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Transient Overvoltage Testing of Environmental Controllers

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ABSTRACT

The integrated electronic control system will provide a new method for the day-to-day management of environmental control of animal production systems. No standards are currently accepted for transient overvoltage protection of these controllers. To assess the adequacy of existing designs, a test circuit was designed and used for a transient open circuit over-voltage waveform (ANSI/IEEE C62.41-1980) of 16 environmental control units: a maximum spike of 770 V was applied to the power supplies, and a spike up to 100 V was applied to temperature sensor lines. For these relatively mild tests, no failures were noted due to power supply transients, but three units failed when subjected to transients on their temperature sensor lines. From this research it is suggested that an industry standard be adopted to define the minimum transient overvoltage design conditions by which environmental controllers should be tested.

KEYWORDS. Electric controls, Animal environment, Digital controls, ANSI, Lightning, Testing.

INTRODUCTION

United States animal production systems are at the threshold of a major new method for daily management of environmental control–the integrated electronic control system. These systems generally consist of a controller which is placed in or near the facility or zone to be controlled, with connections for sensors such as temperature, relative humidity, ammonia concentration, water flow or pressure, and various analog and/or digital inputs for feedback purposes. Control connections can include such items as analog or digital output to secondary control devices.

Examples of control are fan speed control, typically done with an analog signal sent to a triac controller, which in turn modulates the fan speed. Fan speed control may utilize speed feedback for more precise control on some systems. Another more prevalent example of control is fan staging, in which sequentially activated relays (either on the main controller, or in a separate box) are used to increase ventilation in stages, as the difference between inside temperature and controller setpoint increases.

Widespread adoption of this technology has the potential for improving production efficiencies through lower management costs, energy savings, and better feed conversion efficiencies. This is expected to occur due to the superior "control resolution" that such systems have, compared with conventional mechanical thermostat control systems. Also, as the size of intensive livestock production systems has increased, environment control in these larger production systems, using conventional thermostat technology, requires many individual mechanical thermostats which are nearly impossible to synchronize.

However, the technical problems of transient surge protection and appropriate mechanical backup systems have not been adequately addressed by the integrated control system industry. Clearly, as livestock production systems increase in size, the costs associated with a complete failure of the environmental control system can be catastrophic for the owner of the facility and the livestock or poultry housed. Controller failure can occur from a variety of causes that are not always predictable. A properly designed and installed system should be capable of maintaining basic life-support functions even after controller failure (Gates et al., 1992a). Therefore, mechanical backups are an essential control system component, even when transient overvoltage protection has been provided.

Currently there is a small market in two fundamentally different "integrated" control systems. These systems can be described as follows:

1. Analog devices which effectively bring all environmental control input/output functions to a central device. These units are effectively "smart" thermostats for staging fans, heaters, coolers, air inlets, and/or curtains. Additional equipment is usually necessary for management functions such as feed, light, and automated weighing.
2. Microprocessor-based devices which, in addition to all the functions described above, may be programmed to monitor system performance, and

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provide warnings of detected problems. They also may control feeding, light, and automated weighing and can be connected to centralized computer systems (usually PC based) for remote control and access to current and past conditions in the facility.

One potential advantage of both of these systems over conventional methods is the integration of many control circuits into one device, with a resultant reduction in errors resulting from incorrectly calibrated or set thermostats, timers and other equipment. Integrated controllers can provide the user with a more "global" perspective of the entire control system, and allow for rapid determination of component equipment failure.

Producers who have adopted these systems generally report greater ease of use, more uniformly maintained environmental conditions, and better feed conversion efficiencies. Problems with microprocessor units, however, include loss of memory and occasional "wild" performance from unknown external stimuli, often blamed without justification on "dirty" power or lightning.

This report describes the results of transient overvoltage tests performed on 16 currently available environmental controllers. The objectives of this work were to:

1) Design, develop, and use a transient surge generation circuit to effectively evaluate, in a standardized procedure, the inherent surge protection of current commercial controllers.
2) Identify the degree to which transient surge protection is being provided by current manufacturers of integrated controllers.

