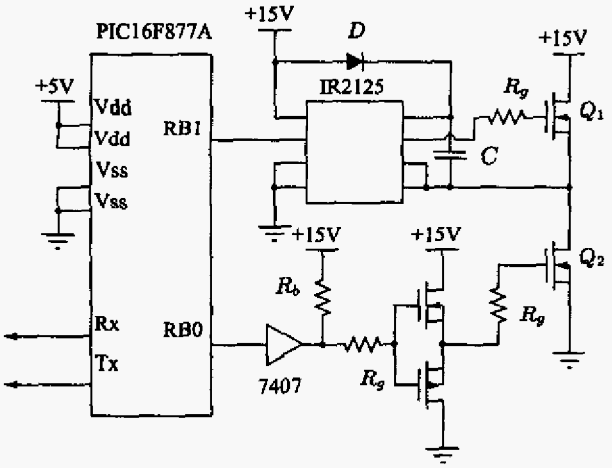

Fig. 4. Gate drive circuitry for one leg of the full bridge inverter. Note that the FETs in the other leg are controlled in a similar manner.

In order to be able to accept and to execute new pieces of code on a regular basis, the PIC is programmed with bootloader software that enables it to simply wait for new code to arrive while the power supply is not in operation. Once new software has been transferred, the PIC does not immediately begin to execute it. Rather, the PIC waits until it receives a start signal over the RS-232 data link. When that signal is received, the PIC immediately transfers program execution to the newly downloaded code and ozone generation begins. When ozone generation is complete, the PIC simply returns to its initial state and begins once again to wait for new code. Further details regarding the overall coordination of the control process are described in Section V.

IV. THE OZONE DETECTOR: AN "HOURGLASS" INTEGRATOR

In the current system, ozone concentration is monitored at several points using heated tin-oxide sensors and low-noise amplifier circuitry. The ozone sensor, which is shown in Figure 5, is a simple device with a resistance that varies in direct proportion to local ozone concentration [6]. To measure changes in the resistance of the sensor, a DC voltage is applied and the resulting current is passed to an integrator. The utility of an integrator in this application may be seen by noting that the natural frequencies associated with the movement of air in an indoor space are normally very low. At these frequencies, the gain of an integrator is extremely high.

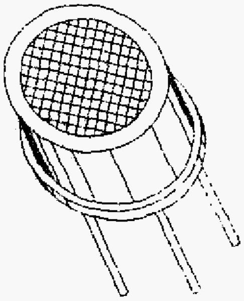

Fig. 5. A picture of the MICS-2610 ozone sensor used in this system.

In order to avoid the non-idealities associated with most practical integrators, the ozone detector makes use of the novel circuit topology shown in Figure 6 [7]. To understand the operation of this circuit, first consider a time when the control signal Φ_A is asserted. During that time period, v_{O1} will increase linearly at the rate $V_{IN}/(R_sC_f)$, while v_{O2} will decrease linearly at the same rate. Once v_{O1} has reached approximately 5V, appropriate feedback circuitry will assert $\overline{\Phi}_A$, and the input current will be passed to the other op-amp. At that time, the slopes of the two output voltages will reverse. Once v_{O2} reaches the same pre-specified threshold voltage (i.e. approximately 5V), the process will repeat. If R_s were to remain constant, this process of alternately charging and discharging the two capacitors at the same rate would continue indefinitely. This circuit is frequently referred to as an "hourglass" integrator, a name that makes reference to fact that the alternate charging and discharging of the two feedback capacitors is analogous to the movement of sand from one half of an hourglass to the other [7]. An output waveform generated by a constant current input is shown in Figure 7.

In the present implementation of this system, the differential output of the hourglass integrator is sampled at 50kHz by a Pentium-class PC equipped with an Advantech PCI-1710 data acquisition card. Software on the computer differentiates the sampled output voltage using a two-tap FIR filter. The signal returned by the software differentiation module, which remains at a 50kHz data rate, contains an excessive level of

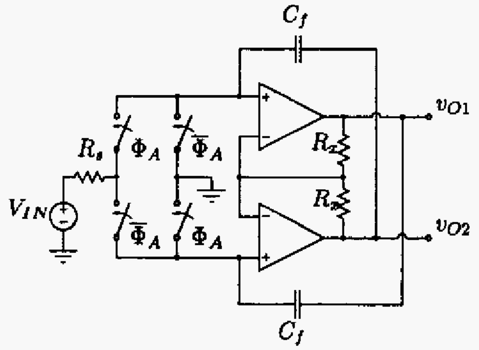

Fig. 6. Basic topology of the hourglass integrator circuit.

