THE NEW SCIENCE OF PROTECTIVE RELAYING IN THE PETRO-CHEMICAL INDUSTRY

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Abstract - *The Petro-Chemical Industry is entering the 21st century with a vast array of protective relaying options ranging from the time proven electro-mechanical to the high speed digital, multifunction relays. While there is still an "art," there is much more "science" involved with the design and implementation of protective relaying schemes. This paper will present the new science of protective relaying in the petro-chemical industry. A comparison is made between the time proven electromechanical and digital relays; a comparison is made between the discrete and the multifunction relays; a discussion is made on the Boolean algebra logic typically required for the multifunction relays;. a discussion is made on the use of symmetrical component options available with many multifunction relays; and several multifunction relay applications are presented including rotating equipment protection, bus and feeder protection, and transformer protection.*

Key words: Boolean algebra, bus protection, digital relays, feeder protection, generator protection, microprocessor based relays, motor protection, multifunction relays, protection, protective relaying, relay burden, relaying logic, microprocessor based relays, symmetrical components and transformer protection.

I. INTRODUCTION

During the last 25-30 years, there have been numerous advances in the area of protective relaying. With the advent of the transistor, some electro-mechanical relays were replaced with enhanced solid state relays during the 1970's and early 1980's. The solid state relays, for the most part, duplicated the functions of the electromechanical relays. In the 1980's, the microprocessor based relays were introduced and became widely used. Now, in the 1990's, the high speed digital relays are truly making another advance to the science of protective relaying.

According to the late J.L. Blackburn, "Protection is the science, skills and art of applying and setting relays and/or fuses to provide maximum sensitivity but to avoid their operation on all permissible or tolerable conditions." [1] Protective relays were originally designed using magnetic circuits, resistors, capacitors and inductors. The protective relays were very complex, the magnetic circuits tended to drift, periodic testing and calibration were essential, and compromises were often made in the protective relaying schemes. Because of all of this, Russell Mason titled his 1956 book as *The Art and Science of Protective Relaying*. [6] At that time, there was as much "art" as "science" in the design and implementation of protective relays.

There are a number of reference books on protective relaying, several of which are shown under the list of references. [1,2,3,6] These books provide an excellent basis for studying and understanding protective relaying. However, with the introduction of the high speed, digital, multifunction relays of the 1990's, these books need to be supplemented with the newer technology. That is not to say that those books have become obsolete, because a basic understanding of protective relaying is necessary to apply the present day equipment. The basic science of protective relaying is the same, it just happens that the application of the science has been dramatically increased. Logic which was either not available or practical with discrete electro-mechanical relays is readily available with the multifunction relays. Properly utilizing this logic becomes a challenge with the multifunction relays. Knowing what logic to use, knowing when to use it and knowing how to use it are all challenges with the multifunction relays. Since the multifunction relays are so all-inclusive with logic building blocks, an understanding of the "new science" of protective relaying is essential. It is important not to overprotect the system as well as not to underprotect it. Therefore, it is important not to use features just because they are available. This fundamental rule happens to be one of the important aspects in applying the multifunction relays.

At the root of the "new science" of protective relaying is the knowledge and understanding of the power system, how it reacts under normal conditions and how it responds under transient and abnormal conditions. The advanced technology of protective relays has resulted in relays which are sophisticated, compact and relatively inexpensive. Many of the relays are programmable and the programmed logic is typically left up to the system engineer. The installation and testing have also become more complex while the calibration has typically become much easier.

The tools required of the protection engineer include a good understanding of electric power systems, a knowledge of symmetrical components and knowledge of Boolean Algebra logic. Furthermore, a thorough understanding of electrical components such as power transformers and electric machinery is necessary to understand how the electric equipment operates.