Controllers Tested

Both analog and microprocessor systems were evaluated. Testing performed on the units was focused on the effect of transient overvoltage (waveform pattern as given by ANSI/IEEE C62.41-1980) imposed directly to the power supplies and temperature sensors of the controllers. A brief overview of the controllers is given here, and a complete description of these controllers, their functions and features, can be found in Gates et al. (1992b, 1991c).

Sixteen commercially available environmental controllers from fourteen different manufacturers were tested. A summary of controller features is given in Table 1. These models are not identified by manufacturer due to confidentiality agreements. The models ranged from simple analog stage controllers to sophisticated units with the ability to control multiple modulating devices simultaneously (e.g. air inlets, fan speed, motorized shutters). Of the sixteen different controllers, ten utilized a microprocessor. Thirteen units had internal power supply circuits, rather than some type of external supply such as a "wall pack".

Several units were constructed with mild steel or other unsealed enclosures inappropriate for the harsh environment for which they were designed (according to advertisements). Apparent concern by manufacturers regarding proper sealing varied considerably, as judged by instructions and usage labels. Several of these same units also incorporated some type of alarm feature, and consequently violate ASAE Standard S417.1 (ASAE, 1989) with respect to appropriate enclosures.

TABLE 1. Overview of controllers evaluated

ID	Analog (A) vs. Micro-processor (M)	Temperature Sensors		Control Features			
		Inside	Outside	Alarm Feature*	# Control Relays	Variable Speed Control	Interval Timers
1	M	1	1	D	7	No	2
2	M	1-4	1	R, D	5	Yes	0
3	M	1-2	1	R, D	5	No	0
4	A	1	0	–	12	No	1
5	A	1-2	0	–	2-7	No	0
6	M	1	0	R, D	N/A	No	0
7	A	1	1	R, D	12	No	1
8	M	1	0	–	4	No	0
9	M	1	0	–	4	No	0
10	M	1	0	–	2	No	0
11	M	1	0	D	2	Yes	0
12	A	1	0	–	2	No	0
13	M	1	1	R, D	6	No	0
14	A	1	1	R, D	6	No	0
15	M	2	1	R, D	6	Yes	0
16	A	1	0	D	6	No	0

* D = displayed (error code or short phrase)
R = Relay enabled (for external alarm)
-- = None.

Sensors for the controllers consisted of one or more inside temperature readings, and for one controller, relative humidity also. Seven units used an outside temperature sensor. Several units had no means for temperature sensor calibration; two of these units (8 and 9 in Table 1) had uncorrectable errors in excess of 3.5° C (8° F).

Most units were configured strictly for staged ventilation (i.e., no modulating control such as fan speed). Six to eight control relays were typical of the units, although this varied tremendously. Most units utilized "dry contact" control relays so that installers could use whatever control voltage was appropriate for the coils of the relays that switch the power equipment.

Transient Overvoltage Test Development

Direct measurement of transient waveforms occurring in residential and industrial facilities has formed the historical basis for the development of guidelines for testing electronic equipment (IEEE, 1970; Martzloff and Hahn, 1970; Odenberg and Braskich, 1985). One result of the earlier research was the emergence of ANSI Standards C62.41 (ANSI, 1980) and C62.45 (ANSI, 1987).

Two waveforms are specified (Standler, 1989; EFI, 1990; ANSI, 1980). The first is a unidirectional waveform of specified energy content represented by an open-circuit waveform with a 1.2 microsecond rise time, a 50 microsecond fall time, and an amplitude which is determined by the actual test to be performed, up to a maximum of 6 kV. The resultant discharge current waveform, which would occur if this open circuit pulse were shorted, has a rise time of 8 microseconds and a fall time of 20 microseconds.

The second waveform specified by ANSI C62.41-1980 is an oscillating ring wave with a 0.5 microsecond rise time, 100 kHz frequency, and sufficient damping to reduce each subsequent peak by 60% of the previous peak. A maximum of 6 kV amplitude is specified for this ring wave. These waveforms are described and graphed in Standler (1989), EFI (1990), and ANSI (1980).

