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Coordination and isolation of faults on power distribution systems

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COORDINATION AND ISOLATION OF FAULTS ON POWER DISTRIBUTION SYSTEMS

by

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TABLE OF CONTENTS

Page

LIST OF ILLUSTRATIONS. 8

LIST OF TABLES 11

ABSTRACT 12

I. INTRODUCTION 13

II. PROTECTION IN POWER SYSTEM DEVELOPMENT 20

1. History of Electric Power Systems. 20

A. Development of Electric Power Industry . . 20

1. Transmission and Distribution. 21

2. Future Energy Sources. 22

B. Purpose and Need of Protection on Power Systems. 22

1. Major Causes of Failure. 23

2. Short Circuit Protection Philosophy. . 23

3. Types of Faults on Power Systems . . . 25

2. Relays and Classification. 25

A. Protective Relaying System 26

B. Line and Circuit Protection. 27

1. Different Ways to Set-up relays on 3-Phase Systems. 27

C. Sequence Filters 29

D. Solid-State Units. 29

E. Basic Logic Units. 32

F. Application and Setting by Computer. . . . 32

Table of Contents cont'd

	Page
3. Fault Calculations	33
A. Using One-Line Diagrams in Fault Calculations	33
B. Per-Unit Calculations	35
C. Short-Circuit Current Calculations	35
D. Fault Current Calculation Procedure	36
4. Today's Power Distribution Design Criteria	36
III. POSSIBLE FAULTS ON POWER SYSTEMS	42
1. Possible Cases of Faults	42
2. Single Line-to-Ground Faults	42
3. Open Circuit Faults	44
4. Line-to-line Faults	45
5. Double Line-to-Ground Faults	47
6. Three Line-to-Ground Faults	48
IV. THE DESIGN CONCEPT	50
1. Introduction	50
2. Parts of the design	50
A. Sensors	52
B. Sender Unit	53
1. Quadrature-Carrier Multiplexing	53
a. Transmitter	53
b. Signal Generator	56
c. Product Modulator	57
d. 90° Phase Shift	58

Table of Contents cont'd

Page

e. Adder Unit 58

2. Fiber Optic Cables 58

a. Transmission of light in Fiber Optic Cables 60

b. Direct Intensity Modulation,(DIM) . 64

C. Decision making process. 64

1. Band Pass Filter 67

2. Sensors, peak detectors. 69

3. Comparator 71

4. Actual Controller. 72

5. Digital to Analog (D/A) converter. . . 75

6. Human Decision 76

7. Signal generator 76

D. Accomplishment of the decision 76

1. Band Pass Filter, BPF. 79

2. Circuit Breaker. 79

3. Results. 81

V. BUILDING THE DESIGN CONCEPT. 82

1. Building the actual parts of the design in the lab. 82

2. Variance between the theory and the actual circuit. 83

3. Results. 85

VI. RECOMMENDATIONS. 90

1. Detecting Line-to-line faults. 90

Table of Contents cont'd — Page

2. Automatic throw-over switch. 94

VII. SUMMARY AND CONCLUSIONS 96

REFERENCES. 98

List of Illustrations

Figure		Page
2.1	Different ways to set up relays	30
2.2	Logic Gates	31
2.3	One-line diagram and equivalent circuit	34
2.4	Fault current calculation. Page 1	39
2.4	Fault current calculation. Page 2	40
2.4	Fault current calculation. Page 3	41
3.1	Single Line-to-Ground Fault representation. . . .	43
3.2	Open circuit representation on power systems. . .	45
3.3	Line-to-Line Fault representation	46
3.4	Line-to-line Fault simulation	46
3.5	Double Line-to-Ground Fault representation. . . .	48
3.6	Three Line-to-Ground Fault representation	49
4.1	A flow chart demonstration of concept of design .	51
4.2	A 3-Phase 4 wire hook-up for sensors.	52
4.2a	a) Current, b) Voltage monitor circuits	54
4.3	Transmitter of Quadrature-Amplitude Modulator . .	55
4.4a	a) Butler b) Parallel-Mode Oscillators.	56
4.5	Amplitude Modulator circuit	57
4.6	0° to 180° Phase Shifter circuit.	58
4.7	Full duplex, simultaneious transmission and reception of signals in fibre optic cables. . . .	60
4.8	An optic receiver	61
4.9	Schematic of an optic a) multiplexer, b) demultiplexer.	61

Figure | Page

4.10 Surface-emitting LED. 62

4.11 Silicon avalanche photodiode. 63

4.12 DIM-Direct Intensity Modulation 63

4.13 Flow chart of the decision making process 65

4.14a B.P.F. Band Pass Filter Circuit. 68

4-14b B.P.F. Band Pass Filter Circuit. 70

4-15 Receiver of the Quadrature-Amplitude Modulator. . 70

4-16 Peak Detector 71

4-17 Comparator circuits 72

4-18 Programmable controller circuit board 73

4-19 Programmable controller block diagram 74

4-20 4-line to 16-line Decoder/Demultiplexer 75

4-21 SCR, silicon controlled rectifier structures and circuits. 80

4-22 Triac circuits. 80

5-1 Building the basic design concept for a single branch. 82

5-2 A simple buffer circuit 83

5-3 A simple amplifier circuit. 84

5-4 90° Phase Shifter 85

5-5a Input wave for Source 1 87

5-5b QAM output of Source 1. 87

5-6a Input wave for Source 2 88

5-6b QAM output of Source 2. 88

5-7a Input and output waves of the comparator. 89

Figure Page

5-7b Input and output waves of the comparator. 89

6-1 Line-to-line fault detection scheme. 90

6-2 Explanation of wave propagation time delay. . . . 93

6-3 Implementation of automatic throw-over switch . . 95

List of Tables

Table		Page
2.1	Relay protection systems	28
2.2	Functions of fault-sensing and data processing units	33
2.3	Machine reactance and multiplying factors in simplified calculations of short circuit duty	37
4.1	EVB specification	73
4.2	4-line to 16-line Decoder/Demultiplexer	77
4.3	4-line to 16-line Decoder/Demultiplexer	78

ABSTRACT

Faults on power distribution systems can be prevented quickly and reliably by using solid-state devices to coordinate the optimum functioning and operation of the distribution system. This thesis describes specific systems and circuits designed for this purpose. Some parts employed in the isolation of faults are: sensors, quadrature amplitude modulators, fiber optic cables, programmable logic controllers, generators, band pass filters and silicon controlled rectifiers. Design information and test data are presented.

I. INTRODUCTION

Within the course of our very busy lives, science and technology have created ease and facility and, thus, certain expectations. If a radio is turned on, for instance, then one fully expects it to work, but a defective point in the power distribution system will prevent this from happening. It has become almost natural as well, to expect the lights to function in the next room, despite power being drawn from the same distribution system. Due to the protective equipment already installed on the power system, this desire to expect the electrical equipment to function in the next room does come true. Unfortunately, coordination of this protective equipment would become less reliable and predictable if our AC voltage would operate at a higher frequency. This is a typical case for Navy vessels, especially if they are under attack, and the optimum function of their protective equipment could be their only chance for survivability. Under these conditions, our attention is drawn to solid-state devices for their reliability, coordination, and speed in functioning; and their overall advantage in terms of handling complex operations, speed, reliability, and decision making capabilities in locating and isolating faults from the power system.

Current practice in using protective gear relies heavily on mechanical relays for detecting, locating and initiating the removal of a fault from the power system. Despite their proven reliability and protection performance[1], one of the particular difficulties of protective mechanical relays is that the time between operations may be measured in years, during which period defects may have developed unnoticed until revealed by the failure of the protection to respond to a power system fault. This necessitates the testing of relays at suitable intervals in order to assure that their ability to operate has not deteriorated. Testing should be carried out without disturbing the power distribution system operation and permanent connections. This testing may reveal the following problems in mechanical relays:

1) contacts that have become rough or burned owing to frequent operation, or

2) tarnishing owing to atmospheric contamination,

3) coils and other circuits that are open-circuited,

4) auxiliary components that have failed,

5) mechanical parts that have clogged with dirt or corroded to an extent that may interfere with movement.

The main advantage of using solid-state silicon devices, or integrated circuits, is their size, weight and speed in functioning. Solid-state circuits function faster then mechanical relay systems because they have no moving parts that will result in wear. Thus, they are less likely to require maintenance, or lubrication and experience deterioration, tarnished contacts, loose screws, or other problems. This, alone is the tremendous advantage of solid-state devices over mechanical relays, that already contributes to our current lifestyle in keeping our everyday power distribution system in operation while minimizing the effects of power system faults. Solid-state devices are not only faster and require less maintenance then mechanical relays and switch gear, they also operate on lower voltages and currents, resulting in less power drainage from the power system. If solid-state circuits are manufactured in sufficient quantities, their cost will not be excessive. Therefore, to fulfill the requirements of discriminatory protection with optimum speed, silicon controlled rectifiers should be used, whenever possible, in lieu of mechanical relays.

This thesis presents a new idea related to early detection of disturbances: the concept of "Fault Conditions". Fault conditions will utilize solid-state technology for discrimination, coordination and isolation of faults and fiber optic technology for communication to the decision making process. Programmable logic controllers will be used in this decision making process. With the aid of programmable logic controllers and solid-state devices, the time to locate and isolate a fault will be considerably shortened on a power system. With the controller, some logical decisions will be quickly and effectively made in a specific and a predetermined way for each power system configuration.

This thesis is dedicated to providing an early detection and coordination for the decision making process on a small scale of power distribution system, such as those found aboard naval vessels. This thesis will combine different technologies to achieve a fast and a reliable protection system that will be more sensitive to faults:

1) mechanical relays will be replaced with silicon controlled rectifiers for their speed in tripping or functioning;

2) voltage and current sensors will be used for detecting abnormal operating conditions on every branch of the power distribution system;

3) fiber optic cables will be used for their immunity to outside electromagnetic interference, and for their ability to transmit the voltage and current information into a central controller;

4) quadrature amplitude modulation will be used to carry both the voltage and current information from the sensors, via a fibre optic cable, to the central controller, utilizing one dedicated unique frequency for each distinct branch of the power system;

5) a central programmable logic controller will be used to identify each individual branch of the power system and to sense faults related to each distinct branch. It will make faster decisions and will be more intelligent in determining which branch circuit breaker should be tripped. This controller will be the brain of our protective gear; and

6) a different band pass filter will be used for each unique branch of the power system. Each band pass filter will be set to respond to a different unique identifying frequency coming from the controller, and only this special frequency will be able to trip only one circuit breaker connected to that one band pass filter. Each frequency will uniquely identify and correspond to one branch of the power distribution system.

The installation of switch gear alone is not sufficient discriminatory protective gear. Programmable logic controllers must be provided to control the switch gear and designed according to the characteristics and requirements of the power system. Programmable logic controllers will be used to fulfill all the requirements of identifying, discriminating and isolating the system faults with optimum speed, and enough sense and logic, combined with fast and reliable action for the many different configurations of power systems.

To prove that our protective gear combined with the controller will function better than currently available systems, we would choose a small power distribution system, such as the ones previously mentioned on naval ships. It is well worth noticing the importance of a fast and a reliable power system on Navy Ships. The Navy has some sensitive equipment installed on every ship, mainly to protect the ship itself, to attack enemy ships, unfriendly submarines, or simply to communicate with the outside world. As a consequence, the Navy requires a reliable power system that can adequately combat a disruption of power needed to operate effectively and to prevent damage to their equipment, or it could result in unstable power which might result in incorrect radar readings perhaps leading to a misjudged action or a misuse of weapons systems.

As a result, this thesis proposes to stop the fault in its early stages, possibly within the first few cycles of the system fault. The benefit is obvious from the fast, reliable and logical actions of the programmable logic controller combined with solid-state devices, and with sensors in their decision making capability for identifying, isolating, locating and removing the fault condition from the power system. This will keep the maximum number of branches continually in full operation as far as possible, and still give the power system the best service throughout the remaining branches.

In this thesis, the ability to interface sensors with programmable controllers and to discriminate, coordinate and isolate a fault condition will be demonstrated. After all, when all is said and done, a system is not properly designed and managed if it is not adequately protected.

II. PROTECTION IN POWER SYSTEM DEVELOPMENT

1. HISTORY OF ELECTRICAL POWER SYSTEMS

George Westinghouse's purchase of the American patents covering the AC transmission system from L. Gaulard and J. D. Gibbs of Paris in 1885[2], and Edison's discovery of the electric incandescent light bulb on October 21, 1879[3] created the beginning of the need for an electric power supply system. With these developments AC system began to be developed in the United States. The first electric "illumination company" came into reality after William Stanley, an associate of Westinghouse, tested transformers in his laboratory in Great Barrington, Massachusetts and installed the first experimental AC distribution system in the winter of 1885-1886 in the same town supplying 150 lamps. The first transmission line went into operation in the United States in 1890, carrying electric energy created from water power for 13 miles from Willamette Falls to Portland, Oregon. The Pearl Street system in New York, built by Edison, become the most famous illuminating company supplying DC power for lighting lower Manhattan, New York. The Pearl Street system had only one three-hour outage in its first eight years of service, setting a standard of reliability for the electric utility company throughout its history.

1.A DEVELOPMENT OF THE ELECTRIC POWER INDUSTRY

1.A.1 TRANSMISSION AND DISTRIBUTION

Development of the electric power industry started when the operating voltage increased rapidly in the early days of power transmission in the United States. This was due to increased "loads" in the power system which is made up of lights and motors and other electric-powered objects. In 1890 the Willamette-Portland line was operated at 3300 V. Voltages on different lines rose to 100kV in 1907, 150kV in 1913, 220kV in 1923, 244kV in 1926, 287kV in 1936 from Hoover Dam to Los Angeles, 345kV in 1953, 500kV in 1965 and 765kV in 1969. These improvements brought classification of operating voltages: High Voltage, HV, 115 to 230kV, Extra High Voltage, EHV, 345 to 765kV, and Ultra High Voltage, UHV, 1000 to 1500kV. There is an almost constant rate of increase of electrical generating capacity, which is doubling about every 10 years. Until 1917, electrical systems were usually operated as individual separate units. They spread out gradually to cover the whole country. Power transmittability increased, transmission losses decreased and increasing voltage levels caused the power systems to be electrically interconnected into vast "power grids" which are subdivided into regional groups called "power pools". Most generating plants are built close to electrical "load centers" where the major energy demand was located.

1.A.2 FUTURE ENERGY SOURCES

Electrical power is generated by hydro-power, steam turbines, fossil and nuclear fuels. "Size" determines the system structure more than any other factor. To transmit this electric power energy, three different transmission levels are used[4]: 1) distribution, 2) subtransmission, 3) transmission and pool level. To be able to respond to future growth of electric power, there are several possible additional energy candidates[5]: 1) solar power which is a "direct conversion" of solar radiation into low voltage DC power by the use of "solar cells"; 2) wind wave, geothermal, and tidal powers; and 3) nuclear fusion, which is the dream for future generations.

1.B PURPOSE AND NEED OF PROTECTION ON POWER SYSTEMS

Expansion in energy production and generating capacity with vast transmission and distribution systems required a means for protecting the system against lightning and switching surges and against short circuits. Large and complex energy production systems require stability studies. Power distribution systems are designed for limiting the effects of disturbances, which if allowed to persist, may damage generating plants and interrupt the supply of electric energy. These disturbances, described as faults, (short, open circuits) or power swings, result from natural hazards, such as lightning, plant failures, or human error. To facilitate speedy removal of a disturbance from a power system, the system is divided into "protection zones[6]" and relays monitor the system quantities (current, voltage) operating in these zones. Relays can only operate in a predetermined manner within certain specifications.