II. ELECTRO-MECHANICAL VERSUS MULTIFUNCTION RELAYS

Electro-mechanical relays utilize electro-magnetic circuits to provide the necessary logic in the protective relaying schemes. Typically, two fluxes are used to actuate an electro-

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magnetic relay. Inductors, capacitors and resistors are used to properly adjust the flux in an effort to control the torque on the relay. A simple relationship exists with electro-magnetic circuits where the torque is proportional to the cross product of the fluxes:

$$\text{Torque} = K_1(\Phi_1 \times \Phi_2) \qquad \text{Equation (1)}$$

$$= K_1(\Phi_1 \cdot \Phi_2 \cdot \sin\Theta) \qquad \text{Equation (2)}$$

Where,

K_1 = Constant
Φ_1 = Flux in circuit 1
Φ_2 = Flux in circuit 2
Θ = Angle between Φ_1 and Φ_2

The flux in the circuit is normally controlled with secondary currents and voltages from the power system provided through the use of current and voltage transformers. Flux magnitudes and phase angles are typically controlled using various combinations of resistors, inductors and capacitors.

A simple example of this concept is the ac overcurrent relay on an induction disk type of relay. Φ_1 is produced by the current in the coil, and Φ_2 is produced by the use of a shading ring which retards Φ_2 by approximately 90 degrees. This results in maximum torque if Θ is 90 degrees. (See Figure 1)

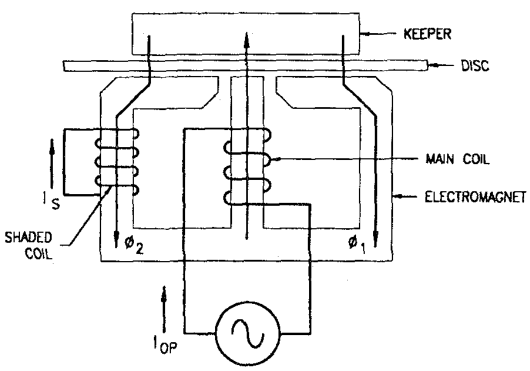

Figure 1 Shaded Pole Electromagnetic Circuit

Electro-mechanical relays typically use a comparison of fluxes generated by one or more currents, voltages or a combination of the two. The flux created by a current is typically produced in a magnetic circuit directly from the current, or phase shifted by a shaded pole. On the other hand, a voltage may be used to generate a current through the use of inductors, capacitors and/or resistors. The impedance is placed across the voltage and used to control the current magnitude and phase angle which produces the flux and resultant torque to the relay.

The multifunction relays are typically digital relays which sample the currents and/or voltages at an extremely high rate. The magnitudes and phase angles of the currents and voltages can be accurately calculated and used with a combination of programmable logic to provide the protection functions. The digital relays operates through the use of high speed sampling, high speed calculations and programmable logic.

The sampling circuits of the mutifunction relays require and utilize minimal energy. As a result, the relays have extremely low burdens. The following are typical burden requirements:

TABLE I

Function	Typical MF Relay Burdens
Power Supply	10-15 Watts
Current	0.25 VA @ 5 Amps
	0.05 VA @ 1 Amps
Voltage	0.15 VA @ 67 Volts
	0.50 VA @ 120 Volts

Electro-mechanical relays, because of their inherent designs, have significant burdens. Due to the higher burdens of the electro-mechanical relays, current transformers with 5 Amp secondaries and voltage transformers with 120 Volt secondaries were developed. With the low burdens of the multifunction relays, it is quite probable that the current and voltage transformers of the future will be much smaller and will utilize lower currents such as 1 Amp and lower voltages such as 10-50 Volts. It is also quite probable that fiber optic signals may be used in place of current and voltage signals.

Finally, electromechanical relays have a tendency to drift over time and require regularly scheduled maintenance and calibration. The multifunction should have regularly scheduled testing to assure that the relay and trip circuits are functioning properly, but calibration requirements of the multifunction relays are typically minimal, if any. Most multifunction relays have a diagnostic circuit which tests the relay on a continuous basis. Therefore, the regularly scheduled relay testing may be more of a function of testing the tripping circuit rather than the relay.