It is important to note that the actual transient imposed on the equipment under test (EUT) is a function of the energy available in the transient, the open-circuit waveform, and the input impedance of the EUT. Consequently, it is effectively impossible to faithfully represent all transients that might be encountered. Rather, because considerable research has been done to quantify the magnitude of transients encountered, the Standard specifies a "worst case" energy content from which the above mentioned waveforms were derived. For a particular application, an appropriate test category for the EUT is selected, and the Standard specifies the appropriate waveform shape and magnitudes (Dash and Straus, 1990a).

There is substantial evidence that the ANSI waveforms are insufficient to characterize transients from either load switching or lightning, in terms of the rise time and the pulse duration. Odenberg and Braskich (1985) measured 277,612 transients in 63 separate locations (nine different cities) over a two-year period. They measured voltage and current waveforms simultaneously. Their principal finding was longer duration voltage and current waveforms than used in the test standard waveforms.

No available standards address a system-wide protection scheme (Uman, 1988), and most standards were developed prior to the development of microelectronics applications (IEEE, 1970). Consequently, most surge testing equipment still incorporates the waveforms stipulated by ANSI C62.41-1980 (ANSI, 1980, 1981, 1987).

As such, the selection of an appropriate transient waveform for testing electronic equipment must necessarily be made with the intended use of the equipment in mind. To protect devices such as electronic controllers used in the agricultural industry, a cascaded system of protection is widely recognized as being necessary (Standler, 1989; Buller, 1987; NFPA, 1986; IEEE, 1982; Lee, 1978, 1979; Timmons, 1968).

In this scenario, both the building and power service are equipped with lightning protection equipment to divert and shield the building components from direct lightning strikes. The equipment consists of air terminals connected with a uniform array of down leads to ground conductors around the building. Grounding of both the lightning protection system, and the electrical service, are crucial to proper operation of the protective equipment (IEEE, 1982; ASAE, 1988; NFPA, 1986). The main service primary is provided with surge protection (a "lightning arrestor") by the power utility.

The building transient protection scheme consists of the external lightning diversion described above, and a surge suppressor, typically a varistor or spark gap sized to clamp and short out any large transient components, installed on the power service. Additionally, a third level of protection is a transient surge suppressor on each electrical circuit that powers equipment that is sensitive or costly.

Finally, sufficient additional surge suppression is necessary on any critical devices within the structure to withstand any residual transients that may have passed through the first three levels of protection. This on-board protection is also typically the only protection for any additional input/output lines to the controller, such as temperature sensors.

Selection of an appropriate test waveform thus requires several assumptions regarding the level of transient protection being used in conjunction with the equipment to be tested (Dash and Straus, 1990a, 1990b; EFI, 1990). For the purposes of this study, we began with the presumption that complete transient protection as described above would be provided. The magnitude of the test waveform can then be selected based upon guidelines from the literature (e.g., Dash and Strauss, 1990a). These suggested values ranged from the full 6 kV for "long" branch circuits and outlets (specified in ANSI C62.45-1987 as category A); 3 kV for "short" branch circuits and load centers (specified in ANSI C62.45-1987 as category B); 1 kV for cascaded protection in which one or more varistors (nominally clamping at 600-1000 V) have already intercepted a portion of the transient (EFI, 1990; Standler, 1989), down to 50-100 V for data lines (Standler, 1989; Odenberg, 1982; Clark, 1989).

