USING CURRENT-LIMITING FUSES TO REDUCE HAZARDS DUE TO ELECTRICAL ARC-FLASHES

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Abstract: Numerous tests were conducted in which arcing faults were initiated in open electrical equipment. Tests were run on circuits protected by both current-limiting fuses and typical industrial circuit breakers. Results showed a dramatic reduction in the amount of damaging energy released upon a worker when current-limiting fuses were utilized. Measurements included voltage, current, temperature, sound, and pressure. High-speed 16mm film, video, and infrared video were also utilized to record the events. Results of the testing were used to develop an award winning IEEE paper[1] and an electrical safety training package now being sold by the Electrical Safety Subcommittee of the Petrochemical Industries Committee (IEEE/PCIC). This paper explains the background for the testing, the tests themselves, and how the fuse industry can use the results of the testing to reduce the hazards associated with electrical arc-flashes.

INTRODUCTION: The installation codes in North America require that equipment be installed in accordance with the way it was listed or certified. The installation codes however do not provide guidance for maintenance workers, and the product standards do not require testing for arcing faults that might occur when the equipment door is open and a maintenance worker accidentally creates an arcing short circuit. As a result, numerous workers are injured and killed each year while working on energized electrical equipment. An ad-hoc working group was formed within the IEEE/PCIC safety committee to help address this situation. The intent of the group was to raise the awareness of electrical workers to the dangers associated with electrical arcs and hopefully reduce the incidents of worker injuries and deaths.

The ad-hoc group consisted of 10 members, of which one was a medical doctor with electrical burn expertise, two were consulting engineers, four were engineers for various petrochemical companies, and three were with an electrical manufacturer. The group had no funding outside of the group itself. Everyone participated in the decision process, provided their expertise, and donated actual electrical equipment when possible. Some equipment was brand new. It had never been put into service. Other equipment was taken out of decommissioned plants. Switchboards, panelboards, busway and motor control centers were donated for these tests. In addition, lab time was donated by a manufacturer in a high-power short-circuit test lab in the Midwest.

BACKGROUND/RELEVANT PAPERS: In 1982, Ralph Lee wrote a paper titled, "The Other Electrical Hazard: Electric Arc Blast Burns"[2]. In that paper he developed a formula for the distance required for various degrees of burns as related to the available MVA and time of exposure. These formulae were developed for arcs in open air.

$$D_c = (2.65 \text{ X } MVA_{bf} \text{ X } t)^{1/2} \qquad (1)$$
$$D_c = (53 \text{ X } MVA \text{ X } t)^{1/2} \qquad (2)$$
$$D_f = (1.96 \text{ X } MVA_{bf} \text{ X } t)^{1/2} \qquad (3)$$
$$D_f = (39 \text{ X } MVA \text{ X } t)^{1/2} \qquad (4)$$

Where

D_c = distance for a just curable burn, (feet)
D_f = distance for a just fatal burn, (feet)
MVA_{bf} = bolted fault MVA at point involved
MVA = transformer rated MVA, 0.75 MVA and over. For smaller ratings, multiply by 1.25
t= time of exposure, (seconds)

Lee's work showed, for example, that skin temperature above 96 degrees C for .1 second resulted in total destruction of the tissue (incurable burn) and that skin temperature below 80 degrees C for .1 second allowed for skin which could be cured (just curable burn).

NFPA 70E [3], Standard for Electrical Safety Requirements for Employee Workplaces, adopted the Lee Formulae to define the safe working distance from a potential arc. While NFPA 70E is not generally enforced as is the National Electrical Code (NFPA 70)[4], it is a consensus document and can therefore be used in a court of law and is considered "readily available public knowledge".

Ralph Lee followed in 1987 with another paper titled "Pressures Developed by Arcs"[5]. In that paper Ralph Lee explored the affects of the expanding metal and the heating of air because of the arc passing through it. Copper expands by a factor of 67,000 times when vaporized. Compare that to the expansion of water, which is only 1670 times.