1.B.1 MAJOR CAUSES OF FAILURE

Current power systems, have sufficient flexibility so that one or more components may be out of service with minimum interruption of service. For adequate protection, the conditions existing on a system during disturbances must be understood. The major types and causes of failures are[7]:

1. Insulation failures: caused by design defects or errors, improper manufacturing or installation or aging of insulation;

2. Electrical transients: caused by lightning or switching surges and dynamic overvoltages;

3. Mechanical failures due to wind, snow or ice contamination;

4. Thermal degradation due to overcurrent or overvoltage.

1.B.2 SHORT CIRCUIT PROTECTION PHILOSOPHY

The equipment that protects a system by isolating the faulted portion is known collectively as the "protection system[8]". A fault is any abnormal state of the power distribution system, so that faults in general consist of short circuits as well as open circuits. Open circuits are much more unusual than short circuits. "Worst case[9]" condition should be assumed for the calculation of fault currents in order to predict the fault current which would flow if a fault were applied at a specified point in the system. When a fault occurs, it causes large amounts of current flow to the fault point producing high mechanical stress in all parts of the circuit. The short circuit is maximum during the first cycle due to the presence of asymmetry and the fact that motors contribute the most short circuit current at that time.

The increase in current and a reduction in voltage caused by the fault can be used to detect that a fault has occurred on the transmission line. The protection system can be subdivided into three subsystems[10]:

1) circuit breakers
2) transducers
3) relays

In case a relay fails to respond to a fault or operate correctly, it is the usual practice to allow for a back-up protection[11] system which would take over the job of protection. In a similar case, zones of protection[12] are specified to define the parts of the system for which various relays are responsible for backing up another disabled relay in an adjacent zone where the fault occurs.

1.B.3 TYPES OF FAULTS ON POWER SYSTEMS

Possible cases of faults on power distribution system[13] are:

1) Single line to ground fault with or without impedance;
2) Line to line fault with or without impedance;
3) Open Circuit;
4) Double line to ground fault with or without impedance;
5) Three line to ground fault with or without impedance.

2. RELAYS AND CLASSIFICATION

Following the extensive use of dash pots, in 1928 Fitzerald published a scheme for pilot wire protection and tabulated circuit breaker specifications required to protect power systems. Wideroe in 1934 designed a series of circuits for common types of protective relays. Loving continued on this work in 1949. Macpherson, Warrington and McConnel updated the developments up to 1948. In later years, these studies were extended by Barnes, Kennedy, Honey, Reedman, Dloughy, Cahen and Cavalier. In all these schemes either thyratrons[14] or thermionic tubes[15] were used, and electronic protection with thermionic tubes has been successfully employed. Over 75% of the existing protective relay requirements are met without undue difficulty by electromagnetic relay elements. The schemes are based on the characteristics of induction disc or cup, and moving coil or moving armature (hinged armature) elements. In 1952, Edgely and Hamilton claimed test and constructional advantages of their relays employing transducers (magnetic amplifiers).

Static relays operate on the principal of producing stationary electrical charges. They are employed for their low current and voltage burden on transformers, which permits miniaturization of the relay module, absence of mechanical inertia and bouncing contacts (thus low maintenance), high resistance to shock and vibration, very fast operation and long life, quick reset action and absence of overshoot, and for their ease of providing amplification which enables greater sensitivity.

2.A PROTECTIVE RELAYING SYSTEMS

Protective relays for power systems are made up of one or more fault-detecting units, along with any necessary logic networks and auxiliary units. A number of these fault-detecting units are used on a variety of relays, which are identified as basic units. There are three types of protective relays[16]:

1) electromechanical, (magnetic attraction, magnetic induction, d'arsonval, thermal units);

2) sequence networks (zero sequence networks, composite sequence networks, sequence voltage networks); and

3) solid-state units.

2.B LINE AND CIRCUIT PROTECTION

Our main concern in this thesis are the faults occurring on a power system on the lines connecting generating sources with usage points or load. The protective schemes vary in their characteristics and configurations due to their relative importance. Relays within a system can be coordinated using graphs or tables, such as the one shown on Table 2.1. The coordination procedure is conducted by first assuming that the desired relay type and current transformer ratio has been determined. Then the six steps are followed.(reference[17] pertains). There are different ways to set up relays for protection on three-phase transmission lines, as shown on Figure 2.1.

1) One way is that everything is balanced in such a way that no excessive current should flow in the ground connection, otherwise a fault would trip the connected relay.

2) All three lines could be connected together to one relay. Since all three phases are balanced, they should

Relay Protection Systems for Ground Faults

Type of Protection	Basic Relay Type	Number Required	Relative Cost (pu)
Time-Overcurrent	CO	1	1.00
Instantaneous and Time-Overcurrent	CO with IIT	1	1.30
Product Overcurrent	CWC or CWP	1	2.20
Instantaneous and Product Overcurrent	CWC or CWP with IIT	1	2.50
Directional Time-Overcurrent	CRC or CRP	1	2.65
Directional Time-Overcurrent	CRD	1	2.85
Instantaneous and Directional Time-Overcurrent	CRC or CRP with IIT	1	2.95
Instantaneous and Directional Time-Overcurrent	CRD with IIT	1	3.15
Directional Instantaneous Overcurrent	KRC or KRP	1	3.60
Directional Instantaneous Overcurrent	KRD	1	3.80
Directional Instantaneous and Directional Time-Overcurrent	IRC or IRP	1	4.10
Directional Instantaneous and Directional Time-Overcurrent	IRD	1	4.40
Directional Time-Overcurrent	CRQ	1	4.65
Instantaneous and Directional Time-Overcurrent	CRQ with IIT	1	4.75
Directional Instantaneous Overcurrent	KRQ	1	6.10
Directional Instantaneous and Directional Time-Overcurrent	IRQ	1	7.00
Zone Distance	SDG-2T plus SDG-4T, plus TD-5	3	27.50
Zone Distance	three KDXG, plus KRT	4	30.00
Zone Distance	two SDG-2T plus SDG-4T, plus two TD-5	5	43.70

Relay Protection Systems for Phase Faults

Type of Protection	Basic Relay Type	Number Required	Relative Cost (pu)
Time-Overcurrent	CO	3	1.00
Instantaneous and Time-Overcurrent	CO with IIT	3	1.30
Directional Time-Overcurrent	CR	3	2.70
Instantaneous and Directional Time-Overcurrent	CR with IIT	3	2.90
Directional Instantaneous Overcurrent	KRV	3	3.40
Step Time-Overcurrent	CO-4	3	3.80
Directional Instantaneous and Directional Time-Overcurrent	IRV	3	4.10
Inverse Time-Distance	two KD-10, plus 2-Element CO	3	6.75
Inverse Time-Distance	KD-10, or KD-5 plus SD-2	2	8.30
Zone Distance	two KD-10, plus KD-11, plus TD-4	4	10.20
Zone Distance	two SKD-T plus SKD-1T, plus TD-4	4	13.20
Zone Distance	two SKD-T plus SKD-1T, plus TD-52	5	14.20

TABLE 2.1 RELAY PROTECTION SYSTEMS

cancel each other, then the connected single relay could sense any abnormalities effectively.

3) All relays for a line to ground fault can be connected together into a ground relay formation, as shown in Figure 2.1, Relay 3. This way line to ground faults, as well as line-to-line faults, can be detected.

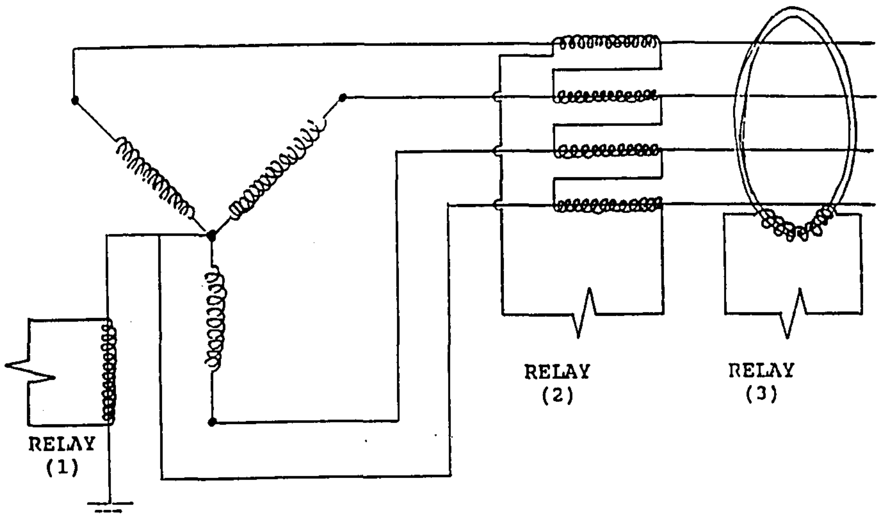
2.C SEQUENCE FILTERS

Sequence filters are widely used as fault sensors. These filters with three-phase current or voltage inputs can provide a single phase output proportional to positive, negative, or zero sequence quantities. There are three different sequence filters[18]:

1) zero sequence networks;
2) composite sequence networks;
3) sequence voltage networks

2.D SOLID-STATE UNITS

These solid-state, semiconductor component relays use various low power diodes, transistors, and thyristors with associated resistors and capacitors. These solid-state logic units are used in many relays because of their stabiliy over a wide temperature range. The principal logic units are[19] AND, OR, NOT, NAND, and NOR gates as shown by Figure 2.2 on page 31.



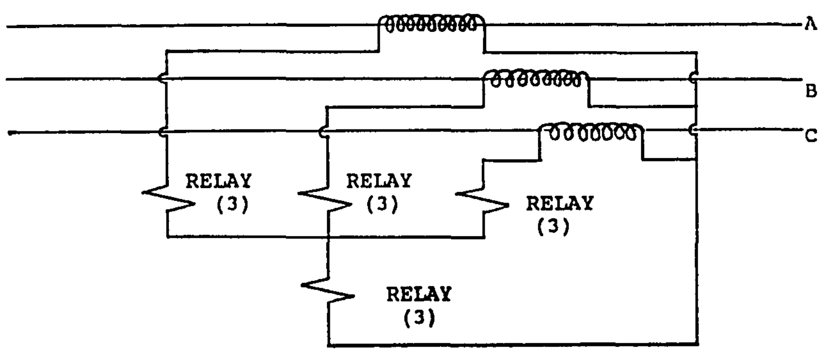


FIGURE 2.1 DIFFERENT WAYS TO SET UP RELAYS

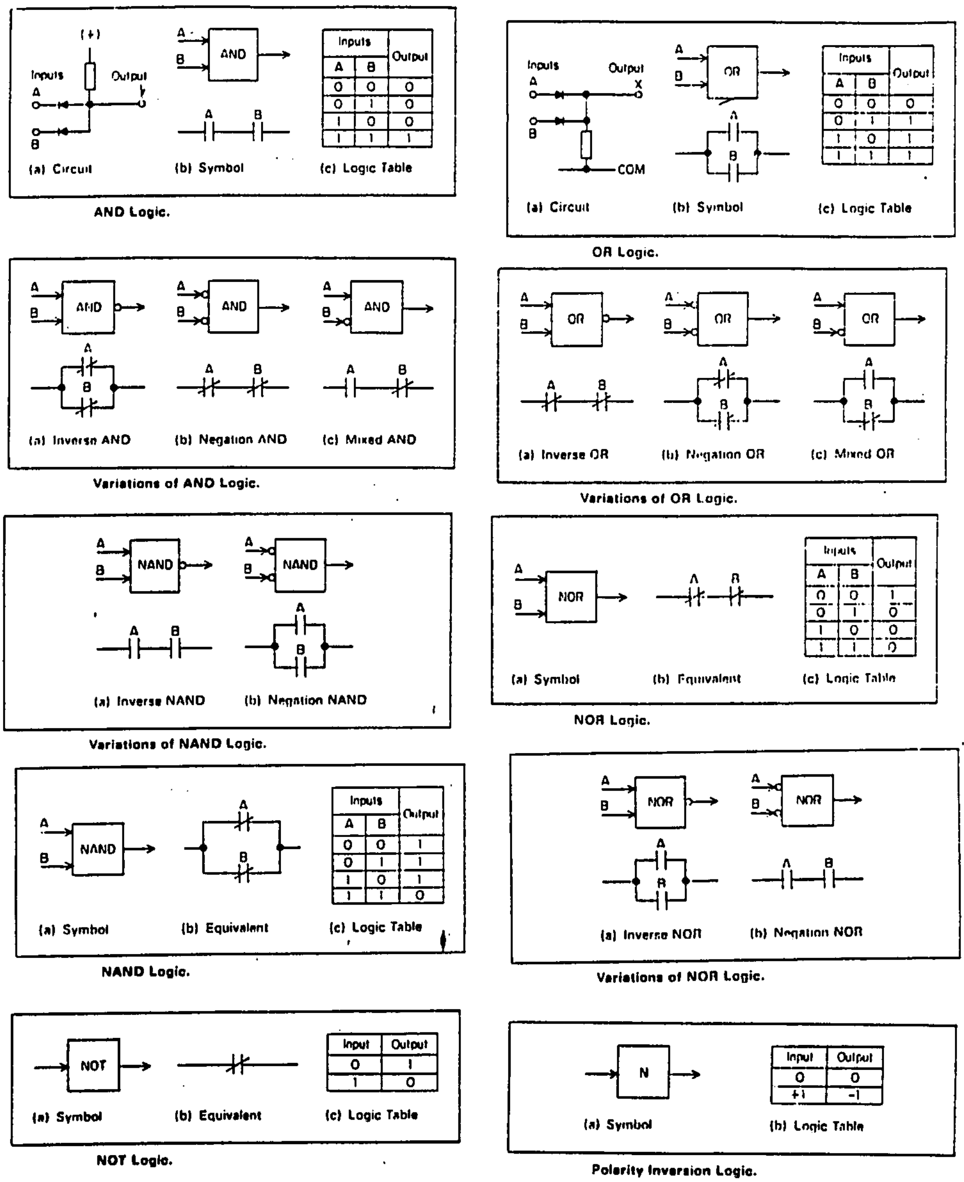


FIGURE 2.2 LOGIC GATES

2.E BASIC LOGIC CIRCUITS

For the protection of power systems, two types of diagrams are used in describing basic logic circuits for providing a complete functional system[20]:

1) The logic block diagram, also called logic schematic diagram, where the units are represented by their logic symbols, and the logic symbol blocks are interconnected for showing a complete system in functional form.

2) Logic circuit schematic diagrams, depict the elements schematically. These diagrams show how the logic units operate.

Solid-state logic units can be combined in a number of ways to provide basic logic units for relays and relay systems. These are Classified as[21]: 1) fault-sensing and data processing units, Table 2.2 pertains, 2) amplification logic units, and 3) auxiliary logic units.

2.F APPLICATION AND SETTING BY COMPUTER

Setting and coordinating protective devices on a power system is a time consuming job that can be eased by the use of an adequately prepared computer program. Pioneered in 1960, the Protective Device Coordination Program (PDCP) is such a complete program for applying, setting and checking coordination of protective relays,

Conventional Functions Obtained by
Fault-Sensing and Data Processing Logic Circuits.