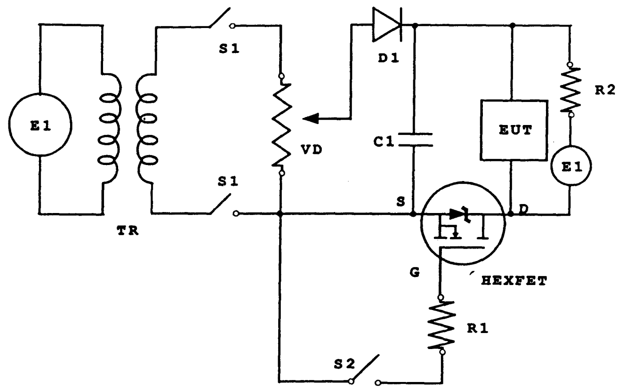
Transient Test Procedure

Based on the review of transient test literature, a nominal 1 kV open circuit test waveform was selected as a reasonable value for testing the controllers' power supplies. This was chosen on the premise that primary, secondary and tertiary protection would be provided on the electrical service to the controller. (This is perhaps an unlikely assumption for most installations to date). A range of smaller magnitudes, 40 to 100 V, was chosen for the temperature sensor lines. The open circuit voltage test was chosen because large magnitudes in the time rate of change of voltage (dV/dt) within semiconductors are known to result in electrical overstress (EOS), and because large currents such as from lightning which travel through a structure can induce very large voltages in nearby wires (Odenberg and Braskich, 1985; Standler, 1989; Clark, 1989; Orville, 1990).

A test circuit was developed to provide the desired open circuit waveform (fig. 1). The appropriate values of resistance, capacitance and inductance were selected by numerical solution of the electrical equations for the discharge of a charged capacitor (Gates et al., 1992c). No inductance other than that provided in the test circuit wiring was used; the error induced in the test waveform was minimal (fig. 2). The magnitude of the test waveform was adjusted by charging the capacitors to different voltage levels.

A typical test operation involved the following steps. First, the capacitors were charged by closing relay S1, which provided AC power (E1) to the diode which in turn half-wave rectified the voltage and charged the capacitor. The magnitude of the charging voltage was adjusted from 0 to 850 V by means of the voltage divider. Note that the HEXFET (International Rectifier IRFPG50) is off when relay contact S2 is open. Second, the charging circuit was disconnected (S1 open). Immediately after opening S1, the pulse switch (S2) was closed, thereby triggering the HEXFET to conduct. Once the HEXFET conducted, the charge stored in the capacitors was discharged, and the transient was released into the equipment under test (EUT) and through the 40 ohm resistor (R2) and E1, if connected.

Neglecting the output resistance of the HEXFET, and denoting the charging voltage across C1 by V_o, the maximum discharge current I_{max} going through E1 and the HEXFET is:



E1 120 VAC
TR Transformer 124/633 V
S1 Contacts of DPST relay
S2 Contact of SPST relay
VD Voltage divider
D1 Diode (3398)
C1 Capacitor 1.5 MF
R1 Gate resistor 50 Ohm
R2 Current limiting discharge resistor, 40 Ohm
EUT Equipment under test
HEXFET Discharge switch (IRFPG50)

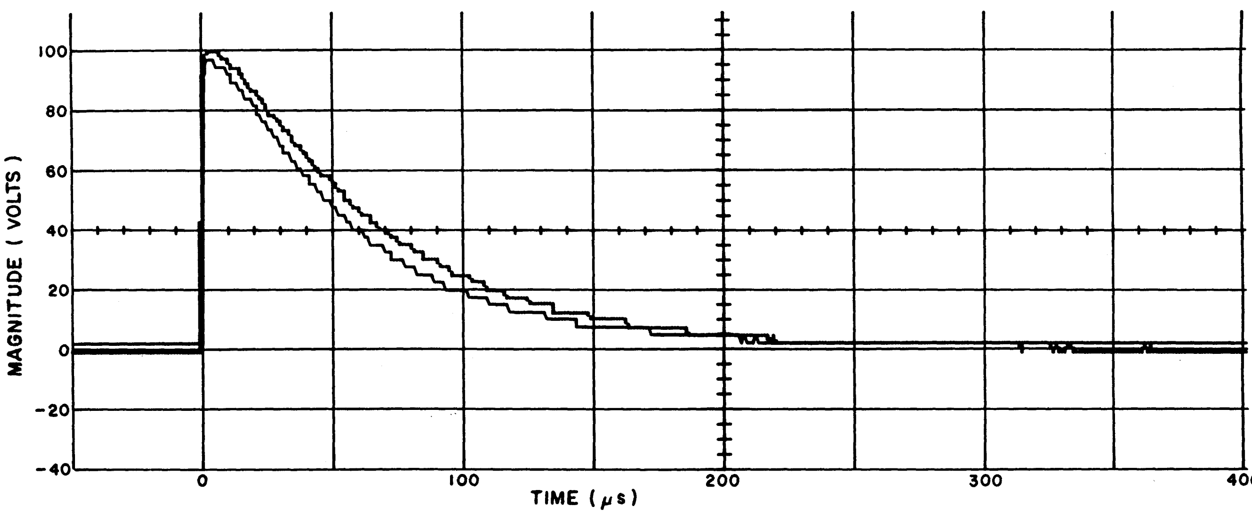
Figure 1–Schematic of the overvoltage surge generating circuit designed and used for this research. A transformer (TR) with a voltage divider (VD) are used to charge a capacitor (C1). Switch S1 is then opened to disconnect power from the capacitor. Switch S2 is closed to trigger the gate of the HEXFET, which in turn applies the desired pulse waveform across the equipment under test (EUT). For tests in which power to the EUT is desired, it is applied in series with the current limiting resistor (R2); for tests on the temperature sensor circuit the EUT block refers to the power leads to the sensor.