In the paper, "Protective Clothing Guidelines for Electric Arc Exposure"[6], the authors used "incident energy" as the basis for choosing the correct protective clothing. The authors state that an incident energy of 1.6 cal/cm^2 is the level at which second degree burns would occur on exposed skin.

In a follow-up paper, "Testing Update on Protective Clothing & Equipment For Electric Arc Exposure"[7], the authors document measured sound pressures of up to 163 dB. For comparison, a 12-gage shotgun produces an intensity level of 130 dB. They state that enclosing a three phase arc in a box has the potential to increase the incident energy approximately three times, depending upon the box dimensions, as compared to an arc in a open air.

The committee was aware of the theoretical papers and wanted to show how the potentially dangerous arc flash events could affect workmen. It realized that it is both equipment failure and human error that contribute to arc flash events. The tests were designed to be different than previous theoretical tests in two ways. First, the tests were to use a mannequin, with measurements taken on or near the mannequin. Second, the tests were carried out with actual electrical equipment, both new and used, with arcs created as they might likely occur in the real world. The purpose of the tests was not to compare equipment manufacturers, but to raise the awareness of arc flash hazards in equipment that was applied according to the manufacturers' recommendations and third-party listing and labeling requirements.

TESTS: A preliminary series of 11 tests were run on March 26-28, 1996. The 27 main tests were run from September 10-12, 1996. The mannequins were positioned in front of the arc as though they were working on the equipment. The closest worker was positioned so that his chest was approximately two feet from the source of the arc, with his hand reaching in.

The equipment used in the September tests is listed in Table I. Available fault levels are shown in Table IV. All tests were carried out within the ratings of the equipment, but there were several major differences between the normal certification tests carried out by the equipment manufacturers and these tests. Normal certification testing is carried out with doors closed, whereas this testing was done with the doors open. Normal testing is done with bolted short circuits, but this testing was accomplished with arcing short circuits. The reasons for these differences are pretty obvious. Certification of the equipment already assures that the equipment will handle relatively high short-circuit currents when the faults are bolted and the doors are closed. But real world troubleshooting techniques often require that maintenance personnel work on hot equipment with equipment doors open. Thus the need for this series of tests.

All equipment was certified by a Nationally Recognized Testing Laboratory except for (1) a field fabricated bus distribution box that was used to distribute power for an outdoor switchrack. (It was removed from service specifically for this testing.), and (2), a shop fabricated three phase, four wire bare copper bus structure with ¼" x 1" x 6' copper bars spaced 1" apart (arcs were started in the middle of the bars and video-taped as they ran away from the source.).

Whenever possible, arcing faults were created with a screwdriver or a wrench placed from phase to phase or phase to ground. Where it was impractical to use a screwdriver or a wrench, a small piece of #18 copper wire was used to initiate an arc. The tests were staged in such a manner because research had shown that it was as close as possible to actual field conditions.

TEMPERATURE MEASUREMENTS: Type "T" thermocouples were placed on the lead mannequin's extended hand(T1), at the front of the neck(T2)and under its shirt at chest level(T3). These thermocouples were connected to an Astromed GE Dash-10 recorder. In addition, temperature measurements were captured by means of an infrared camera and recorded on tape. These measurements were used for the peak temperatures in Table II. The infrared equipment included an Agema Thermovision Scanner 870 (Catalog No. 556192904, Serial No. 4175), monitor, control unit, power supply, dual lenses, and Panasonic VCR. A mirror was used so that the camera could be positioned out of the direct line of the arc-blast.