III. THE "NEW" LOGIC OF PROTECTIVE RELAYING

The discrete electro-mechanical and solid state relays typically incorporate relatively simple relaying logic. For example, an overcurrent relay only uses current magnitude and time as functions for tripping; over and undervoltage relays use voltage magnitude and time for tripping or alarming; over and underfrequency relays use frequency and time for tripping or alarming; and so forth. Some of the more complex discrete relays have additional logic such as zero sequence or negative sequence polarizing to provide directional capability. Otherwise, the relaying logic is quite basic. Relaying systems are built utilizing a combination of discrete relays

The multifunction relays typically have multiple fault detection elements and sophisticated logic blocks which can be combined using simple Boolean algebra to provide better protection functions. The multifunction relays can include voltage, temperature, frequency, current and other sensors and can be combined with tripping, closing, timing, blocking, breaker failure, reclosing, metering, synchronizing, timing and other functions. The information collected from the sensors can be used to calculate sequence components, impedances, abnormal frequency, abnormal temperatures, differential fault currents and fault locations. The data collected can be later used to analyze prefault data, fault data, post fault data and sequence of events recording. The sensors and function devices can then be combined with ***AND, OR, NOT, NAND and NOR*** logic to develop additional protection logic. Finally relays, both local and remote, can be connected via communication links to provide additional logic. See Figure 4 for an example of a simple feeder and bus protection.

In utilizing the multifunction relaying logic, the protective relaying logic should be assembled step by step, just as with the discrete relaying components of the past. For example, the need for a specific type of protection such as overcurrent will still be necessary. Therefore, the current sensor needs to be identified. Now, the logic can be further enhanced using the multifunction relay to utilize various functions such as negative sequence components, zero sequence components, timers and so forth. Further logic may be utilized using a combination of other sensors. For Example, the following logic may be built: (See Appendix A for abbreviations and ANSI device numbers)

TRIP = 51P+51N+(50P*T1)+(50Q*T2)+(50N*T3)+ (81*T4)+ (27*T5)

Where "TRIP" provides the output relay contact to operate.

IV. DISCRETE VERSUS FUNCTION BASED RELAYS

Due to the technology, electromechanical (EM) relays were developed as discrete component relays. Individual relays were then combined to form relaying systems. Part of the "art" of protective relaying involved the selection and the combination of relays to provide reasonable and adequate protection to the circuit being protected. It was not uncommon to utilize an entire 36 inch wide by 90 inch high relay panel with a group of relays to protect a generator or transformer. That same combination of relays can now be replaced with a single multifunction (MF) relay.

One simple example of the use of discrete relays for a protection scheme is where three phase feeder overcurrent protection is necessary. The discrete relay is the standard overcurrent relay which would most likely have both an instantaneous and a time overcurrent element. Three (3) phase overcurrent relays and one ground overcurrent relay would be used for a total of four overcurrent relays. In addition, a discrete reclosing relay with one or more shots of reclosing could be added for a total of five relays.

The MF relays typically have been designed as a relay system with a number of separate functions all combined into one relay. Using the three-phase feeder protection example from the previous paragraph, an MF feeder protection relay might include the following programmable functions:

- Three individual phase overcurrent units
- One ground overcurrent unit
- Multiple pickup values for each overcurrent unit
- Timing units
- Timing curves
- Negative sequence units
- Zero sequence units
- Reclosing functions
- Polarizing (Directional) Functions
- Communication logic
- Metering Functions
- Self Diagnostic Testing Logic

As such, a single MF relay can provide numerous functions and practically unlimited logic building blocks.

Reliability of a relaying system is very important since additional damage will occur and more equipment will be affected by an abnormal power system condition if a relay fails to properly operate. When using an EM relay, redundant relays and overlapping protection are common practice. With the MF relays, the protection engineer may be concerned with a common mode failure which will make the entire relaying system inoperative. To cover this situation, MF relays typically have an internal self diagnostic testing system which continuously monitors the relay. If a problem exists, the self diagnostic circuit can initiate an alarm or tripping signal.