Conventional Function	Logic Circuits	Typical Relay Types
Instantaneous overcurrent	Magnitude Comparison with fixed reference	SI
Time overcurrent	Magnitude comparison with fixed reference and time.	SCO
Ground distance	Magnitude comparison with variable reference	SDG
Directional	Coincidal-time comparison (Ring Modulator)	SRGU

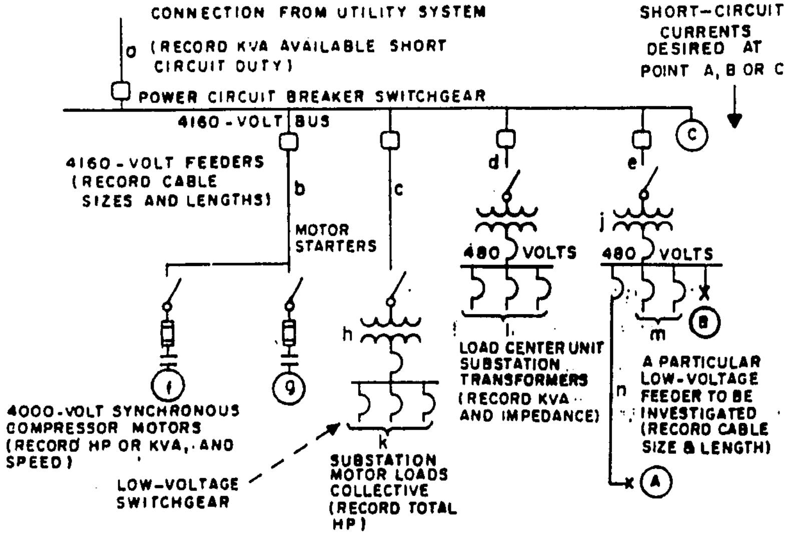
TABLE 2.2 FUNCTIONS OF FAULT-SENSING AND DATA PROCESSING LOGIC UNITS.

fuses and reclosers. The basic reason behind the application and setting by computer is to effectively and wisely isolate faults on power systems in a predetermined logical way.

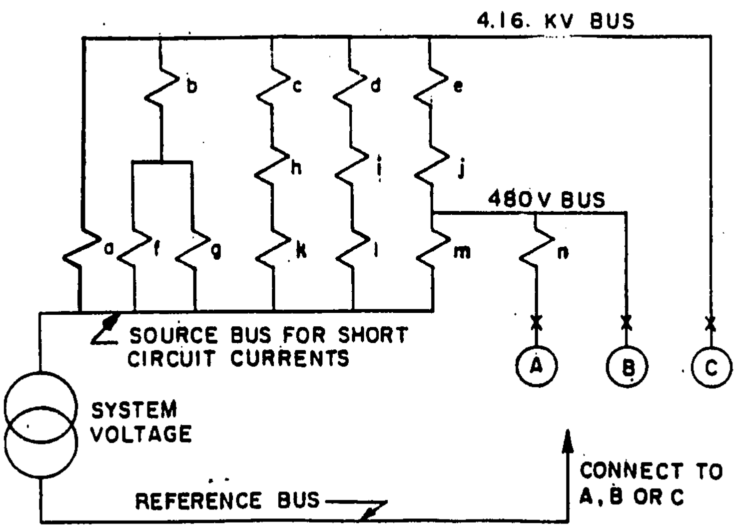
3. FAULT CALCULATIONS

3.A USING THE ONE-LINE DIAGRAMS IN FAULT CURRENT CALCULATIONS

In any short circuit relay coordination study, a one-line diagram[22] is the first step. This one-line diagram should show all sources of short circuit current and other significant circuit elements. Figure 2.3 shows a one-line diagram of a typical industrial system.



One-line Diagram



Equivalent Circuit For Calculations

FIGURE 2.3 ONE-LINE DIAGRAM AND EQUIVALENT CIRCUIT

3.B PER-UNIT CALCULATIONS FOR FAULT CURRENT CALCULATIONS

Once a one-line diagram is converted into an equivalent circuit showing the required impedance data for each element, then these values are transformed to a common basis so they can be converted into mathematical calculations. On one-line diagrams, when any two of the four (kVA,volts, ohms, amperes) are assigned values, then the other two can be derived. A per-unit[23] value is a ratio:

PER-UNIT = A Number/ Base Number

If base values are defined as $|V_b|$, and $|I_b|$[24] in rms voltage and current then:

$V_{pu} = V \div |V_b|$ pu Volts, and $|S_b| = |V_b| \times |I_b|$ VA

$I_{pu} = I \div |I_b|$ pu Amp, and $|Z_b| = |V_b| \div |I_b|$ ohm

3.C SHORT CIRCUIT CURRENT CALCULATION

The short circuit current magnitude, for a single equivalent impedance to the point of short circuit, can be found by allowing the network driving voltage across it, or by longhand or computer calculations.

The first cycle fault currents are sought for mechanical-stress considerations. They are calculated from a transient impedance network in which each circuit branch of the power system is represented by its reactance. A duty calculation, (the interrupting rating of power circuit breakers), is based on a reference reactance network with individual branch reactance selected according to Table 2.3. The final current duty (this duty is used in selecting circuit breakers to protect the power distribution system) is obtained from the above two techniques for calculating the symmetrical currents, then by applying a standardized multiplying current, again as shown in Table 2.3 on page 36.

3.D FAULT CURRENT CALCULATION PROCEDURE

The process for determining fault currents on power systems can be briefly described in four basic steps[25], as shown in Figure 2.4.

1) A one-line diagram of the system should be drawn.

2) Develop the equivalent circuit. This circuit should include all sources of short-circuit current, with an imaginary "reference" or "zero voltage" bus.

3) Solve the symmetrical currents at critical points within the power system.

4) Apply appropriate multiplying factors. The DC component must be considered in the total current wave, which produces an offset asymmetry and decays to zero in a few cycles.

4. TODAY'S POWER DISTRIBUTION DESIGN CRITERIA

Today's power distribution systems are designed, tested and judged by the following standard rules[26]:

1) Design for normal operation.

TABLE 2.3 MACHINE REACTANCE AND MULTIPLYING FACTORS IN SIMPLIFIED CALCULATIONS OF SHORT CIRCUIT DUTY.

- Machine Reactance and Multiplying Factors Used in Simplified Calculations of Short-circuit Duty

Equipment	Type of Short-circuit Rating	Machine Reactances to Use: Synchronous Generators	Machine Reactances to Use: Synchronous Motors	Machine Reactances to Use: Induction Motors	Multiplying Factor to be Applied to Calculated Symmetrical Value*: For protective device selection or duty check		For Protective Devices Coordination: Instantaneous	For Protective Devices Coordination: Time Delay
L-V Power Circuit Breakers L-V Molded-case Circuit Breakers L-V Motor Controllers (Incorporating Fuses or Molded-case Circuit Breakers) L-V Fuses L-V Busway Bus Bracing in: L-V Switchgear L-V Switchboards L-V Motor-control Centers L-V Panelboards	Symmetrical Amperes Available	Subtransient (X")	Subtransient (X")	Subtransient (X")	1.0		1.6	1.0
Power Circuit Breakers (above 600 volts) with Rated Interrupting Times of 8 cycles (Refer to the Total Current Rating Basis-- ASA C37.6-1971)	Momentary-Asymmetrical Amperes Available	Subtransient (X")	Subtransient (X")	Subtransient (X")	1.6‡	1.5‡		
	Interrupting-Symmetrical Amperes or MVA Available	Subtransient (X")	Transient (X')	Neglect	General Case † 1.0	Special Case † 1.1		
Fuses and Fused Cutouts (above 1500 volts)	Interrupting-Asymmetrical Amperes Available	Subtransient (X")	Subtransient (X")	Subtransient (X")	1.6δ	1.2δ		

* The calculated symmetrical value to which the multiplier is applied should be in rms amperes, kV, or MVA depending on the terms in which the rated capability of the particular equipment is expressed.

† Use special-case multiplier ONLY if the calculated symmetrical value exceeds 500 MVA AND the circuit is principally fed direct from generators or entirely through current-limiting reactors; otherwise use general-case multiplier.

‡ Use special-case multiplier ONLY if operating voltage is 5000 or less AND the circuit is NOT principally fed direct from generators or entirely through current-limiting reactors; otherwise, use general-case multiplier.

δ Use special-case multiplier ONLY if the operating voltage is 1500 or below, AND the fuses are NOT of the current-limiting type, AND the supply-circuit X/R is less than 4; otherwise use general-case multiplier.

Note: The multipliers used in this table are associated with the method of calculating fault currents described in ANSI C37.5-1969. This Standard applies to low voltage (below 1000 volts) and will yield sufficiently accurate values of fault current for relay coordination work for both low voltage and medium voltage (1 kV to 15 kV) systems. A supplementary Standard ANSI C37.010-1972 is now in force for medium voltage equipment. This is a more complex calculation schedule and does not yield results which are sufficiently more accurate to make the calculation worthwhile for coordination purposes. However, it should be used in selection and application of medium voltage circuit breakers. ANSI C37.010-1972 is specifically designed for medium voltage equipment such that if momentary and interrupting duties were calculated for a whole system using this approach, a second momentary calculation would be necessary on the basis of C37.5-1969 to obtain usable values of current on the low voltage portion of the system.

2) Design to prevent failure, the following aspects must be considered:

a) System stability and out of step relaying;

b) Reclosing and synchronizing;1

c) Testing and maintenance of protective relays;

d) Pilot wire protection; and

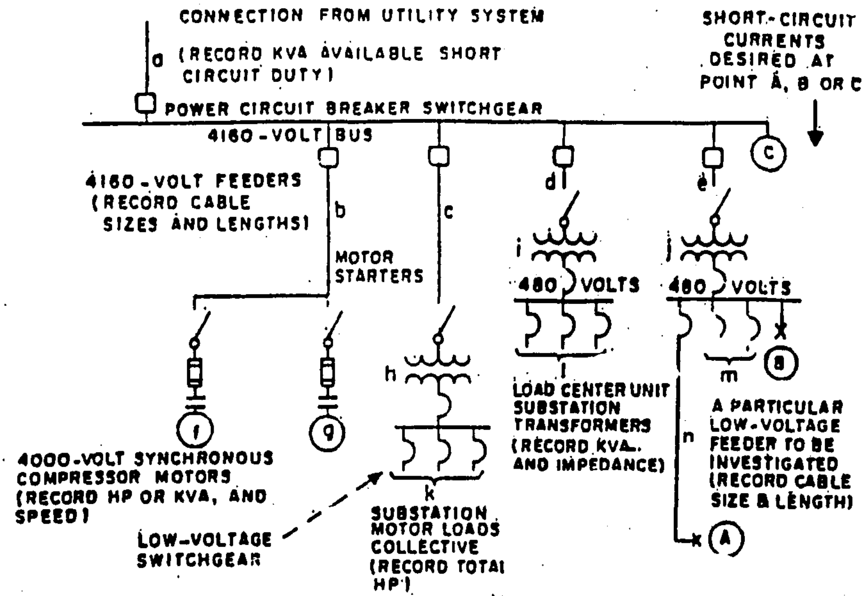
e) Back-up protection.

3) Contingency plan to minimize the effect of failure. This is where relays, control, and circuit breakers come into the design. A redundant circuit with regard to its economic, value, is created. This is where over current, ground fault, overvoltage and voltage unbalance come into consideration.

4) Under-frequency of the power being delivered to users especially to businesses where the connected equipment may not work properly.

5) Phase-sequence of the generated power systems should be interconnected in the same phase sequence to prevent faults.

6) Differential protection, where $I_{in} = I_{out}$ for busses, transformers, motors, and generators. These are very common on large power distribution systems over 1000kVA.



One-line diagram

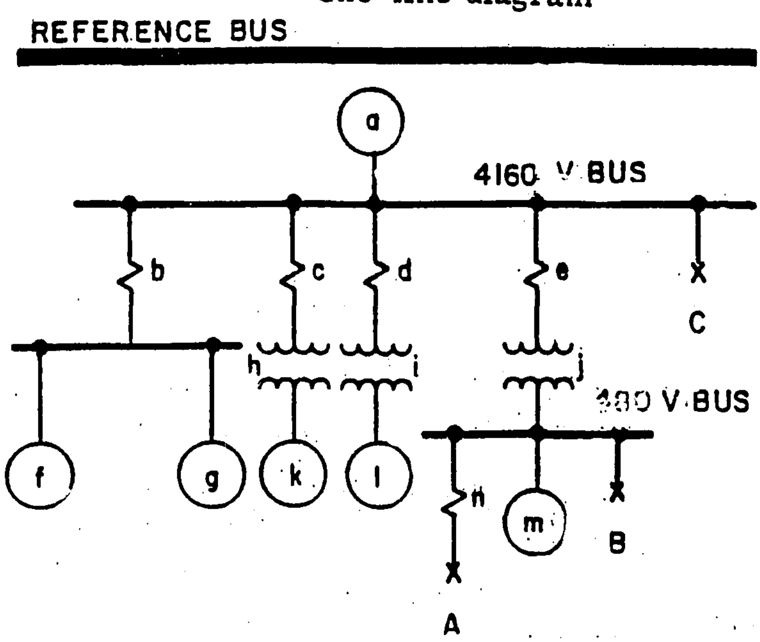
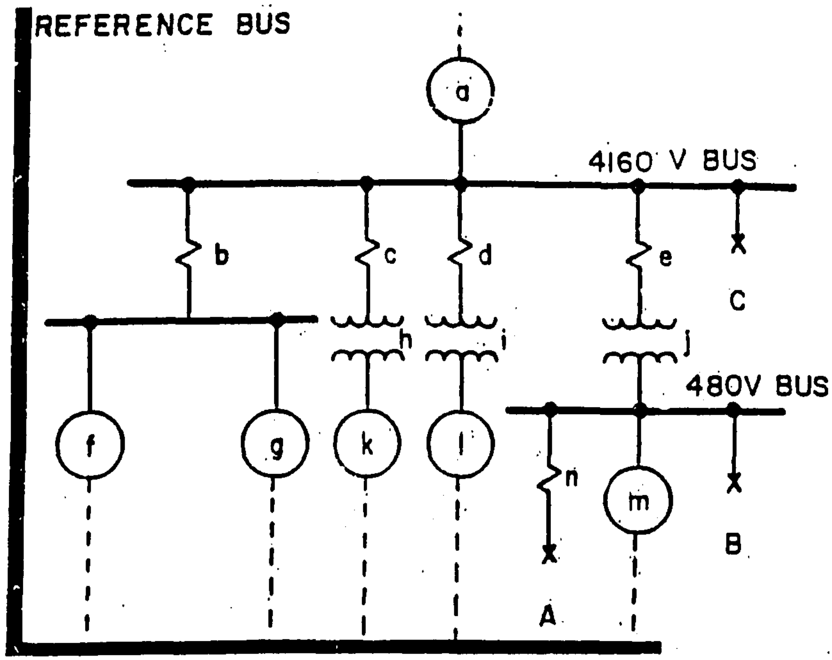
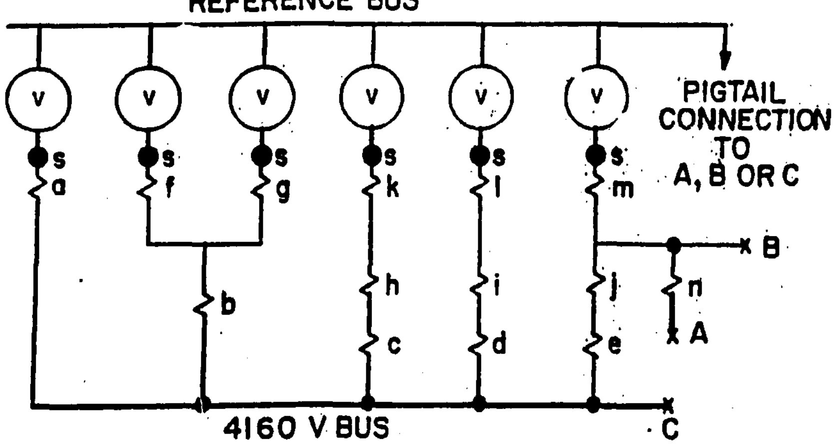