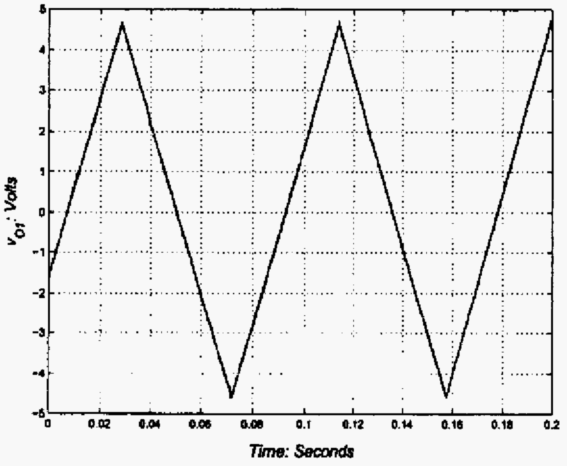

Fig. 7. Voltage waveform output by the hourglass integrator in the presence of a constant input current.

detail, as the frequency of ozone generation is typically less than 4 pulses per hour. Moreover, once the data has been processed and stored with floating point precision, it will quickly fill up most reasonably-sized storage devices. For this reason, the differentiation module is followed by a series of decimators, each of which includes an M-th band anti-alias filter. The use of M-th band filters allows for a reduction in the overall number of operations that must be performed during the computationally intensive decimation process [8].

Although the sampling and post-processing operations performed by the PC could be handled by a DSP, the PC greatly simplified the interface to the power-line carrier modem modules.

V. SUPERVISORY CONTROL

As mentioned in previous sections, intelligent supervisory control is required in order to create a system capable of providing sufficient information on the flow of air in buildings. In this section, we examine how the aspects of indoor air flow patterns can be used to create appropriate control software for the high voltage power electronics.

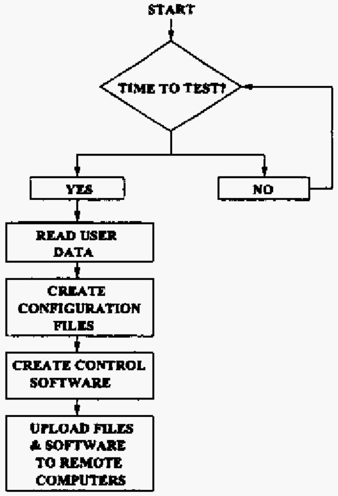

Fig. 8. Operations performed by the master computer prior to an air flow test.

During most air flow tests, the generators are instructed to create a series of ozone pulses by alternately energizing and de-energizing their high voltage power supply. From a measurement perspective, a pulse train is particularly useful as it provides the ability to distinguish changes in the sensor resistance due to injected ozone from changes caused by other factors such as natural variations in ozone concentration and the cross-sensitivity of the sensor to humidity. By conducting tests in this fashion, we are essentially performing the synchronous detection of ozone molecules.

Before any measurements can begin, the master computer must prepare a series of command files to be sent to each unit in the system. To do so, that machine is loaded with a configuration file created by the building operator that contains the start time for the particular test, the number of pulses to be created by each generator, and the length of time required for a single pulse. Based on this information, the software on the master computer creates a program to be used by the PIC16F877A microcontroller to control the generation of the appropriate series of high voltage pulses. Once this program has been compiled, the master computer uploads it to those stations that are to operate as generators. Additionally, the master computer also sends each unit in the system a series of configuration files. The first of these contains the start and stop times for the test; the second contains a command informing each unit of the mode in which it is to operate. Figure 8 presents a summary of the tasks performed by the central computer prior to conducting a set of measurements.

A daemon running on each of the remote PCs checks at the beginning of each minute to see if new configuration files have been recently uploaded. If so, the computer first determines the mode in which it is to operate. If that mode is generation,

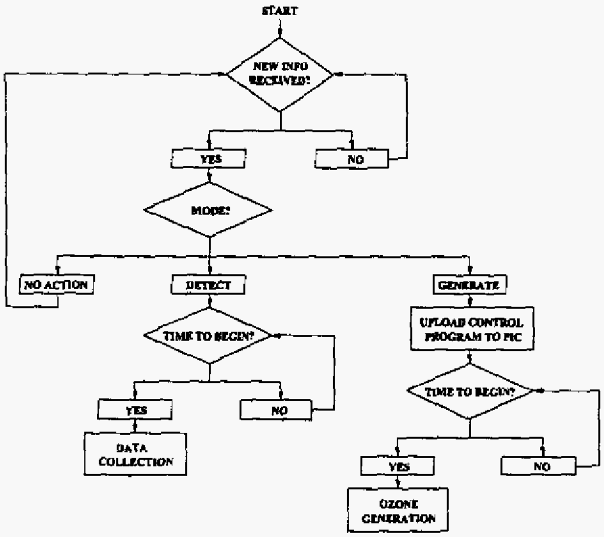

Fig. 9. Operations performed by a remote computer prior to an air flow test.

the new control software for the parallel resonant converter is uploaded to the PIC using an RS-232 data link. At that point, the computer and the PIC wait until the appointed start time. When that time arrives, the computer sends a command to the PIC instructing it to begin executing its new control software. If it is desired to stop the test prior to the pre-specified time, the computer can send an emergency stop sequence to the PIC instructing it to immediately cease ozone generation. Otherwise, the PIC will continue to generate ozone until it has performed the pre-determined number of ozone pulses.

For those units which operate in detection mode, the procedure is similar. At the scheduled start time, these units begin to sample, process, and store the detector output voltage. As soon as the current time matches the stop time provided in the configuration file, the control daemon running on the detector computers immediately stops data collection and transfers the resulting data file to the master computer. A complete summary of the operations performed by the remote computers is given in Figure 9.