Table I [1]
Equipment used in tests and overcurrent device operation

Test No.[a]	Equipment	Overcurrent device	Fault Initiation	Overcurrent device result
1	Size 1 combo starter w/ 30 A fused switch	601A Class L, 30A RK 1	Load side—screw-driver—C to gnd.	30 A RK–1 opened
2	Size 1 combo starter w/ 30 A fused switch	601 A Class L	Load side—screw-driver—C to gnd.	None
3	**Size 1 combo starter w/ 30 A fused switch**	**601 A Class L**	**Load side—screw-driver—C to gnd.**	**Class L opened**
4	**Size 1 combo starter w/ 30 A fused switch**	**640 A - Pwr CB**	**Load side—screw-driver—C to gnd.**	**CB did not open**
9	MCC # 2 w/insulated bus	601 A Class L, 30 A MCP	Load side—#18 wire—C to gnd.	30 A MCP tripped
10	MCC # 2 w/ insulated bus	601 A Class L, 70 A MCP	Load side—#18 wire—C to gnd.	70 A MCP tripped
11	MCC # 2 w/insulated bus	601 A Class L, 70 A MCP	Load side—#18 wire—B to C	70 A MCP tripped
12	MCC # 2 w/insulated bus	30 A MCP	Load side—#18 wire—B to C	30 A MCP tripped
13	MCC # 2 w/insulated bus	640 A - Pwr CB	Line side bucket—#18 wire—A, B, C	CB did not open
14	MCC # 2 w/insulated buss	640 A - Pwr CB	Line side bucket—#18 wire—A, B, C	CB did not open
15	600 A distribution duct	640 A - Pwr CB	#18 wire— A, B, C	CB did not open
16	225 A power panel	30 A MCB—3 Phase	Load side—screw-driver—C to gnd.	30 A MCB tripped
17	600 A distribution duct	640 A - Pwr CB	# 8 wire—A, B, C	CB did not open
18	Size 2 combo starter w/ 50 A MCP	601 A, Class L, 50 A MCP —200 A 170 Limiter	Load side—screw-driver—C to gnd.	200 A 170 Limiter and 50 A MCP opened
19	Size 2 combo starter w/ 50 A MCP	601 A Class L, 50 A MCP	Load side—screw-driver—C to gnd.	50 A MCP did not open
20	Size 1 combo starter w/ 35 A MCB	601 Class L, 35 A MCP	Load side MCB—#18 wire—C to gnd	35 A MCP did not open
21	Size 2 combo starter	50 A MCP	Load side MCP—#18 wire—A, B, C	50 A MCP did not open
22	MCC # 4	601 A Class L, 50A MCB	Load side starter A, B, C— #18 wire	50A MCB tripped
23	**MCC # 4**	**601 A Class L**	**Incoming lugs —wrench**	**Class L opened**
24	**MCC # 4**	**640 A - Pwr CB**	**Incoming lugs —wrench**	**CB did not open**
25	MCC # 3 Size 2 starter with limiters	601 A Class L, 50 A MCB, M limiter	Load side starter—A, B, C— #18 wire	CB did not open
26	MCC # 3 Size 2 combo starter	601 A Class L, 50A MCB	Load side starter—A, B, C— #18 wire	50A MCB did not open
27	MCC # 3	640 A - Pwr CB	Line side—A, B, C —#18 wire	CB did not open

[a] Tests 5, 6, 7, and 8 were product tests and were not recorded.

Table II [1]
Measured temperatures

	°C		Time in mS				°C		Time in mS			°C	Time in mS	
Test No.[a,b]	Infra-red Temp.	T1 pk	90% rise	90% fall	90% to 80°C	90% to 70°C	T2 pk	90% rise time	90% fall time	90% to 80°C	90% to 70°C	T3 pk	90% rise time	90% fall time
3	**180**	**>175**					**62**	**220**	**460**					
4		**>225**	**10**	**2000**	**>250**	**>2500**	**>225**	**120**				**50**	**230**	**360**
13	150						30							
14	200	105	120	300	70	170	120	200	390	420	450			
16	150													
19		30					30							
20	150											83	190	250
21	90											45	100	175
24	**200**	**>100**	**160**	**1600**	**1400**	**1500**	**52**	**1200**	**2500**					
27	150	65	400	500			40	75						

[a] Temperature measurements were not recorded for tests 1,2, 5, 6, 7, 8, 9, 10, 11, 12, 15, 17, 22, 23, 25, and 26.
[b] The number 18 was not used.