FIGURE 2.4 FAULT CURRENT CALCULATION, Page 1

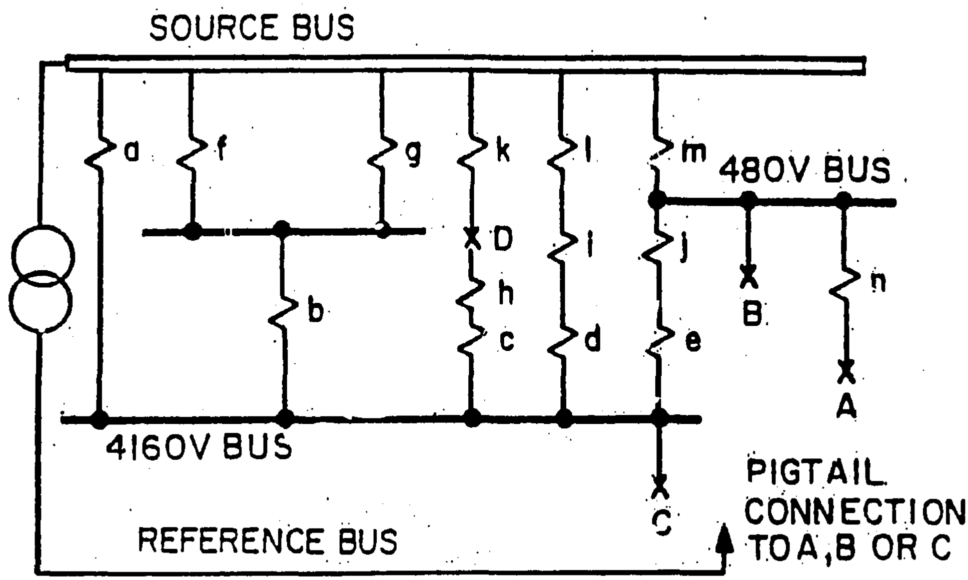


Preliminary Equivalent Circuit



Preliminary Equivalent Circuit

FIGURE 2.4 FAULT CURRENT CALCULATION, PAGE 2



Equivalent Circuit for Calculations

FIGURE 2.4 FAULT CURRENT CALCULATION, PAGE 3

III. POSSIBLE FAULTS ON POWER SYSTEMS

1. POSSIBLE CASES OF FAULTS:

The possible cases of faults on a three-phase power distribution system are[27]:

1. single-line-to ground fault;
2. open circuit;
3. line-to-line faults;
4. double line-to-ground faults; and
5. three line-to-ground faults.

2. SINGLE-LINE-TO GROUND FAULTS

A single-line-to ground fault occurs when any one of the three-phase lines are grounded. Figure 3.1 demonstrates how a single-line-to ground fault is analyzed on a three-phase power system. Following equations will be satisfied for a single line-to-ground fault:

$V_a = 0,\ I_b = 0,\ I_c = 0,\ I_a >> 0$

The fault location on a power system is on the branch where $V_a = 0$ and I_a is very large. This type of fault can be visualized as a battery where the outputs are shorted. This circuit will cause a large amount of current to flow through the battery terminals while the voltage across the terminals will be about zero.

It is desirable to limit disturbances to the smallest possible part of the distribution system. Therefore, to locate

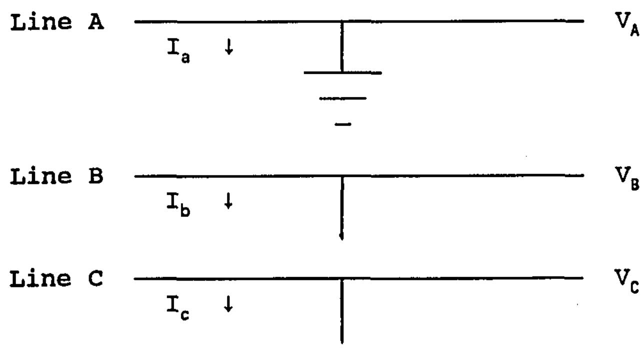


Fig.3.1 Single Line-To-Ground Fault Representation

the fault, tests will be done on each branch, starting from the bottom of the power system and proceeding upstream. Only one location is assumed to be grounded on the power system, all branches below the fault location will have V=0 as well as I=0, but the branch where the fault has occurred will have V≈0 and I>>0. V would be approximately zero and I would be very large. As tests continue on each branches going up-stream from the fault location, current -I- will be high, while voltage will become more and more positive - V>0-. Thus, starting from the lowest possible branch of the power system, the Line-to-Line fault will be on the first branch where:

1) V ≈ 0

2) I >> 0, very large.

On a three-phase system, if the generator is not grounded, all three phase currents should add up to zero, if this is not the case, then there is a fault on the system. If the generator is not grounded then:

$I_a + I_b + I_c = 0$

If the generator is grounded then:

$I_a + I_b + I_c + I_N = 0$, where I_N is the ground current, otherwise a fault has occurred. There can be a motor on a branch, and since starting currents can be high on a motor, ($I_{Starting} = 6 \times I_{Full\ Load}$) this should also be considered when measuring high currents and slightly lower voltage on branches. Time delay units are used for this purpose, however Line-to-Line fault currents will be much higher then $6 \times I_{Full\ Load}$ currents and voltage will only slightly dip, but not nearly as close as zero volts AC. Thus for our purpose using time delays will not be necessary and a clever use of voltage comparators will accomplish the job adequately.

3. OPEN CIRCUIT FAULTS

On a power system, an open circuit occurs when a branch is disconnected from the rest of the system. This causes a power flow discontinuity within the power distribution system. Provided that there are no other feeds to the bus B location, as shown in figure 3.2, then the fault location is located as follows:

1) Upstream from the branch where the fault has occurred, voltage will be larger than zero.

2) Voltage as well as current will be zero (I=0 and V=0) downstream from the branch where the fault has occurred.

For security, as well as to prevent a possible ground from occurring on a power system, the branch where I=0 but V>0 should be removed from the system.

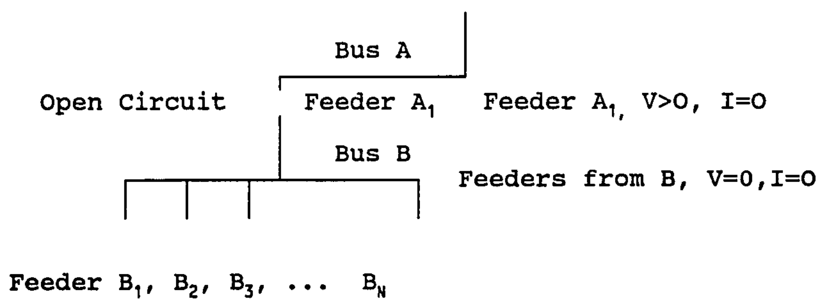


Fig. 3.2 Open Circuit representation on power systems

4. LINE-TO-LINE FAULTS

On a power distribution system, a line-to-line fault can occur when 2 lines are shorted on a three-phase power distribution system, as shown in figure 3.3. This fault will satisfy the below equations:

$I_a = 0$, $I_b = I_c$ and $V_b = V_c$

Positive (+) and negative (-) sequence networks should be connected in parallel at the fault location in order to simulate a line-to-line fault as shown in figure 3.4. The result of this line-to-line fault is:

1) Line (a) stays the same;

2) (+) and (-) sequences nullify each other for lines (b) and (c).

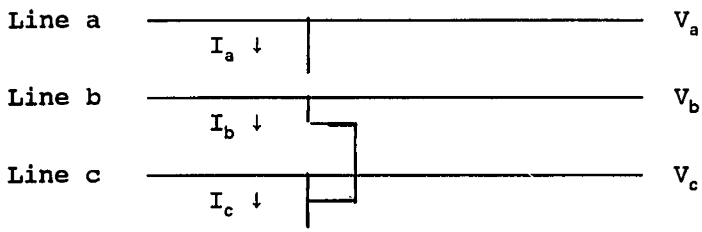


Fig. 3.3 Line-to-Line Fault representation.

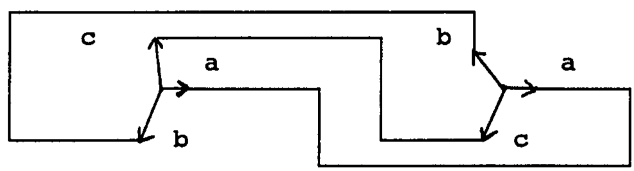


Fig. 3.4 Line-to-Line Fault simulation

Line-to-Line faults need not be corrected immediately on power distribution systems. On the other hand, motors and certain controls will not function properly and a malfunction will be detected on the operation of the connected machinery. A scheme to detect the fault location and disconnect the branch with a fault is explained on the recommendations section of this thesis. This scheme uses wave propagation to precisely identify the fault location and eliminate the branch where the fault is. This scheme accomplishes the job in a fraction of a second.

On a single-line diagram, which actually represents a three-phase line diagram, Line-to-Line voltage difference on two phases will be nearly zero for a Line-to-Line fault. As the voltage proceeds either up or down stream from the fault location, Line-to-Line voltage will be greater then the line (Bus) above or below it. Thus to detect Line-to-Line faults, precise voltage measurements are needed. Line-to-Line fault location can be eliminated by starting to disconnect the lowest power system branches, and proceeding up stream. Everytime a branch is disconnected from the system, then a precise Line-to-Line voltage measurement will be done, and the fault location will be on the first branch where Line-to-Line voltage difference is minimum, or closest to zero. This will locate the fault location properly. Thus, a reasonable distance from the fault location can be reached by either measuring Line-to-Line voltage differences, or with precise measurements of Line-to-Line resistances.

5. DOUBLE LINE-TO-GROUND FAULT

In a double line-to-ground fault, two lines will be touching each other and they will also be grounded. In this case, as shown in figure 3.5, the following equations will be satisfied:

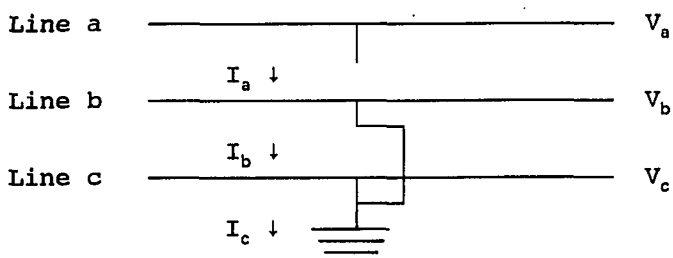


Fig. 3.5 Double Line-to-Ground Fault representation.

$V_b = 0$, $V_c = 0$ and $I_a = 0$, $I_b = I_c$

Two things should be done to eliminate double line-to-ground fault:

1) Eliminate Line-to-Ground fault as in section 2 above, and;

2) Eliminate Line-to-Line fault as in section 4 above.

If only two lines are in contact without touching the ground, then only line-to-line fault needs to be eliminated.

6. THREE LINE-TO-GROUND FAULT

This could be either three line-to-ground fault or possibly only three lines touching each other but they are not grounded, as shown in figure 3.6.

Again, two things can be done to eliminate three line-to-ground fault:

1) Eliminate the ground fault as in section 2 above; or

2) Eliminate Line-to-Line fault as in section 4 above. Since there are three lines touching each other, the steps explained in section 4 above may have to be repeated twice. If all three lines are touching each other on the same branch location, steps explained in Section 4 above need only to be done once. If all three lines are not touching each other on the same branch, then this case needs to be repeated twice. First repetition will eliminate the first line-to-line fault, and the second try will eliminate the second area where the two lines are touching each other. In this case, some resistance will be involved between the three line connection of figure 3.6.

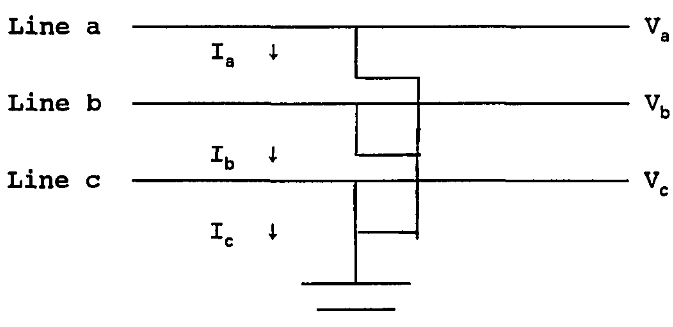


Fig. 3.6 Three Line-to-Ground Fault representation.

IV. THE DESIGN CONCEPT

1. INTRODUCTION

This section explains the basic concept and operation of the system. The main purpose of this design is a fast response to a fault while keeping the maximum allowable number of branches alive. Figure 4.1 is a flow chart showing a branch of a one-line diagram on a power system. It explains the flow of information, organization and function of the design with specific contribution and performance of each part. Basic sections of the design are:

A. Sensors - which constantly monitor voltage and current levels on each branch;

B. Sender unit - Q.A.M. and fiber optic cable identifies, and uniquely distinguishes each branch and their data. Sends the collected data to the next unit via fibre optic cable.

C. Decision making process where each branch data is identified, evaluated separately and a predetermined, appropriate decision is made about the behavior and performance of the power system. This process uses a Programmable Logic Controller.

D. Execution of the decision is accomplished through the use of Band Pass Filters and Circuit Breakers.

2. PARTS OF THE DESIGN

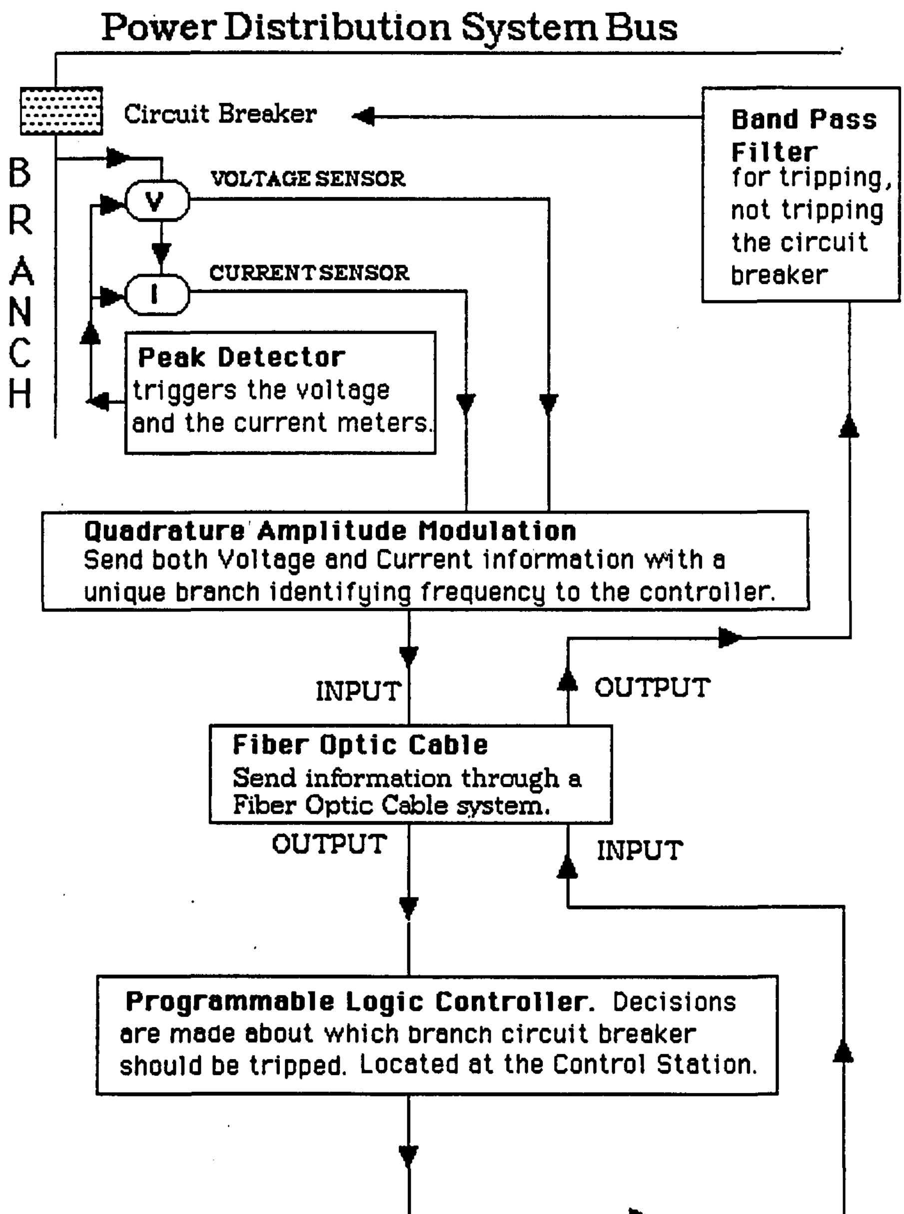


Fig. 4-1 A flow chart demonstration of concept of the design.