A second reliability concern lies with the possible lack of redundancy with the protective relays. Should the relay fail, what device will be used to trip the circuit? **Three options** are typically used:

- Installation of a second, redundant MF relay
- Use of the self diagnostic system contact for tripping
- Use of both an MF relay and redundant discrete relays

Complexity versus simplicity is another aspect to applying MF relays over the EM relays. MF relays have a vast array of logic options available. It would be simple to make the protection system overly complex which makes commissioning, testing and trouble shooting more difficult. A complex system may "overprotect" or "underprotect" a system, both conditions are undesirable. Furthermore the decisions of which logic functions to use can be difficult and time consuming. It is the authors' opinion that one of the more difficult aspects in applying the MF relays is knowing which logic to use, how to use it and when to limit the use of the logic. Just because the relay has numerous functions and logic capability does not mean that all of it must be utilized. The "New Science" of protective relays provides the opportunity to build simple or complex logic circuits. The "Art" is knowing when not to use certain features.

Relay life expectancy and technology changes are another aspect to consider when applying the "new science" of protective relaying. Electro-mechanical relays have a proven track record to show that with reasonable maintenance, a protective relaying system will have a life of 20, 30, 40 or more years. Can we expect the MF relays to last as long? Or, will the life of MF relays be similar to that of the personal computer which is periodically upgraded or replaced. As MF relaying systems continue to evolve, additional features such as monitoring/metering of circuits, fault data collection, sequence of events reporting and fault location equipment will become standard features. While it is quite likely that many MF relaying systems will be installed and left in service for decades, it is also quite probable that many systems will be periodically upgraded much like to trend to upgrade personal computers. MF systems may also require replacement in the future more often than EM relaying systems due to technology changes and product support constraints.

V. THE USE OF SYMMETRICAL COMPONENTS

An important tool in analyzing power systems is symmetrical components. Symmetrical components is a mathematical tool which greatly simplifies the complexities of analyzing the three phase power system. Symmetrical components provides the means to take three unbalanced vectors such, as I_a, I_b and I_c or V_a, V_b and V_c, and represent those vectors with three systems of balanced vectors: positive sequence, negative sequence and zero sequence (2).

The use of symmetrical components with EM relays as a sensing tool is mostly limited to zero sequence currents and voltages because of the ease of the computations:

$$I_o = 1/3(I_a + I_b + I_c) \qquad \text{Equation (3)}$$

$$V_o = 1/3(V_a + V_b + V_c) \qquad \text{Equation (4)}$$

Other common uses of symmetrical components with electromechanical relays include zero sequence polarizing, negative sequence polarizing, negative sequence current and negative sequence voltage relays. The negative sequence relays typically use fairly complex magnetic circuits and are normally limited to special applications.

The multifunction relays can easily utilize symmetrical components as a logic tool for protective relaying. The multifunction relay can sense the input current or voltage; perform mathematical computations to calculate the positive, negative and zero sequence components; and finally perform the Boolean Algebra necessary for the protection of the circuit being protected. Therefore, the technology has advanced to a point where relatively sophisticated calculations and logic can be utilized to provide a better protection system.

For example, assume that a resistance grounded transformer is supplying load current to a 4160 Volt bus. The ground fault current is limited to 400 Amps and the maximum load current from the transformer is 2000 Amps. The load current is in excess of the maximum ground fault current. Sensitive ground fault protection is required. Standard discrete relay protection would dictate that a phase relay set no lower than the maximum load current of 2000 Amps would be required which could not sense a 400 Amp ground fault. Therefore, some means of ground fault overcurrent protection would also be required.

Utilizing a multifunction relay allows progressively more sophisticated techniques using symmetrical component logic. For instance, the following tripping logic may be employed:

51P - Phase Time overcurrent sensing logic set at 2250 Amps
50Q - Negative Sequence overcurrent set at 150 Amps
50N - Zero Sequence overcurrent set at 100 Amps
TQ - Negative Sequence timer set at 250 milliseconds
TN - Zero Sequence timer set at 200 milliseconds

TRIP = 51P + 50Q*TQ + 50N*TN

As one can see, the circuit has better protection for three phase, phase-to-phase, phase-to-phase-to ground and ground faults. In addition, the negative sequence element provides primary protection for phase-to-phase faults and backup protection for ground faults since ground faults have positive and negative sequence currents.