SOUND MEASUREMENTS: Sound measurements were recorded in two different ways:

1. Pressure probes were installed on the lead mannequin. These were Omega DPX 101-250 piezo-electric sensors. After amplification, the signals were sent to the Astromed Dash-10. Probes were placed a distances of 2' and 6' from the arc source.

2. Condenser microphones from Bruel and Kjaer were located on tripods at distances of 20'(D_1) and 25' (D_2) from the source of the arc. See Table III. It was felt that the reasons for the difference between the ideal and measured distance effect were due to a nonspherical pressure wave, reflective laboratory, and nonideal source.

For comparison of the advantages of using current-limiting fuses, the measured pressure, in Test 3, when the 22,600 ampere short was cleared by a 601 amp Class L fuse was 504 lbs/ft^2 while, in Test 4, the pressure was measured at greater than 2160 lbs/ft^2 when the circuit was protected by the 640 amp Power Circuit Breaker. Eardrum rupture occurs at a pressure of 720 lbs/ft^2, while the threshold for lung damage is 1728 lbs/ft^2.

Table III[1]
Pressure[a]

Test No.[b]	P1[c]	P2[c]	Sound @ 20 ft	Sound @ 25 ft	Sound @ 2 ft[d]	Test No.	P1[c]	P2[c]	Sound @ 20 ft	Sound @ 25 ft	Sound @ 2 ft[d]
1						14	5.00	3.75		1.20	8.38
2						15					
3	**3.50**		**0.21**	**0.15**	**1.27**	16					
4	**>15.00**	**1.80**	**0.57**	**0.54**	**3.38**	17	>15.00			6.81	47.10
5						18					
6						19	0.25				
7						20	0.75		4.25	3.49	24.80
8				0.93	6.43	21			2.90	2.31	16.90
9			0.86	0.76	5.06	22			5.81	5.40	31.60
10						**23**			**0.44**	**0.44**	**2.59**
11			0.52	0.40	3.01	**24**					
12				0.59	40.50	25			5.05	4.90	29.50
13				6.29	43.50	26			1.02	0.82	5.90
						27			7.74	6.97	45.10

[a] Measured in psi.
[b] Pressure measurements were not recorded for tests 1, 2, 5, 6, 7, 10, 15, 16, and 24. The number 18 was not used.
[c] Some of the test data is missing because the pressure-sensing device was destroyed, due to extreme pressure and temperature.
[d] Calculated by extrapolation.

VIDEO/FILM: Tests were filmed(16mm) at 10,000 frames per second using a Photec IV camera no. PSI-164-8-115. This required only 1.5 seconds for 450' of film. Color VHS video was also utilized at ground level and from an observation deck 15' above the test floor.

ELECTRICAL MEASUREMENTS: Electrical measurements are shown in Table IV. Note the significant reduction in let-through I^2t between Tests 3 (22.6kA cleared by a 601 amp Class L fuse) and 4 (22.6kA protected by a 640 amp Power Circuit Breaker) and between Tests 23 (65kA cleared by a 601 amp Class L fuse) and 24 (65kA protected by a 640 amp Power Circuit Breaker). This is due to the fact that the Class L fuse was current-limiting while the Power Circuit Breaker was set at 12 cycles (to discriminate with downstream overcurrent protective devices). The arc flash energy was greatly reduced, as can be witnessed in the high speed film and VHS video. This reduction in arc flash energy is a tremendous benefit for the fuse industry. It minimizes workmen's exposure, surely saving lives in the long run.