2.A SENSORS: Sensors will be used to continuously keep track of the operating values of voltage and current levels on each line of the power system. They will perform as individually mounted and wired ammeters and voltmeters. A peak detector, shown in figure 4-1, can only be used for voltage and current monitor at the peak of the AC voltage waves for each branch. The usefulness of this idea will be elaborated in Section 6. Figure 4-2 demonstrates a 3-Phase 4 wire hook up for voltage and current sensors. The actual

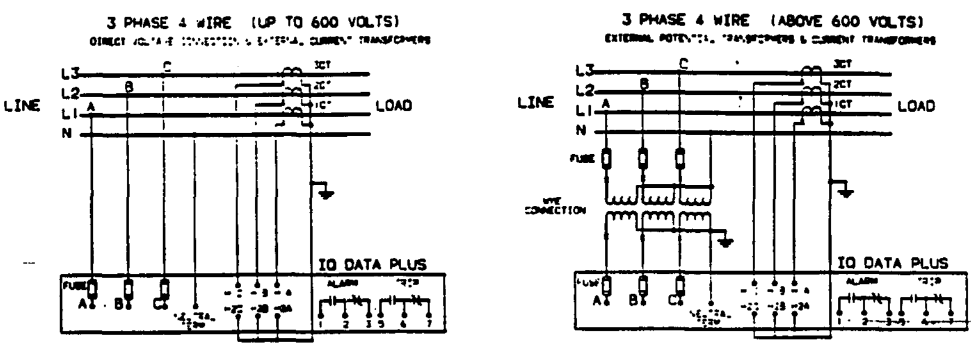


Fig 4-2 A 3-Phase 4 wire hook up for sensors

operating voltage and current levels are monitored independently and the per phase power system branch hook up is shown in figure 4-2a.

2.B SENDER UNIT: The sender unit has two divisions:

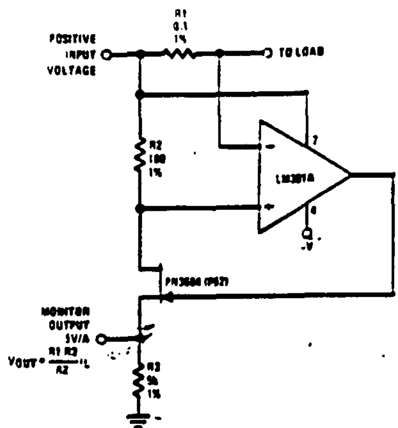
1. Quadrature-Carrier Multiplexing for uniquely collecting one branch information and identifying one branch voltage and current data with each branch identification signal. This process is repeated for every power distribution system branch and each separate branch is identified with a different unique frequency.

2. Fiber Optic Cable for transferring the collected data to the decision making unit.

2.B.1 QUADRATURE-CARRIER MULTIPLEXING: Quadrature-Carrier Multiplexing or Quadrature Amplitude Modulation (QAM) is a bandwidth conservation design enabling two independent messages (two Double SideBand Suppressed Carrier (DSBSC) modulation waves, -Voltage and Current signals-) to use the same transmission bandwidth. The QAM transmitter combines the two separate data (voltage, current) on one frequency, while the receiver section distinguishes and sets the collected data apart.

2.B.1.a TRANSMITTER

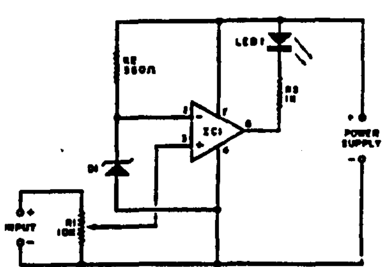
CURRENT MONITOR



Circuit Notes

R1 senses current flow of a power supply. The JFET is used as a buffer because $I_D = I_S$; therefore the output monitor voltage accurately reflects the power supply current flow.

VOLTAGE MONITOR/COMPARATOR



POPULAR ELECTRONICS

Fig. 15-2

Circuit Notes

A portion of the monitored voltage (determined by R1's adjustment) is compared to a fixed voltage obtained from a zener reference network, R2-D1. As long as the monitored voltage remains at or above its present monitor point (determined by R1's setting), the output indicator, LED1, remains dark. If the voltage drops below this level, the LED goes on. D1 is a 3.3-V zener. A 12 Vdc power supply is suitable for monitoring input voltages of up to 12 volts.

Fig 4.2a (a) CURRENT (b) VOLTAGE MONITOR. Circuits, TAB Books, Inc.,Blue Ridge, PA, page 203; 2) Encyclopedia of Electronic Circuits, Volume 2 by Rudolf F. Graf, Page 104.

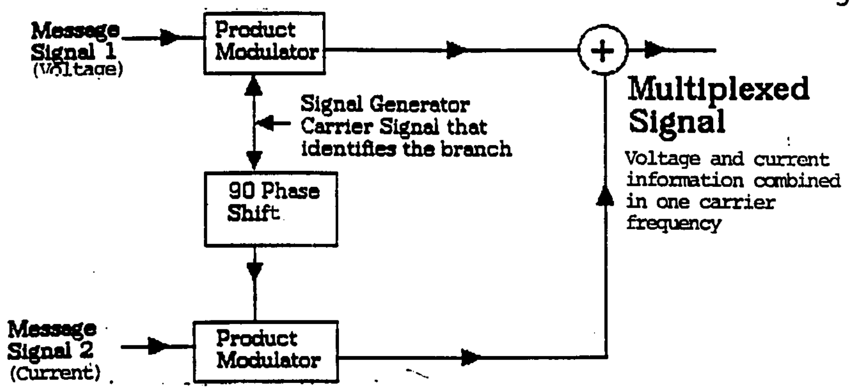


Fig. 4-3 Transmitter of Quadrature-Amplitude Modulator

The QAM[28] operates with two separate product modulators supplied with two carrier waves of the same frequency with a 90° phase variation as illustrated in figure 4-3. The transmitted signal s(t) consists of the sum of these two product modulator outputs:

$$s(t) = A_c m_1(t)\cos(2\pi f_c t) + A_c m_2(t)\sin(2\pi f_c t)$$

where $m_1(t)$ and $m_2(t)$ indicate two different message signals (Voltage and Current data) applied to the product modulators, and W is the message bandwidth of $m_1(t)$ or $m_2(t)$. Thus s(t) occupies a transmission bandwidth of 2W centered at the carrier frequency. $A_c m_1(t)$ could be looked as the inphase component of the multiplexed signal s(t), and $A_c m_2(t)$ as its quadrature component. The output signal s(t) will be at a different frequency for unique identification of every separate branch, and every separate identification frequency will carry three separate bits of information:

1) Information about the branch voltage level, V(t);

2) Information about the branch current level, I(t);

3) The carrier frequency which identifies the branch where V(t) and I(t) data is coming from.

The QAM transmitter is formed of four sections:

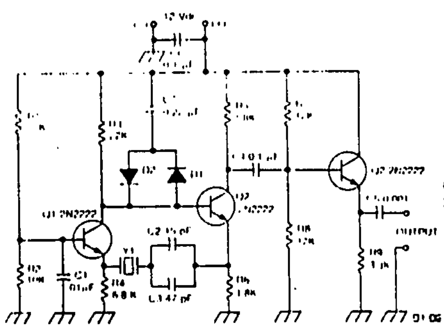
1) signal generator

2) product modulator

3) 90° phase shift

4) adder unit

2.B.1.b SIGNAL GENERATOR: For frequencies from 50kHz to 500kHz a Butler Aperiodic Oscillator, Figure 4-4a, and for



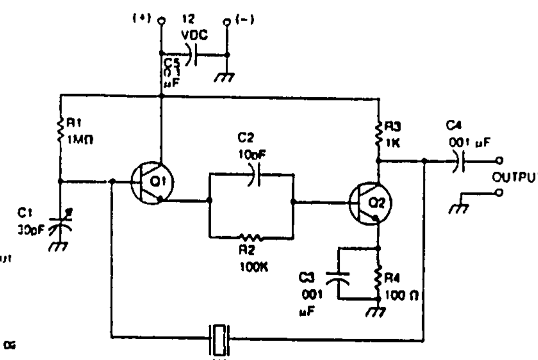


Fig 4-4.a BUTLER Fig 4-4.b PARALLEL-MODE OSCILLATORS:The Encyclopedia of Electronic Circuits by Rudolf F. Graf, (Tab Books Inc., Blue Ridge Summit, PA 17214, 1985), page 196, Volume 1. Detailed information on The Complete Handbook of Amplifiers, Oscillators & Multivibrators by Joseph J. Carr, (Tab Books Inc, Blue Ridge Summit, PA 17214, 1981, Book No. 1230) pages 329-331.

frequencies from 500kHz to 10MHz a Parallel-Mode Aperiodic Crystal Oscillator, Figure 4-4b, will be used. A different frequency is generated as an identification tag for each power system branch.

2.B.1.c PRODUCT MODULATOR: Motorola type MC1596G balanced modulator, which functions as amplitude modulator, will be used, as shown in figure 4-5.

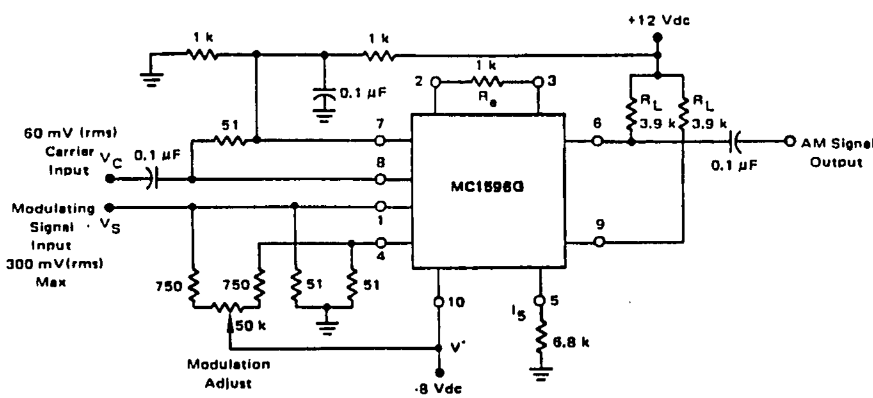


Fig 4-5 Amplitude modulator functions when carrier signal is unbalanced enough to insert proper amount of carrier into output signal. Provides excellent modulation from 0% to well over 100%. R. Hejhall, "MC1596 Balanced Modulator," Motorola, Phoenix, AZ 1975, AN-531,p 7. From Modern Electronic Circuits Reference Manual by John Markus, McGraw Hill Book Company, New York, 1980, page 560.

2.B.1.d 90° PHASE SHIFT: A 90° phase shift can be acquired by adjusting R_1 so that $Q = 90°$, where R_1 and R_2 can be chosen as $R_2=R_1/5$ as shown in figure 4-6.

2.B.1.e ADDER UNIT: No circuits are required for combining the two signals, except that the impedance of both wires should be matched.

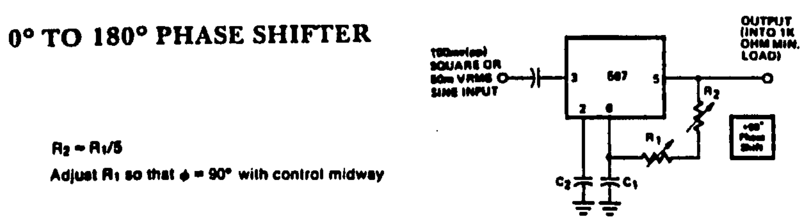


Fig 4-6 0° to 180° Phase shifter. $R_2=R_1/5$ Adjust R_1 so that $Q=90°$ with control midway. Rudolf F. Graf, The Encyclopedia of Electronic Circuits, Tab Books Inc., Blue Ridge Summit, PA, 1985.

2.B.2 FIBER OPTIC CABLE (F.O.C)

The main reasons for choosing fiber optic cable in this design to carry the generated data from the quadrature amplitude modulator to the decision making unit, and from the signal generator to the band pass filter (refer to figure 4.1) are:

1) F.O.C. have technical and economic limitations.

a) Cost of installation, operation and maintenance. A broken line requires splices needing an optical connecter, resulting in high cost, loss of transmission efficiency and time consuming installation.

b) Electrical isolation. Common ground is eliminated between fiber transmitter and receiver with optic couplers.

2) Ability to transmit a great deal of data on a single fiber.

3) Glass is a good insulator.

a) No spark or fire hazard.

b) Short circuit protection, no current flow.

c) Surge current and transient immunity.

4) Optic wave is trapped within the fiber optic cable enabling:

a) EMI (Electromagnetic Interference)/RFI (Radio Frequency Interference) noise immunity, and no electromagnetic coupling.

b) No signal radiation or noise emission resulting in transmission.

5) Lightweight, small diameter cable.

6) F. O. C. have low transmission loses, 4dB/km[29], allowing long communication links (more than 100km[30]), however high frequency increases signal loss in glass fiber[31].

7) Despite the apparent nature of glass, fibre cables are surprisingly strong and flexible. However, it is hard to bend

a fiber enclosed in plastic sheath into a small radius to break the fibre. Some loss occurs at a very tight bend. Glass fibers can withstand extreme temperatures (800° C)[32] before deteriorating. Corrosion due to water or chemicals is less severe for glass then the copper it replaces. However, water must not penetrate the glass.

8) Signals can propagate simultaneously in both directions along a single fibre. This process is called "Full-duplex"[33].

2.B.2.a TRANSMISSION OF LIGHT IN FIBER OPTIC CABLES

Optic beams propagate without interfering with one another resulting in simultaneous existence of transmitter and receiver signals as illustrated in figure 4-7. The simultaneous transmission of multiple channels of data, each having a different wavelength, on a single fibre is called

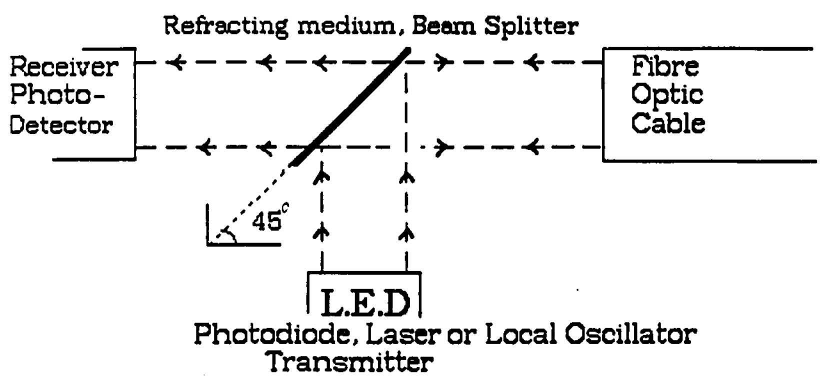


Fig 4-7 Full Duplex, simultaneous transmission and reception of signals in fiber optic cables.