VI. PROTECTION SCHEMES

Generator Protection

Most protection reference books devote an entire chapter to the protection of electric generators. There are many aspects which need to be considered to adequately protect the generator for faults both within and outside of the unit. The type, size and voltage rating of the generator along with the power system to which it is connected are all factors which need to be considered in designing the protection system. The selection of the individual discrete component relays used to be a major task in the development of the protection logic. The multifunction relay simplifies that task by including all of those functions plus additional functions in one package. The major task with the multifunction relay is with the selection and development of the logic to provide proper protection. Figure 2 shows a typical device logic diagram for a MF generator relay compared to discrete EM relays.

The MF generator protection relay typically includes the following function selections:

24 - Volts per Hertz protection
27 - Undervoltage protection
27G - Generator ground under voltage protection
32 - Reverse power protection
38 - Bearing temperature alarm and tripping

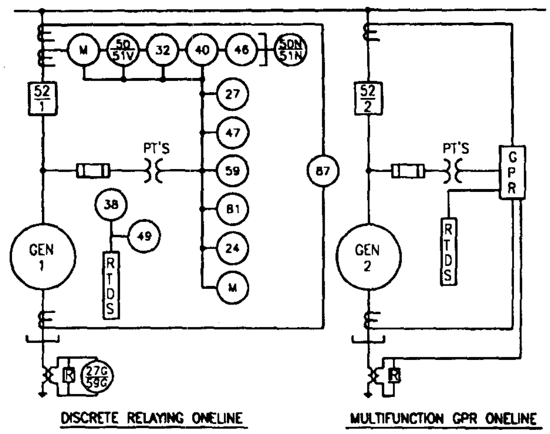

Figure 2 Generator Protection Scheme

40 - Loss of field protection
46 - Negative sequence current alarm and tripping
47 - Negative sequence voltage protection
49 - Stator and bearing temperature alarm and tripping
50 - Instantaneous overcurrent protection
51V - Voltage restrained or controlled overcurrent protection
51N - Ground overcurrent protection
59 - Overvoltage protection
59G - Generator ground over/undervoltage protection
81 - Frequency protection: over and underfrequency
87 - Differential current protection

Most of the protection of the synchronous generator is self explanatory. However, the grounding and ground fault protection of the generator need additional comments. Synchronous generators usually have extremely low zero sequence impedances and are, therefore, typically impedance grounded. A resistor or combination of resistor and transformer are the most common forms of grounding. In order to provide ground fault protection, a ground overvoltage relay, 59G, is commonly placed across the resistor to measure the zero sequence voltage on the neutral of the generator. Since the voltage may have a significant third harmonic voltage, a third harmonic voltage filter eliminates that voltage and the relay is typically sensitive to the fundamental voltage waveform. However, 100% machine ground fault protection cannot be provided with a 59G relay due to the fact that a fault near the neutral will produce minimal zero sequence voltage.

In order to protect the machine for 100% of the windings, a 3rd harmonic undervoltage relay, 27G, with additional programming logic to allow starting and stopping of the machine can be used. Under normal operating conditions, a third harmonic voltage is produced which can be measured at the neutral of the generator. If a fault close to the neutral occurs, the third harmonic voltage is shorted and the undervoltage relay can be used to alarm or trip the generator breaker. (The 27G relay may have some operating problems if the generator has a 2/3 pitch and the 3rd harmonic voltage is minimal. Prior to application of the relay, the amount of third harmonic voltage generated in the neutral should be determined and can be found by contacting the generator manufacturer. Otherwise, field testing may be required to determine proper relay settings.)

Motor Protection

The electric motor is perhaps the most commonly used device in the petro-chemical industry. It's protection is essential and many aspects need to be considered to adequately protect the motor from faults and abnormal system conditions. Similar to the generator, the type, size and voltage rating of the motor along with the power system to which it is connected are all factors which need to be considered in designing the protection system. The major task with the MF relay is with the selection and development of the logic to provide proper protection. Figure 3 shows a typical device logic selection diagram comparing a multifunction motor relay to discrete relays.