Table IV[1]
Measured current

		Peak let-through X 1,000				**I^2T let-through X 1,000**			
Test No.	**Avail. Current (kA)**	**Aφ**	**Bφ**	**Cφ**	**N**	**Aφ**	**Bφ**	**Cφ**	**N**
1	22.60	0	0	29.80	0	0	0	0	0
2	22.60	0	0	0	0	0	0	0	0
3	**22.60**	**17.70**	**17.40**	**18.10**	**19.70**	**6.54**	**8.57**	**7.66**	**7.72**
4	**22.60**	**28.00**	**27.10**	**16.00**	**28.90**	**>65.85**	**>24068.00**	**>1088.00**	**>3561.00**
5	22.60	0	0	1.60	0	0	0	1.04	0
6	18.00	0	0	1.71	0	0	0	11.60	0
7	18.00	0	0	1.21	0	0	0	1.32	0
8	18.00	0	0	2.94	0	0	0	32.40	0
9	40.30	0	0	9.44	0	0	0	222.00	0
10	40.30	0	17.40	17.70	0	0	510.00	511.00	0
11	40.30	0	0	5.47	0	0	0	37.80	0
12	40.30	0	14.80	14.80	0	0	544.00	520.00	0
13	51.10	0	35.10	29.10	12.30	4992.00	4193.00	4278.00	923.00
17	35.00	50.20	39.00	60.00	15.50	85600.00	109351.00	68338.00	12675.00
19	40.30	13.90	6.00	14.20	2.65	436.00	70.60	562.00	9.92
20	40.30	4.58	8.21	17.30	13.10	66.20	235.00	594.00	470.00
22	69.50	13.10	0	13.30	0	290.00	0	312.00	0
23	**65.00**	**24.10**	**18.90**	**13.60**	**2.16**	**836.00**	**367.00**	**279.00**	**3.85**
24	**65.00**	**47.00**	**63.20**	**53.60**	**36.40**	**130027.00**	**167438.00**	**147740.00**	**30006.00**
25	46.10	4.66	0	4.87	0	7.29	0	7.60	0
26	46.10	10.70	0.31	10.90	0.27	201.00	0.13	208.00	0.09
27	46.10	40.00	59.20	36.80	20.80	25634.00	29891.00	20199.00	5920.00

[a] Current measurements were not recorded for tests 14, 15, 16, and 21.
[b] The number 18 was not used.

ADVANTAGE FOR THE FUSE INDUSTRY: Because of the increased requirement for worker safety, consulting engineers and industrial plants are more frequently specifying fuses in their distribution systems. This is due to the tremendous reduction in arc-flash energy that is associated with the use of current limiting fuses. (Workmen still need to wear proper protective clothing while working on or near live equipment because not all faults will be of a high enough value to be within the current-limiting range of the fuse.) Fuse manufacturers can take advantage of this opportunity by promoting the IEEE paper and video, or by producing and promoting a similar safety oriented package.

CONCLUSION: A volunteer ad-hoc committee was formed to try to increase the awareness of arc-flash hazards in the workplace. After the testing was complete, it became obvious that the current limitation provided by modern current-limiting fuses provided a real reduction in arc-flash energy, and associated temperatures, pressures, and let-through I^2t. Various measurements were documented, including very dramatic video and high speed film. Because of the increased level of employee safety, this advantage of current-limiting fuses can be used to help persuade consulting engineers and plant engineers to specify current-limiting fuses as the preferred overcurrent protective devices.

References:

[1] Ray A. Jones, Mary Capelli-Schellpfeffer, Robert E. Downey, Shahid Jamil, Danny P. Liggett, Terry Macalady, L. Bruce McClung, Vincent J. Saporita, Lynn F. Saunders, and Arthur Smith, "Staged Tests Increase Awareness of Arc-Flash Hazards in Electrical Equipment," IEEE Petroleum and Chemical Industry Conference Record, September 1997, pp. 313-322. A copy of the video (VHS), paper, and CD (training presentation) of "Staged Tests Increase Awareness of Arc-Flash Hazards in Electrical Equipment" is available for $75.00 (US), from: IEEE/PCIC Safety Subcommittee, c/o Kim Eastwood, Thermon Manufacturing Company, 100 Thermon Drive, San Marcos, TX 78666, Phone: (512) 396-5801, Fax: (512)754-2424. Make checks payable to PCIC Electrical Safety Workshop.

[2] Ralph Lee, "The Other Electrical Hazard: Electrical Arc Blast Burns," IEEE Transactions on Industry Applications, Vol. 1A-18, No. 3, P. 246, May/June 1982.