$$I_{max} = \frac{(V_o + 120\sqrt{2})}{40} \quad (1)$$

if the EUT is not connected in the circuit. For the values of capacitance and resistance shown in figure 1, the open circuit waveform specified by ANSI C62.41-1980 is applied to the power input terminals of the EUT.

The open circuit transient overvoltage waveform generating circuit was first tested to ensure that appropriate values of resistance and capacitance were being used. The capacitor was charged to 770 V and the maximum recorded discharge voltage (recorded using an HP model 502A digital oscilloscope) was typically 610-620 V without power to the EUT, and 730-740 V with 120 VAC power to the EUT. The difference between the applied voltage and the peak discharge voltage is believed to be due primarily to energy dispersed within the HEXFET (i.e. voltage drop due to internal resistance). The magnitude of discharge voltage also varied somewhat due to the slightly uneven time period between manual opening of switch S1, and the manual closing of switch S2.

The waveform shape was altered very little when the various EUTs were connected to the discharge circuit (fig. 2). However, with E1 connected to the circuit (i.e. power applied to the EUT) the magnitude of the peak discharge voltage across the EUT changed with each test, because the nominal 120 VAC was added to the discharge voltage. If the power phase was at a positive peak, an additional 170 V ($120\sqrt{2}$) was added to the pulse; conversely, if the power phase were at its negative peak, then the peak voltage was 170 V less.



	Timebase	Delay/Pos	Reference	Mode
Main	50.0 us/div	-50.0000 us	Left	Repetitive
	Sensitivity	Offset	Probe	Coupling
Channel 1	20.0 V/div	40.0000 V	100.0 : 1	dc (1M ohm)
Pmemory 1	Status - ON			

Trigger mode : Edge
On Positive Edge Of Chan1
Trigger Level
Chan1 = 40.0000 V (noise reject OFF)
Holdoff = 40.000 ns

Figure 2–An example oscilloscope tracing of the test waveform applied to a temperature sensor circuit. The top trace is the open circuit discharge voltage measured with no EUT connected. The lower trace is the discharge voltage measured with the EUT connected, and indicates that the waveform accurately represents the ANSI/IEEE waveform.

Using this basic circuit, we conducted discharge tests for three cases: 1) with neither EUT nor E2 in the circuit; 2) with only E2 in the circuit; 3) with both EUT and E2 in the circuit.

The limiting component affecting the test waveform magnitude was the capacity of the MOS HEXFET used to switch the capacitor discharge circuit. The maximum pulse voltage that the HEXFET was capable of sustaining was 1000 V at 19 A, which clearly limited the severity of the tests. A more preferable approach would be to utilize a commercially available surge generator. However these surge generators are rather expensive. Thus the tests reported here are not particularly severe tests of the equipment and this should be considered when evaluating the test results.