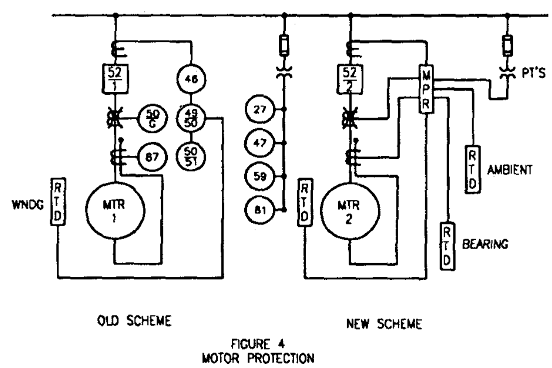

Figure 3 Motor Protection

Bus and Feeder Protection

The Petro-Chemical industry utilizes medium voltage metalclad switchgear in many of its plants. As such, main and feeder breaker protection is quite common. Figure 4 shows a typical protection scheme for the pre-multifunction relays and then a typical scheme using the MF relays.

In the past the main breaker EM relays typically consisted of standard overcurrent relays which sometimes required directional elements. Relatively long coordination times (Typically 0.4 - 1.0 seconds) between the feeder and main breakers were required. Furthermore, the main breaker tripping time could be substantial if large loads or generation was attached as a feeder circuit. Therefore, bus fault clearing times were typically quite long and considerable damage could be done prior to the main breaker opening. In order to minimize the clearing time for a bus fault, bus differential relays were often used. Additional current transformers, typically dedicated for the bus differential scheme, were required. The total bus differential scheme was rather costly and required a large amount of wiring. However, fault sensing times of approximately 16 msec were achieved with total clearing time being in the 100 msec range.

The feeder breakers required discrete overcurrent relays and sometimes a combination of synch-check, reclosing and directional overcurrent relays. All of these functions and more can be included in a simple multifunction relay. In addition, high speed logic can be easily communicated between the feeder breaker and the main/tie breakers in order to provide relatively fast bus fault protection. The entire design is much more economical and simpler to install.

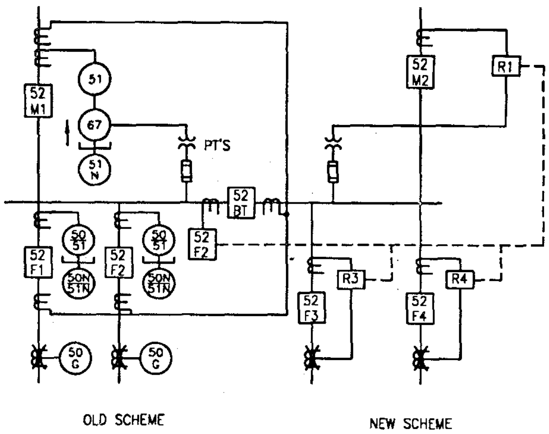

Figure 4 Bus and Feeder Protection

Transformer Protection

Many plants in the Petro-Chemical industry interface their electrical systems with the local electric utility through large step-down transformers typically from transmission line voltage levels of 69 kV and above. Common protection practices typically dictate complex protection systems for high voltage transformers rated 7500 kVA and above. These complex protection systems commonly utilize a combination of differential and overcurrent protection as shown in Figure 5. Figure 5 shows both a typical standard discrete component based relay scheme along with an MF relay system.

As can be seen, the transformer protection system typically consists of harmonic restrained transformer differential relays, secondary and primary overcurrent relays as well as temperature, oil level and fault pressure type protection. The EM harmonic restrained overcurrent relays are quite expensive, require complex testing and require a considerable amount of panel space. The MF relays provide a great deal of flexibility and logic which is typically not available with the standard EM relays. Harmonic differential (with multiple slopes), primary overcurrent, secondary overcurrent and other features are typically included.

The multifunction transformer protection relays no longer require complicated current transformer connections to compensate for differences in the transformer winding connections and ratios. That compensation is commonly included in the MF relay system.