VI. Operating Examples

The air flow monitor described in this paper is suitable for use in determining several key quantities related to a building's indoor air flow patterns. In this section, we examine how the system can be used to determine localized air speed and direction information.

A knowledge of air speed and direction at various points in a building is critical for the characterization of the overall flow in a building. The importance of such information is made very clear in the case of naturally ventilated buildings[1]. In most commercial facilities of this type, it should be the case that warm outdoor air moves from open windows to air outlets in the roof of the building [9]. On the upper floors, where air is expected to be warmer, this may not be the case, and it may be necessary to introduce moderate amounts of mechanically-assisted ventilation in order to ensure adequate air quality.

Figure 10 shows an example arrangement which has been used to simulate the types of flow patterns which might be encountered in a naturally-ventilated building. In this setup, a unit in generating mode was placed in a room between two units in detection mode. Using a fan placed in an adjacent room, a flow pattern was created in which air moved from right to left.

Figures 11 and 12 show the results of two different tests that were performed using the arrangement presented in Figure 10. During each of these experiments, ozone was pulsed several times at a frequency of 600μHz. At that rate, ozone is generated using pulses lasting approximately 14 minutes. In both cases it is clear that the sensor located downstream of the generator measured a larger change in sensor resistance and thus a larger change in ozone concentration[2].

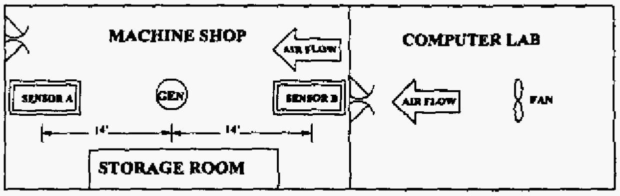

Fig. 10. Arrangement used during the initial air flow direction experiments. The units labeled "Sensor A" and "Sensor B" are in detection mode. The unit labeled "Gen" is in generating mode."

VII. Conclusion

The feasibility of a low cost, ozone-based tracer gas system has been investigated. It has been shown that it is possible to coordinate the generation and detection of ozone molecules using a computer that is given input data from a user. In the future, the master computer will be equipped with software that can automatically extract information such as air speed and direction from the ozone concentration data sent back to it from remote detectors. Additionally, it should be possible to integrate this system with a building's HVAC controls in a manner that can reduce overall energy costs.

Acknowledgment

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[1] Naturally ventilated buildings use little or no mechanical means to provide fresh air to their interiors. In appropriate climates, this technique can be used to reduce energy costs [9].

[2] Experiments have shown that the response of the ozone sensors is also sensitive to changes in quantities such as temperature and relative humidity. Since we have not yet fully characterized these effects, we have reported our measurements in terms of resistance and not in terms of concentration

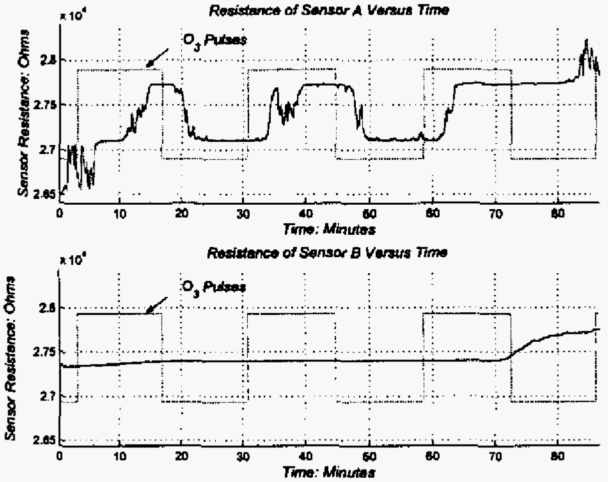

Fig. 11. The response of two different sensors during a direction test. Sensor A was located downstream of the ozone generator. Sensor B was located upstream.

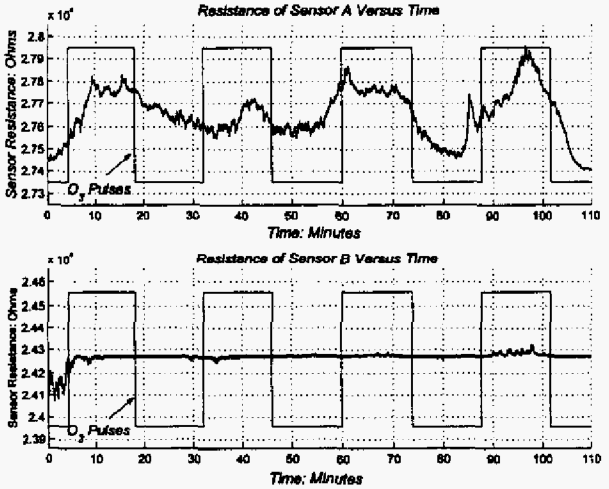

Fig. 12. The response of two different sensors during a second direction test. Again, sensor A was located downstream of the ozone generator and sensor B was located upstream.

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