"wavelength division multiplexing" (WDM).[34] The collection of several data from every branch of the power system on one fibre cable is achieved with an "optic multiplexer" which couples light from different sources to the transmitting fibre as shown in figure 4-8 and figure 4-9. A surface emitter

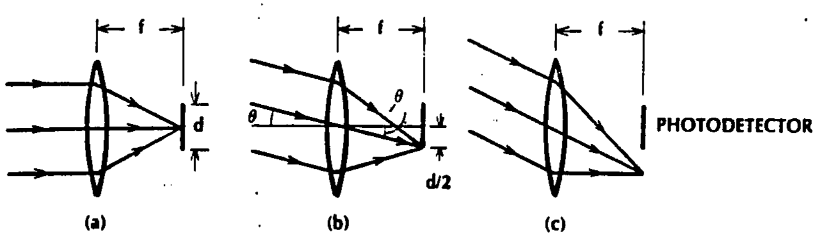


Fig 4-8 An optic receiver with the photodetector placed in the focal plane of the lens.In (a) light is incident parallel to the lens axis, in (b) the light rays are at the extreme angle for reception (acceptance angle), in (c) the incident rays are beyond the system acceptance.

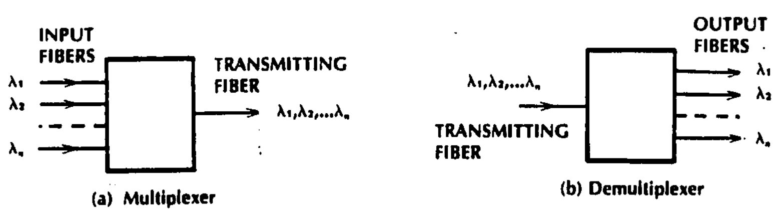


Fig 4-9 Schematic of an optic (a) multiplexer (b) demultiplexer. Joseph C. Palais, Fiber Optic Communications. Prentice-Hall, Inc. Englewood Cliffs, N.J. 1984, page 195.

(Burrus Type) LED[35] will be used for the transmission of data by emitting the light carrying signal into the fiber optic cable as shown in figure 4-10. An avalanche photodiode, APD[36], is used as an optical communications detector as its configuration is shown in figure 4-11. The LED connects a source of signal to its ultimate destination with an optic cable and a light detector which comprise the assembly shown in figure 4-12. In our case, the signal processor is the QAM (Quadrature Amplitude Modulation) and the demodulator part of the design will be accomplished by the decision making unit. Disadvantage of simultaneous transmission and receiving signals on a single fibre is the loss of efficiency due to signal beam spreading, this can be justified for small ships where the transmission cable length is shorter than a kilometer.

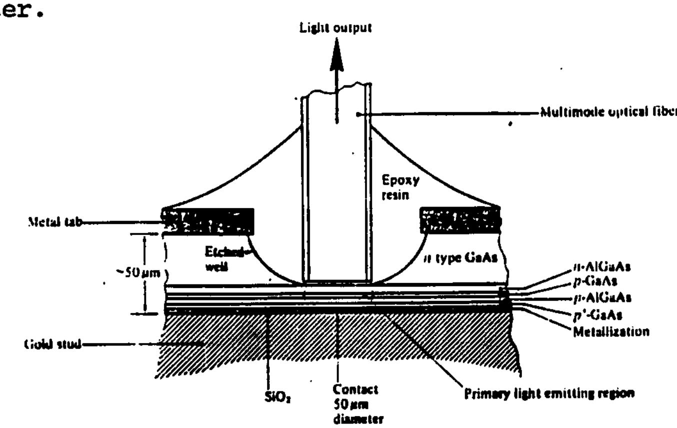


Fig 4-10 The surface of an AlGaAs DH surface-emitting LED (Burrus type). Joseph C. Palais, Optical Communications Principal, Prentice-Hall Englewood Cliffs, 1985, page 305

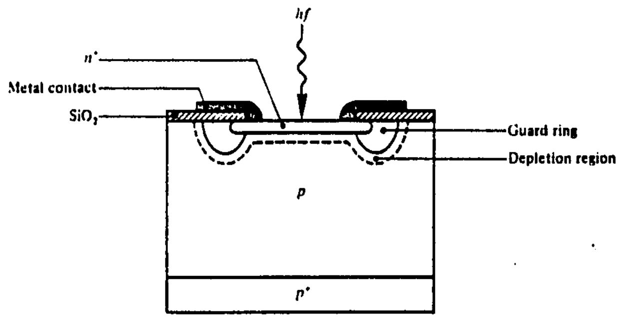


Fig 4-11 Structure of a silicon avalanche photodiode. Joseph C. Palais, Optical Fiber Communications Principle & Practice, Prentice Hall International, Englewood Cliffs, NJ, 1985, page 341.

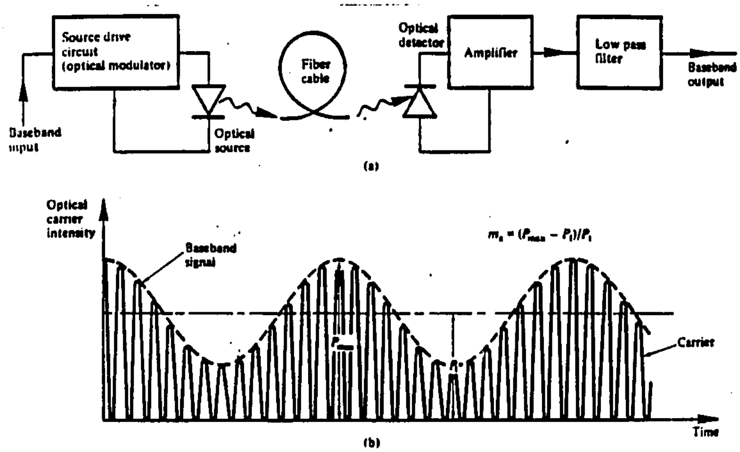


Fig 4-12 (a) Analog optical fiber system employing direct intensity modulation. (b) Time domain representation showing direct intensity modulation of the optical carrier with a baseband analog signal. Joseph C. Palais, Optical Fiber Communications Principle & Practice, Prentice Hall International, Englewood Cliffs, NJ, 1985 page 452.

Direct-Intensity Modulation (DIM) which employs analog transmission, figure 4-12, is used to avoid cost and complexity of digital equipment and degradation due to quantization noise which necessitates high optical input power, high end to end linearity to escape distortion and prevent crosstalk between different channels of multiplexed signal.

2.B.2.b DIRECT INTENSITY MODULATION (DIM)[37]

Direct Intensity Modulation (DIM) will be used for the purpose of transmitting and collecting data. This technique requires no electrical modulation or demodulation making it both inexpensive and easy to implement, as shown in figure 4-12.

2.C DECISION MAKING PROCESS

The decision making process is the brain of the new design which distinguishes and analyzes data coming from each power system branch. This section of the new design will make a decision about which branch circuit breaker should be operating and if necessary, which ones should be tripped. The decision making process is explained in figure 4-13 and the parts are:

1) Band Pass Filter, and QAM receiver

2) Sensors

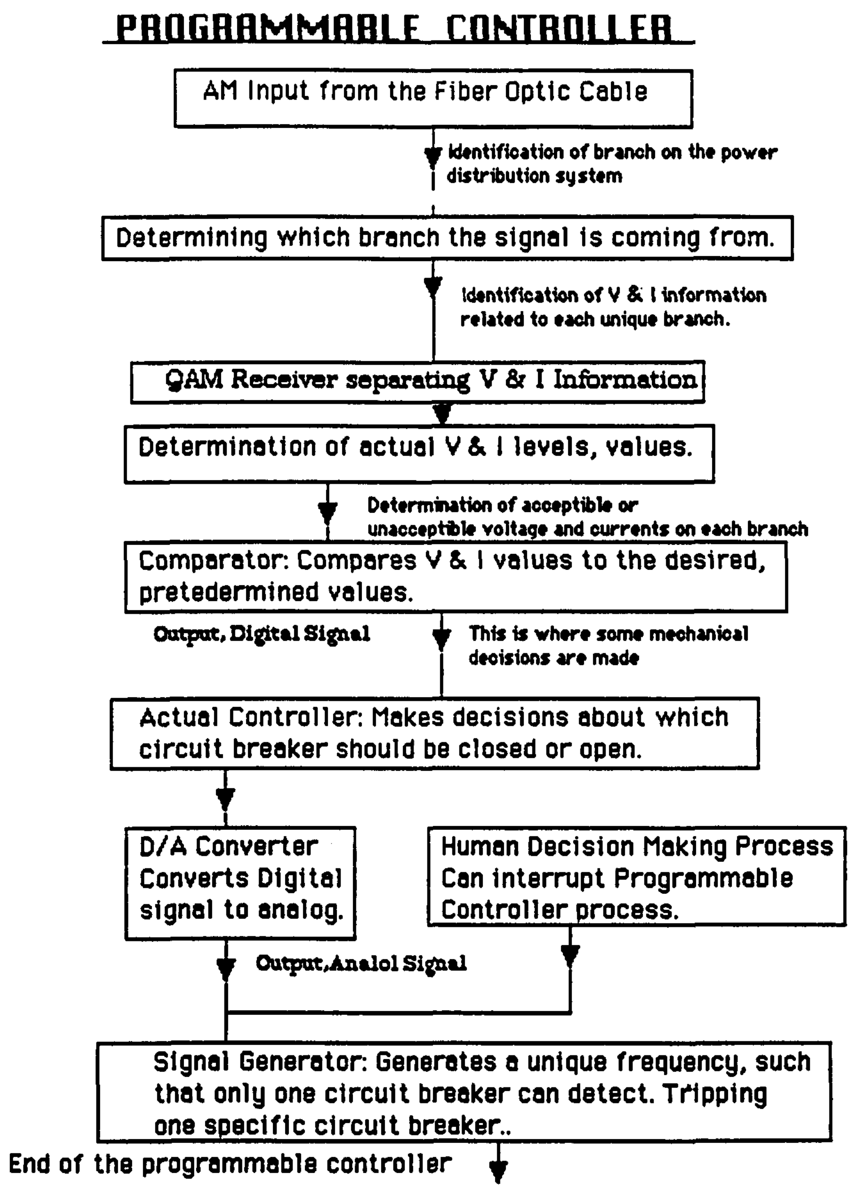


Figure 4-13 A flow chart of the decision making process

3) Comparator

4) Actual Controller

5) Digital to Analog Converter

6) Human Decisions

7) Signal Generator

The time it takes for the data to travel from the decision making unit to the circuit breaker is proportional to the length of the fibre cable. If the distance between the two units is estimated as 1 kilometer and provided that a signal in a fibre optic cable travels approximately with the speed of light in vacuum, $2.997\ 924\ 58 \times 10^{8}$ m/s[38], it would take data 3.34×10^{-6} seconds to travel that distance. To catch a possible fault on its first cycle of a 400Hz wave, $1/400 = 2.5 \times 10^{-3}$ seconds is required. Considering the time for the controller to make a decision (4 to 200×10^{-9} seconds)[39], as well as the time to take action, signal propagation time in the fiber optic cable as well as the time it takes for the S.C.R. circuit breaker to function[40], plus necessary circuits to process the information, this design is capable of disconnecting the branch where the fault has occurred within the first cycle of the wave. This new design will also be able to make this decision in a predetermined logical way which would disconnect the least number of branches thereby allowing maximum system network operation.

2.C.1 BAND PASS FILTER

Incoming signal from the fiber optic cable will contain as many frequencies as the available power system branches. Each frequency will identify and carry the information related to one specific branch of the power system. Each one of these frequencies will be identified and separated by using a different Band Pass Filter (B.P.F.) as shown in figures 4-14a and b. This band pass filter is realized in an inverting form. This will not effect the design or the functioning speed of the decision making system. The value of the system components is represented as shown in the following equations:

$$R_3 = R_4 = R_5 = 100\ K\Omega$$

$$R_6 = 10\ K\Omega$$

$$C_1 = C_2 = 1000pF$$

$$R_1 = R_2 = \frac{5.0329\times10^4}{f_n}\ K\Omega \qquad (4-1)$$

Where f_n : Center Frequency

$$R_7 = \frac{100\ K\Omega}{3.4785\ Q - 2} \qquad (4-2)$$

$$H_0 = -\frac{100\ K\Omega}{R_3} = -\frac{100\ K\Omega}{100\ K\Omega} = -1 \qquad (4-3)$$

Therefore, $H_0 = -1$ @ Center Frequency

$$Q = \frac{f_n}{B.W.} \qquad (4-4)$$

Where, B.W. = Band Width

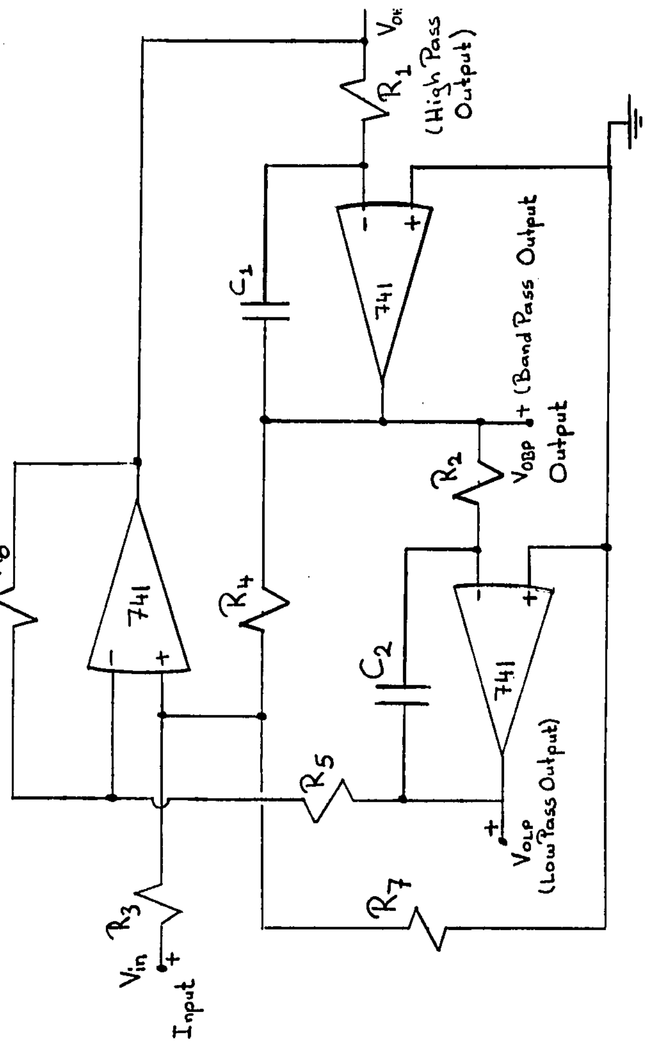


Fig. 4-14a The modified state variable, universal, active Band Pass Filter Source: L.P. Huelsman, P.E. Allen, Introduction to the Design of Active Filters, McGraw-Hill Book Company, New York, 1980, pages 224-227.

In this design, the bandwidth will be chosen as 1000Hz, and once a center frequency is chosen, then Q-from equation (4-4)-, $R_1 = R_2$-from equation (4-1)-, and R7-from equation (4-2)- will be calculated to build as many different band pass filters as necessary. These band pass filters will be used to identify every single frequency arriving from each,branch of the power system, via fiber optic cable, into the decision making unit. Each separate frequency will contain the operating voltage and current information of one branch of the power distribution system.