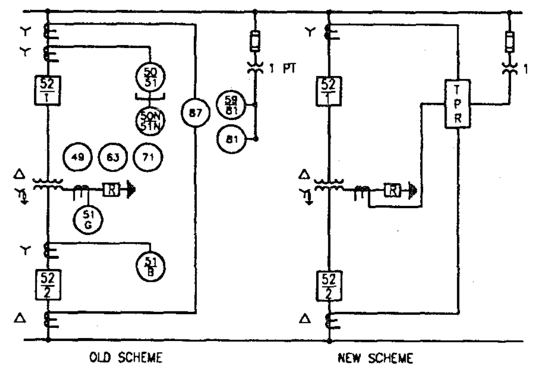

Figure 5 Transformer Protection

VII. CONCLUSIONS

The multifunction relay has greatly expanded the science of protective relaying. While there is still an "art" to protective relaying, the advances in technology are overshadowing that art with new advances in relaying technology and logic. The "new science" of protective relaying has resulted in the following improvements and benefits to the petrochemical industry:

- The multifunction relays typically have a large array of functions which can be used for electrical equipment protection. As a result, one multifunction relay can be used to replace numerous discrete components as was common with the electro-mechanical relays which were typically single function devices.

- The multifunction relays are typically less costly than the equivalent package of discrete electro-mechanical and solid state relays. The cost savings is further increased in savings in space, wiring and control design.

- The programming logic provided by most multifunction relays allows for sophisticated protection schemes which were either not possible or economical with the discrete protection components of the past. However, a warning should be made that being more complex is not necessarily better. Therefore, some constraint on the engineer's part is necessary to combine the proper amount of protection logic into the design.

- The burden requirements of the multifunction relays is typically very low. As a result, smaller current transformers, potential transformers and substation batteries may be possible. With equipment advances, the use of smaller signals such as 1 Amp current transformers and the use of fiber optic control transformers will become more common further reducing the size and costs of relaying equipment.

- With the increases in technology, the testing and calibration of protective relays is changing. First, the circuitry of multifunction relay does not require the regular calibration as was necessary with the electro-mechanical relays. Secondly, the multifunction relays typically have a "self diagnosis" test circuitry which continually verifies that the relay is functioning properly. Functional commissioning and periodic testing is still required to verify the tripping logic of the relay.

- Advances in technology in the future may result in a decreased life expectancy of protective relay packages of the future. Where EM relays had life expectancies of over 40 years, new MF relays may have a life expectancy of only 10 or 20 years.

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IX. APPENDIX A

The drawings associated with protection schemes utilize a series of abbreviations and ANSI device numbers. A reference to the ANSI Standards or one of several text books on protective relaying is one quick source for the complete list of the abbreviations and ANSI device numbers. To try to understand protective relaying without knowing its language is like going to a foreign country and not being able to speak and understand the local language. A few of the abbreviations and ANSI device numbers are listed in this appendix as an introduction to the unique language of protective relaying.

TABLE A-1
Typical ANSI Device Numbers

Device Number	Device Description
21	Distance (impedance) device
24	Volts per hertz device
27	undervoltage relay
27N or G	27N or G Ground undervoltage relay (typically 180 Hz)
32	Power Relay
32R	Reverse power relay
38	Bearing temperature device
40	Loss of field relay
46	Negative sequence current relay
47	Negative sequence voltage relay
49	Winding temperature device
50	Instantaneous overcurrent relay
50N	Ground inst overcurrent relay
51	Time overcurrent relay
51N	Ground time overcurrent relay
51V	Voltage controlled overcurrent relay
59	Overvoltage relay
59N or G	Ground overvoltage relay
67	Directional overcurrent relay
67N	Ground directional relay
79	Reclosing relay
81	Frequency relay
87	Differential relay

TABLE A-2
Typical Logic Symbols

Symbol	Function	Example
*	AND	50*T1
+	OR	51P + 51Q + 51N
T	TIMER	T1 = 50 milliseconds
=	EQUAL	50 = 25.0 Amps
Q	Negative Sequence	50Q
P	Phase	51P
N	Neutral/Res Zero Sequence	51N

TABLE A-3
Typical Relaying Abbreviations

Abbreviation	Meaning
BT	Bus Tie
CT	Current Transformer
EM	Electromechanical (relay)
Fdr	Feeder
F	Forward
GPR	Generator Protection Relay
MPR	Motor Protection Relay
MF	Mutifunction (relay)
PT	Potential(Voltage) Transformer
P.U.	Pickup
R	Reverse
T1,T2,etc	Timer
V	Voltage
VT	Voltage Transformer