The tests were first done on the power supply lines, with the EUT powered off. Ten applications of the test pulse, with approximately a 20-30 s delay between applications, were done. The EUT was then powered up and checked. Then, the EUT was subjected to 10 to 15 additional tests while power was applied. The resultant actual magnitude of the imposed pulse varied with the phase of the power line.

Finally, a series of tests were performed on a temperature sensor line on each controller. The initial test magnitude was approximately 45 V, followed by 60 V and then 100 V. Operation of the controller was checked after each pulse, and if the controller failed, testing was discontinued. The transient voltage was applied directly to the two sensor leads, with approximately 0.5 m of wire from the discharge circuit to the controller.

Results of Controller Tests

The tests performed on the power circuits of sixteen electronic controllers both with and without power resulted in no noticeable damage to the controllers. Since all controllers utilized a step down transformer to provide low level voltage (typically 12 V), these transformers effectively reduced the imposed test transient by the input/output ratio of the transformer.

For a few controllers which used 240 VAC, we provided a step up transformer to perform the tests with power to the EUTs. Consequently, these controllers had an additional inductance between the transient surge and their power supply in the imposed test transient voltage.

Tests on the controller temperature sensor lines resulted in three obvious failures: one unit failed at 45 V (fig. 3), one unit failed at 60 V, and one unit failed at 100 V. Two of these three units utilized analog control; the third utilized a microprocessor. All other units appeared to function normally for imposed transients as high as 100 V. An oscilloscope tracing of one of the failures (fig. 3) suggests that a component failure occurred early in the transient discharge, resulting in a slight "dip" in the voltage, followed by a continued rise and subsequent voltage decay.

Symptoms of the three failures were varied. One controller failed with all the cooling relays closed and all heating relays opened, and was clearly damaged because no digits were displayed, only a decimal point. Another controller's temperature indication locked onto 28.8° F (probably the low limit value for the temperature circuit) and the entire display flashed, indicating a minimum temperature error. The same unit was repaired and subjected to another pulse (45 V) which caused more apparent damage—several display codes were changed to dashes. The third controller failed with the temperature display locked onto 143° F (probably the upper limit value of that temperature circuit). No alarm indication was present. In all cases, a failure of the controller would have resulted in the positive actuation of some part of the heating/ventilating system. In two cases, all available ventilation would have been turned on, and in the other case the heaters would have been turned on.

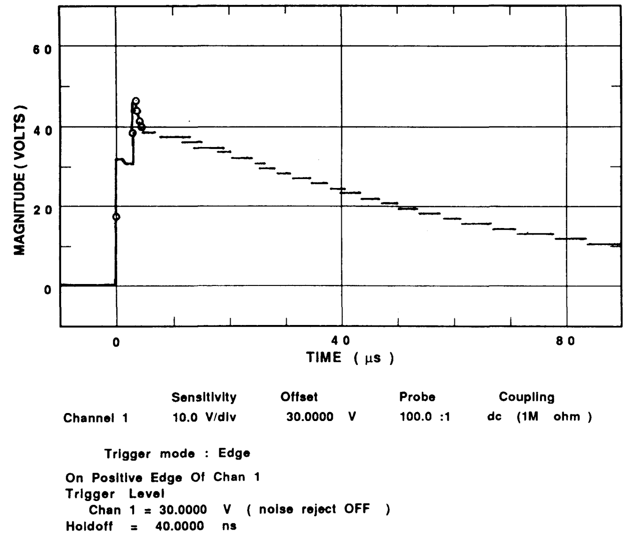


Figure 3–Tracing of an oscilloscope capture of a test in which a temperature sensor failed. Note the applied voltage was only 45 V. An apparent component failure occurred very soon after initiation of the discharge, as represented by the dip in the curve near 30 V. Controller response to this failure was to display a low temperature error condition and turn on the heaters; similar failures for two other controllers resulted in all ventilation relays turning on, as if a high temperature condition existed.