2.C.2 SENSORS

Every frequency is identified for which system branch data they contain. This signal will be further separated to obtain the voltage and current data, which will be accomplished by the receiver part of the quadrature-amplitude modulation as shown in figure 4-15. After voltage and current information is separated, then each distinct power branch will detect the actual voltage and current levels by the use of a peak detector as shown in figure 4-16. A separate comparator will be used to check the operating values with the desired, predetermined values for that particular power system branch, as shown in figure 4-17.

So far this new design has:

a) Identified every power system branch, and their data;

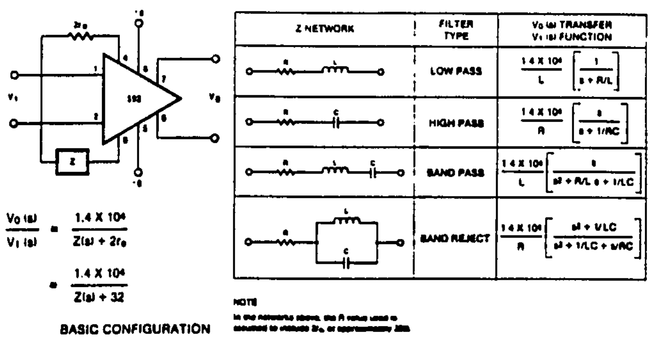


Fig 4-14b Band Pass Filter

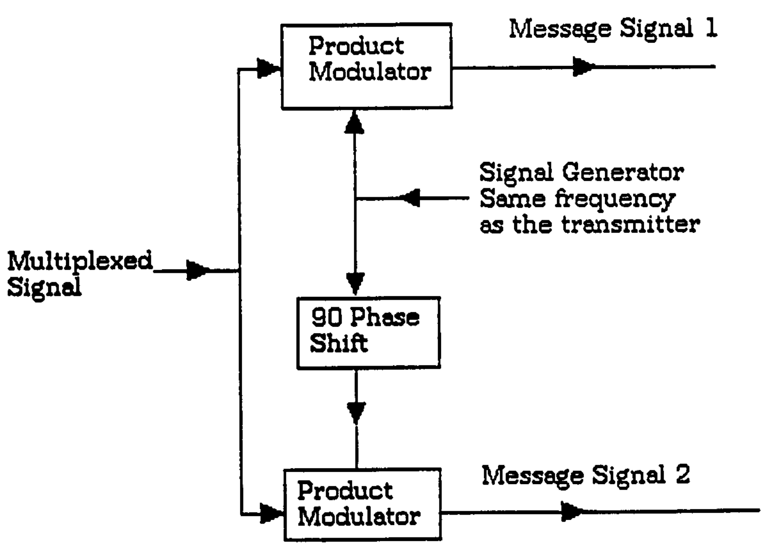


Fig 4-15 Receiver of the Quadrature-Amplitude Modulator.

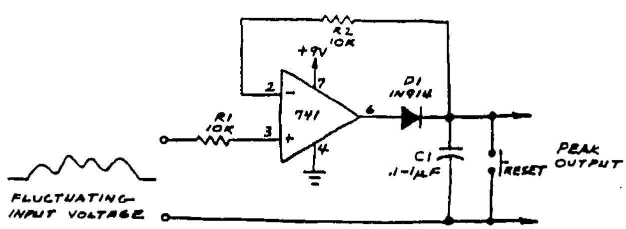
b) Separated actual voltage and current data;

c) Determined the operating voltage and current values;

d) Checked to see if the operating voltage and current values are acceptable.

2.C.3 COMPARATOR

A separate comparator will examine the operating voltage and current levels with the predetermined acceptable values on each power distribution system branch. Two separate comparators will be employed for each power system branch, one comparator for examining the voltage level, the other



POPULAR ELECTRONICS   Fig. 68-2

Fig 4-16 Peak Detector. The comparator will charge C1 until the voltage across the capacitor equals the input voltage. If subsequent input voltage exceeds that stored in C1, the comparator voltage will go high and charge C1 to new higher peak voltage. Rudolf F. Graf Encyclopedia of Electronic Circuits, Volume 2, Tab Books Inc,. Blue Ridge Summit, PA, 1988, page 436.

comparator for current level. A comparator circuit is shown in figure 4-17.

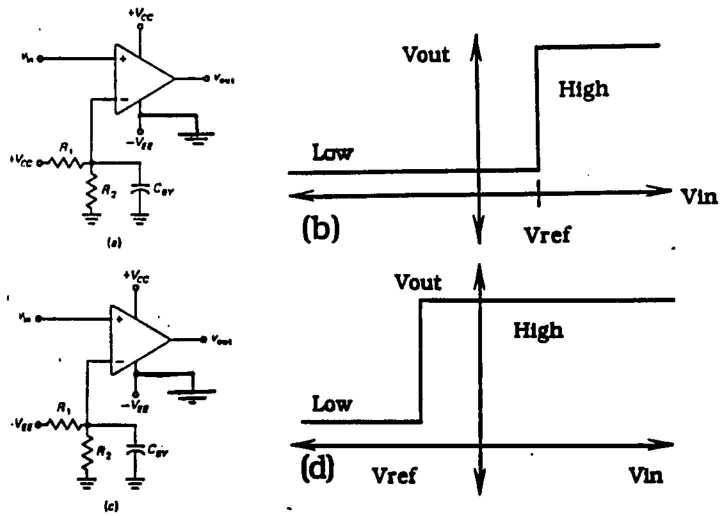


Fig. 4-17 (a) Comparator with adjustable positive trip point. (b) Transfer characteristics. (c) Comparator with negative trip point. (d) Transfer characteristic with negative trip point. Albert Paul Malvino, Ph.D, E.E., Electronic Principles, McGraw-Hill Book Company, New York, 1989, page 553.

2.C.4 ACTUAL CONTROLLER

A programmable controller will be used to receive and evaluate the collected data for making decisions on the operations of the power distribution system. The specifications for the operation of this unit are shown in table 4.1. Figure 4-18, pictures the actual controller. A block diagram is shown in figure 4-19. Once a decision is

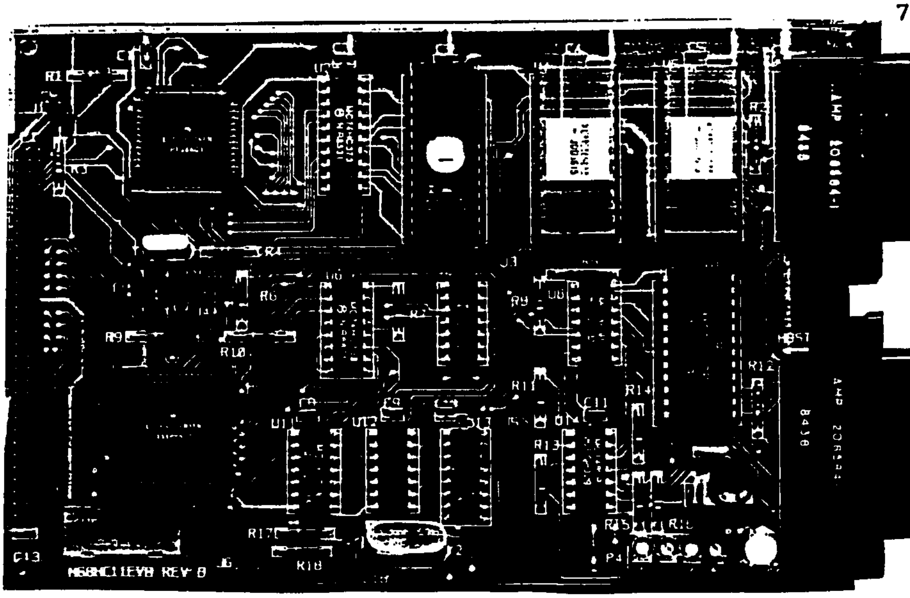


Fig. 4-18 Programmable Controller, M68HC11EVB Evaluation Board.

CHARACTERISTICS	SPECIFICATION
MCU	MC68HC11A1FN
PRU	MC68HC24FN
ACIA	MC68B50
I/O ports:	
Terminal	RS-232C compatible
Host Computer	RS-232C compatible
MCU extension	HCMOS-TTL compatible
Temperature:	
Operating	0 to 50 degrees C
Storage	-40 to +85 degrees C
Relative Humidity	0 to 90% (non-condensing)
Power requirements	+5 Vdc @ 0.5 A (maximum)
	+12 Vdc @ 0.1 A (maximum)
	-12 Vdc @ 0.1 A (maximum)
Dimensions: Width, Length	17.8cm(7in),11.75cm(4.6in)

TABLE 4-1 EVB Specifications

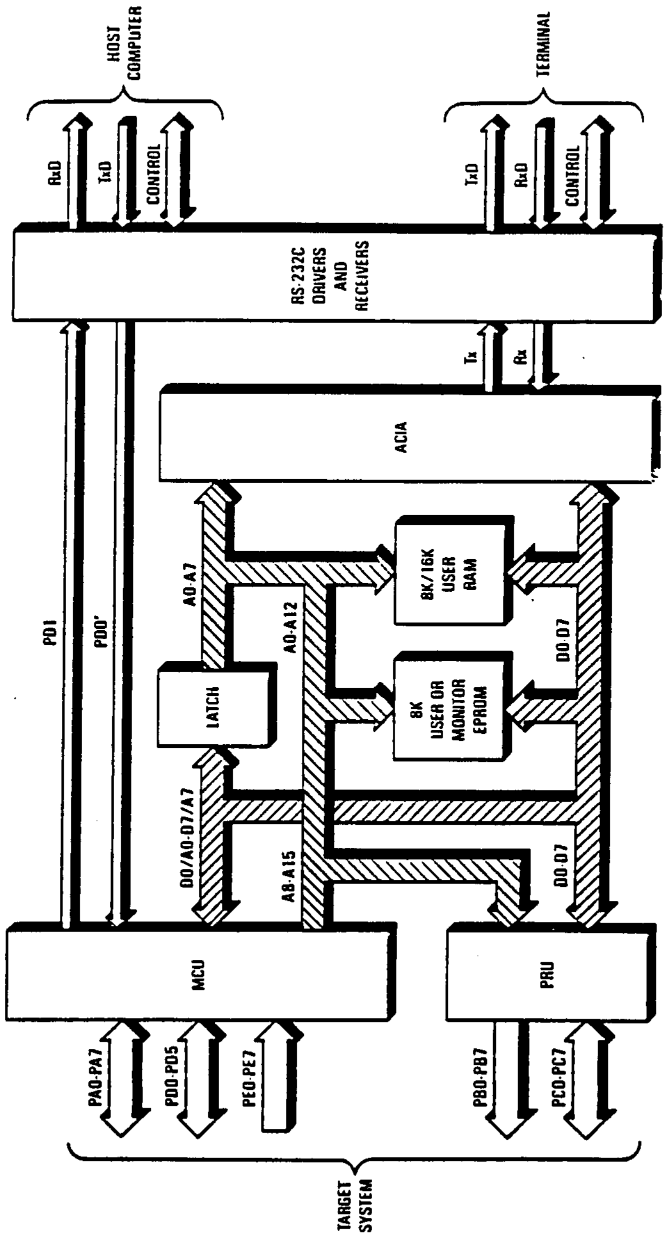


Fig 4-19 Programmable controller, EVB Block Diagram. M68HC11EVB Evaluation User's Manual by Motorola.

made, the controller will follow up to see if the decision did correct the operation of the power system, otherwise the controller will go through the predetermined program and will try again. For each different power system arrangement a specific program has to be written for the proper operation of the controller.

2.C.5 DIGITAL TO ANALOG CONVERTER

A digital to analog converter, D/A, will direct the controller's digital output to the designated signal generator. A decoder/demultiplexer, as shown in figure 4-20 and Table 4-2 and 4-3, will be used for the purpose of selecting one available unit of many.

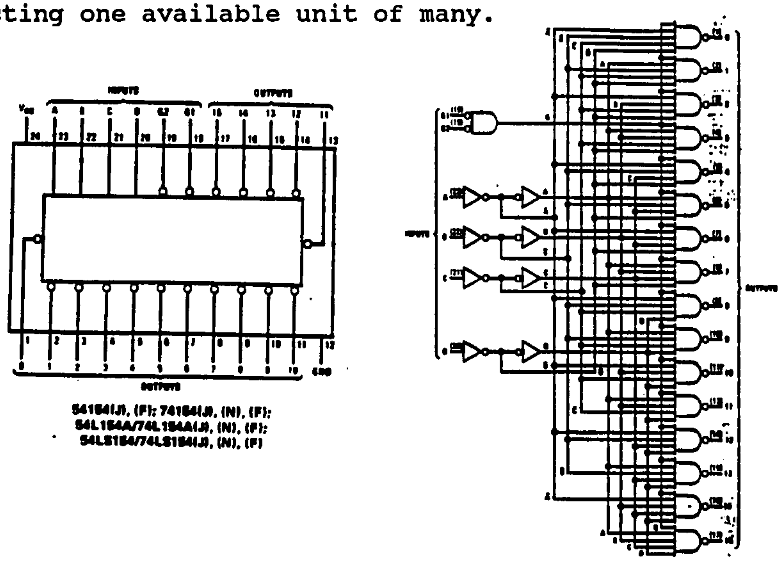


Fig 4-20 A 4 line to 16 line Decoder/ Demultiplexer connections and Logic Diagram. TTL Data Book, National Semiconductor, 1976, page 2-60.

2.C.6 HUMAN DECISION

Human decision can only approve or disapprove the normal operation of the power system. This will be accomplished by AND gates, indicating that the power system operation has to be approved simultaneously by both the controller and a human operator. A status board with annunciators is helpful for monitoring the operation of the power system.

2.C.7 SIGNAL GENERATOR

When the actual controller makes a decision to turn off one circuit branch, then the digital to analog converter will send a signal and activate only one signal generator which will generate one and only one unique frequency which is intended for turning off one specific malfunctioning branch of the power system. That specific branch will be the one that failed to function properly, the branch where the fault is on the power system.

The generator will send one specific frequency through the fiber optic cable to all circuit breakers that would correspond and activate only one selected circuit breaker. The same type of signal generators as mentioned in this chapter, section 2.B.1.b, will be used.

2.D ACCOMPLISHMENT OF THE DECISION

Although the transmitted frequency by the signal

	PARAMETER	CONDITIONS			DM54/74 154 MIN	TYP(1)	MAX	DM54L/74L L154A MIN	TYP(1)	MAX	DM54LS/74LS LS154(4) MIN	TYP(1)	MAX	UNIT
V_{IH}	High Level Input Voltage				2			2			2			V
V_{IL}	Low Level Input Voltage			DM54			0.8			0.7			0.7	V
				DM74			0.8			0.7			0.8	
V_I	Input Clamp Voltage	V_{CC} = Min	I_I = −12 mA				−1.5			N/A				V
			I_I = −18 mA										−1.5	
I_{OH}	High Level Output Current						−800			−200			−400	μA
V_{OH}	High Level Output Voltage	V_{CC} = Min, V_{IH} = 2V, V_{IL} = Max, I_{OH} = Max		DM54	2.4	3.4		2.4	2.8		2.5	3.5		V
				DM74	2.4	3.4		2.4	2.8		2.7	3.5		
I_{OL}	Low Level Output Current			DM54			16			2			4	mA
				DM74			16			3.6			8	
V_{OL}	Low Level Output Voltage	V_{CC} = Min, V_{IH} = 2V, V_{IL} = Max, I_{OL} = Max		DM54		0.25	0.4		0.15	0.3		0.25	0.4	V
				DM74		0.25	0.4		0.20	0.4		0.35	0.5	
I_I	Input Current at Maximum Input Voltage	V_{CC} = Max	V_I = 5.5V				1			0.1				mA
			V_I = 7V										0.1	
I_{IH}	High Level Input Current	V_{CC} = Max	V_I = 2.4V				40			10				μA
			V_I = 2.7V										20	
I_{IL}	Low Level Input Current	V_{CC} = Max	V_I = 0.3V							−0.18				mA
			V_I = 0.4V				−1.6						−0.36	
I_{OS}	Short Circuit Output Current	V_{CC} = Max(2)		DM54	−20		−55	−3	−9	−15	−30		−130	mA
				DM74	−18		−57	−3	−9	−15	−30		−130	
I_{CC}	Supply Current	V_{CC} = Max(3)		DM54		34	49		4.8	6.0		5	14	mA
				DM74		34	56		4.8	6.0		9	14	

Notes
(1) All typical values are at V_{CC} = 5V, T_A = 25°C.
(2) Not more than one output should be shorted at a time, and for DM54LS/74LS duration of short circuit should not exceed one second.
(3) I_{CC} is measured with all inputs grounded and all outputs open.
(4) Tentative data.