[3] NFPA 70E Standard for Electrical Safety Requirements for Employee Workplaces, 1996 Ed. Quincy, Massachusetts: National Fire Protection Association, 1995

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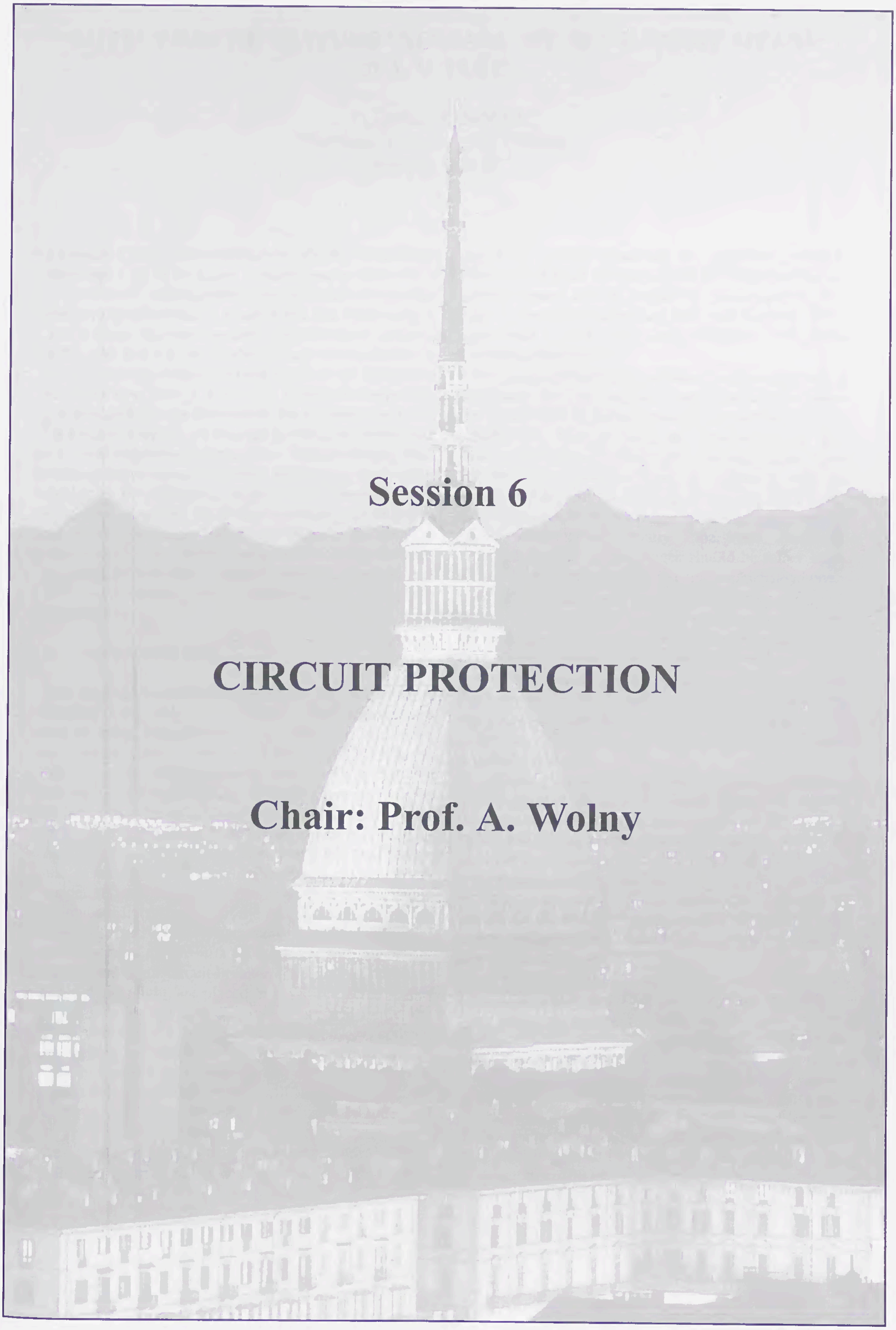

Session 6

CIRCUIT PROTECTION

Chair: Prof. A. Wolny