Discussion

The transient surge generation circuit that was developed to test controllers is a successful and relatively inexpensive alternative to commercially available units. The chief limitation of this design is that the maximum discharge voltage must be less than 1 kV, due to the HEXFET device used as a switch to initiate the discharge. For sensor circuits, and other data lines with lower overvoltage test thresholds, the circuit presented in figure 1 is quite adequate.

The results of the overvoltage tests on the controller power supplies indicate that these supplies are reasonably designed, despite the lack of any standard set of design specifications. As described above, however, these tests were of very modest magnitudes and never exceeded 740 VAC. Selection of a power supply transformer is very important because this provides essential isolation between possible transients and the controller power supply. Transformers block common-mode voltage, such as occurs when a transient raises the ground reference potential suddenly. However, parasitic inductance is a problem in transformers which do not have adequate shielding between primary and secondary coils (Standler, 1989), and if these shields are not adequately grounded their value is also lost. Many of the controllers tested had no visible shielding around the supply transformer, and only three had supplies external to the enclosure. While all units survived these limited overvoltage tests, visual inspection of the designs suggested a general lack in following guidelines for power supply design. These guidelines can be summarized as (Standler, 1989, chapter 18):

1. Protection from common-mode and normal-mode excessive primary voltage.
2. Protection of rectifiers from excessive current, and excessive reverse voltage.
3. Protection of the input port of the voltage regulator, and the filter capacitor, from excessive voltage.
4. Protection of the output port of the voltage regulator from overvoltage, with a means to bypass for noise reduction.

The extent to which each of these items is followed has obvious cost implications. A reasonable level of protection, however, should include varistors across the primary winding of the transformer to protect the rectifier, filter capacitor, and voltage regulator from normal-mode overvoltages. Additionally, because of the likelihood of an overvoltage source on the secondary side of the power supply (from sensor lines, for example), protecting the voltage regulator from reverse-biasing is important.

Several controllers utilized switching power supplies, in contrast to the conventional linear power supply. While these supplies provide very stable output voltages for a wide range in supply voltage, and inexpensive protection against brief interruption of the primary voltage, protection from transients on the main supply is difficult (Standler, 1989). Several of the switching power supplies were not mounted in shielded enclosures.

Data line transient protection (i.e. temperature sensors) varied considerably among the units. One unit had transient protection at the temperature sensor as well as on the signal conditioning circuit; many units utilized varistors; several units had no obvious means of protection, including the three that experienced sensor circuit failure. While it would be too expensive to design for a very high level of protection, data lines should be protected from overvoltages such as electric shocks and induced voltages from nearby load switching. A test waveform, such as that applied in this work, should be a standard means of assessing the reliability of data line transient protection.

The specification of a test protocol for environmental control units should incorporate the following information: 1) peak values of overvoltage; 2) description of transient waveform applied to each conductor; 3) requirement that the unit should be on during testing; and 4) the number and frequency of test sequences performed to assess degradation. Additional specifications regarding the power supply ability to withstand over and under voltages, and brief outages (i.e., number of cycles "slipped"), should also be provided. Industry acceptance of a rational test protocol can provide very effective and rapid adoption of this technology, without the major problems associated with poorly designed transient protection.

Recommendations

Based on results of the research reported here, the following recommendations are offered.

Testing

The development of a standard waveform and test procedure to supersede ANSI C62.41-1980 and C62.45-1987, that is more appropriate for simulating actual measured power line transients, is recommended. Once such a test protocol is developed, ASAE, in cooperation with controller manufacturers, should adopt it as a standard test for both the controller power supply and sensor lines. Manufacturers should also specify the number of complete power cycles that can be "slipped" without disruption, and the allowable range in supply voltage.

Alarms

A method for alarm notification due to temperatures outside of specified limits should be integral to each installation. A systematic and standardized approach to controller operation when an alarm condition is noted should be adopted by ASAE. Such an approach must take into account the issue of liability.

Mechanical Backup

Thermostat and timer backups should be installed to provide basic life supporting functions in the event of controller failure. Controller failure alarms, such as a watchdog timer, should be developed by manufacturers to provide early warning of failure. The ASAE should provide a leadership role in the development and promotion of standardized methods for mechanical backup of integrated control systems.

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