TABLE 4-2 Table for 4-Line to 16-Line Decoder/Demultiplexer.
TTL Data Book National Semiconductor 1976, page 2-61.

TABLE 4-3 4-Line to 16-Line Decoder/Demultiplexer

Switching Characteristics $V_{CC} = 5V, T_A = 25°C$

PARAMETER		DM54/74 154 CONDITIONS	MIN	TYP	MAX	DM54L/74L L154A CONDITIONS	MIN	TYP	MAX	DM54LS/74LS LS154(4) CONDITIONS	MIN	TYP	MAX	UNITS
t_{PLH}	Propagation Delay Time, Low-to-High Level Output, From A, B, C, or D Inputs Through 3 Levels of Logic	$C_L = 15$ pF, $R_L = 400\Omega$		18	36	$C_L = 50$ pF, $R_L = 4$ kΩ		35	70	$C_L = 15$ pF, $R_L = 2$ kΩ		24	36	ns
t_{PHL}	Propagation Delay Time, High-to-Low Level Output, From A, B, C, or D Inputs Through 3 Levels of Logic			21	33			75	150			22	33	ns
t_{PLH}	Propagation Delay Time, Low-to-High Level Output, From Either Strobe Input			17	30			35	70			20	30	ns
t_{PHL}	Propagation Delay Time, High-to-Low Level Output, From Either Strobe Input			18	27			55	110			18	27	ns

Truth Table

INPUTS						OUTPUTS															
G1	G2	D	C	B	A	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
L	L	L	L	L	L	L	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H
L	L	L	L	L	H	H	L	H	H	H	H	H	H	H	H	H	H	H	H	H	H
L	L	L	L	H	L	H	H	L	H	H	H	H	H	H	H	H	H	H	H	H	H
L	L	L	L	H	H	H	H	H	L	H	H	H	H	H	H	H	H	H	H	H	H
L	L	L	H	L	L	H	H	H	H	L	H	H	H	H	H	H	H	H	H	H	H
L	L	L	H	L	H	H	H	H	H	H	L	H	H	H	H	H	H	H	H	H	H
L	L	L	H	H	L	H	H	H	H	H	H	L	H	H	H	H	H	H	H	H	H
L	L	L	H	H	H	H	H	H	H	H	H	H	L	H	H	H	H	H	H	H	H
L	L	H	L	L	L	H	H	H	H	H	H	H	H	L	H	H	H	H	H	H	H
L	L	H	L	L	H	H	H	H	H	H	H	H	H	H	L	H	H	H	H	H	H
L	L	H	L	H	L	H	H	H	H	H	H	H	H	H	H	L	H	H	H	H	H
L	L	H	L	H	H	H	H	H	H	H	H	H	H	H	H	H	L	H	H	H	H
L	L	H	H	L	L	H	H	H	H	H	H	H	H	H	H	H	H	L	H	H	H
L	L	H	H	L	H	H	H	H	H	H	H	H	H	H	H	H	H	H	L	H	H
L	L	H	H	H	L	H	H	H	H	H	H	H	H	H	H	H	H	H	H	L	H
L	L	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	L
L	H	X	X	X	X	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H
H	L	X	X	X	X	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H
H	H	X	X	X	X	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H

H = High Level, L = Low Level, X = Don't Care generator is received by all circuit breakers, only one is tripped by the use of band pass filters. Once a signal reaches a band pass filter, only one filter will be transparent to that frequency allowing the signal to reach its intended target, tripping a specific circuit breaker where the fault has occurred.

2.D.1 BAND PASS FILTER

Band pass filters (BPF) leak only certain frequencies and block all others. The frequency that can pass through the band pass filter is the one that is intended for that specific branch, and if it is rejected then that signal is not intended for that branch. The same BPF configuration as mentioned in this chapter, section 2.C.1, will be used for the purpose of selecting, separating and identifying signals.

2.D.2 CIRCUIT BREAKERS

Circuit breakers are the last piece of the design that serves to separate a branch from the power system where the apparent fault has occurred. A silicon controlled rectifier[41] (SCR) is equivalent to a latch with a trigger input as shown in figure 4-21 and since AC waves are used, a bidirectional thyristor[42], called triacs, will be employed as shown in figure 4-22 that can handle currents from less than 1A to more than 2500 A and more than 2500 V[43]. In most SCRs, the delay

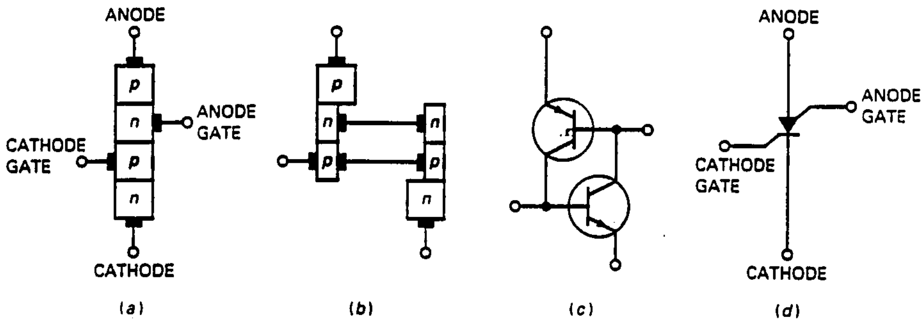


Fig.4-21 Silicon Controlled Rectifiers (SCR). (a) Structure (b) Equivalent Structure. (c) Equivalent Circuit. (d) Schematic symbol. Albert Paul Malvino, Ph.D.,E.E., Electronic Principles, 4th Edition, McGraw-Hill Book Company, New York, 1989, page 544.

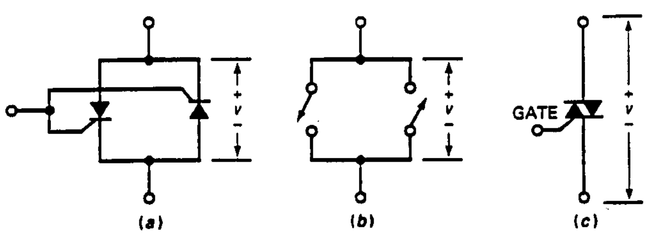


Fig. 4-22 Triac. (a) Equivalent to parallel back-to-back SCR's (b) Equivalent Circuit.(c) Circuit representation. Albert Paul Malvino, Ph.D, E.E. Electronic Principles, McGraw-Hill Book Company, New York 1989, page 547.

time is less than a few microseconds, and the required gate current for turn-on is only a few miliamperes. The primary time is less than a few microseconds, and the required gate current for turn-on is only a few miliamperes. The primary advantage of silicon devices is that they have no moving parts and are not susceptible to corrosion, additionally silicon devices operate almost instantaneously and have high reliability. These factors support the decision to use silicon controlled rectifiers.

3. RESULTS

This knowledge-based design is a fast acting intelligent scheme for disconnecting branches of the power system where a fault has occurred during the first cycle of the operating AC wave. Each system can be designed in the same way but programmed to suit different power system configurations, i.e., if the system changes then the design can change with it due to programmability of the system.

V. BUILDING THE DESIGN CONCEPT

5.1 BUILDING THE ACTUAL PARTS OF THE DESIGN IN THE LAB

This section explains an actual implementation of the design concept. The idea is tested to prove the concept by building a section of the design only for one single branch of the power system, as shown in figure 5-1.

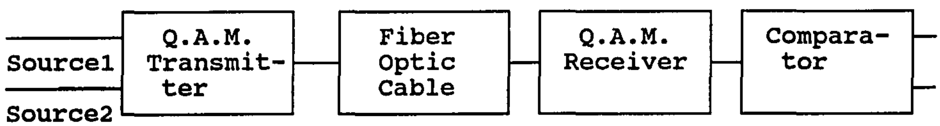


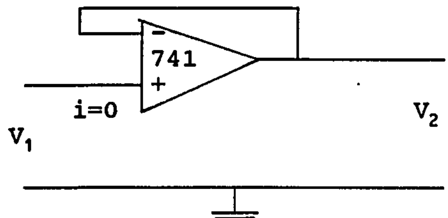
Fig. 5-1 Basic design concept for a single branch.

Source one and two represent the voltage and current information obtained from each circuit branch of the power distribution system by the use of sensors. In a laboratory environment, these two signals are treated as information coming from two separate function generators. Each wave amplitude can be varied independently from the other by the means of operating the related function generator control. The fluctuations of the amplitude of the generated sine wave implements the voltage and current amplitude variance of the supplied power on one particular branch. These sources are combined on a carrier frequency which is generated on a third oscillator. These two information signals and the carrier signal are coupled with the two amplitude modulators, as shown in figure 4-5, to form the transmitter part of the Quadrature Amplitude Modulator(QAM), as shown in figure 4-3. The output of the QAM is applied to the transmitter circuit of a fiber optic cable. The other end of the fiber cable is coupled to a fiber optic receiver circuit. The output is applied to a receiver of a QAM as shown in figure 4-15. The output of this receiver gives the actual operating voltage and current amplitude values of one particular power system branch. The output is applied to a comparator circuit as shown in figure 4-17 to prove that the actual operating values are within reasonable limits, otherwise the comparator output is not null and a signal output is generated. This signal will be used to disconnect the related misfunctioning power system branch.

5.2 VARIANCE BETWEEN THE THEORY AND THE ACTUAL CIRCUIT

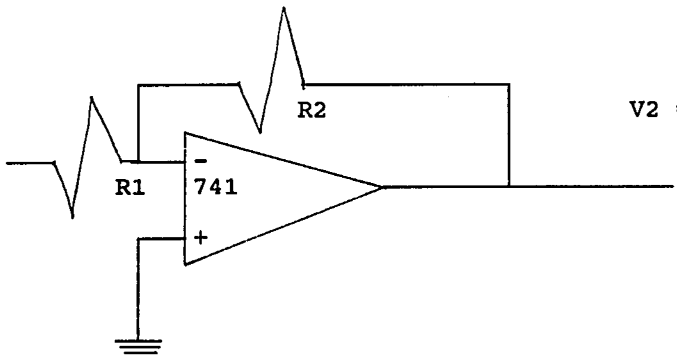
Simple buffers, as shown in figure 5-2, are used to separate each circuit as well as to prevent the loading of the circuits when they are interconnected.

The applied signal sources are greatly reduced in



$V_1 = V_2$

Fig 5-2 A simple buffer circuit.



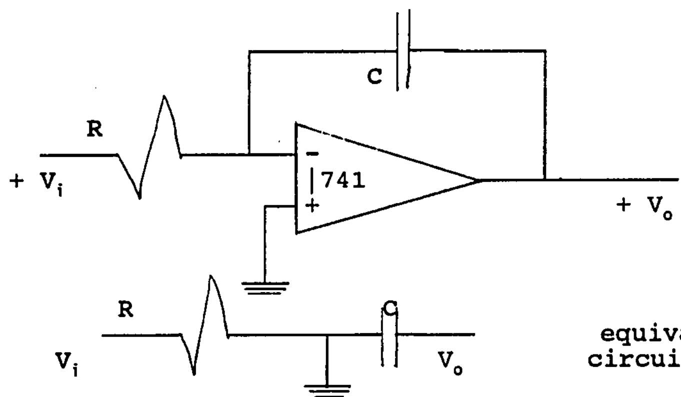
$$V2 = -\frac{R2}{R1} \times (V1)$$

Fig 5-3 A simple amplifier circuit.

amplitude as they pass through each circuit. Simple amplifiers, as shown in figure 5-3, are used to strengthen the signal amplitudes.

The input voltage levels for the amplitude modulators are very low -60 and 300mv(rms). This allows the noise levels to be a problem on each circuit that is built on a breadboard. The laboratory building power system, as well as other operating equipment in the lab, generates noise, and these frequencies are picked by each wire of the modulator circuits. Some simple low pass filters as well as buffers at various locations were used to combat the noise problem. This noise problem is evident in the obtained output signal pictures from the oscilloscopes.

The 90° phase shifter mentioned in Chapter IV, section 2.B.1.d, and in figure 4-6 does accept either a square wave or a sine wave input. The output of this circuit is a square wave for both cases. In building the QAM circuit in the lab to prove that the concept works, a sine wave output was needed. To combat this difficulty a home built 90° phase-shifter was designed as shown in figure 5-4.



equivalent
circuit

$V = IR$, $I = V/R$
$i_1 + i_2 = 0$ or $i_1 = -i_2$
$V = I / (sC)$, $I = V(sC)$

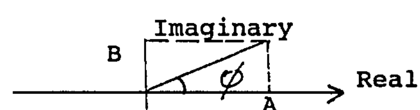
$$(V_i) / R = - V_o(sC)$$

$$\frac{V_o}{V_i} = -\frac{1}{R(sC)} = -\frac{1}{jwRC}$$

$\pi - 90 = 90°$, $\sin(90) = I = \pi - 90 = 180° - 90° = 90°$
$wRC \approx 1$

$w = 2\pi \times 10^4$

f = 10 kHz C = 0.01 μF R = 1.6 KΩ



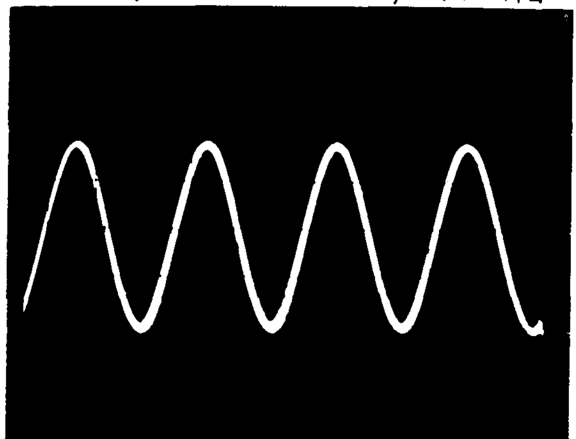
$z = A + jB$
Real = A
Imaginary = B
$\phi = \arctan \frac{B}{A} \Rightarrow \phi = \tan^{-1}\left(\frac{B}{A}\right)$

Figure 5.4 90° Phase Shifter

5.3 RESULTS

Fig 5-4a shows the actual input signal 1 and figure 5-4b demonstrates the output of the same signal from the QAM. The same input and outputs are shown for the second signal in fig 5-5a and b. The noise levels are evident in these pictures as mentioned earlier. Fig 5-6a and b show the output of the comparator. In these pictures the input and output waveforms are shown simultaneously. The sine wave is the cleaned output of the QAM, and the second wave is the output of the comparator. Here a 2VDC reference voltage is used. This voltage represents the max allowable voltage (or current) range of one particular branch of the power distribution system. In figure 5-6a, the input wave to the comparator is below 2VDC, so that no output signal is observed, and when the comparator input reference voltage exceeds 2VDC, then an alerting signal is observed on picture 5-6b. In the actual implementation, this output will cause a circuit branch to be disconnected from the power system.

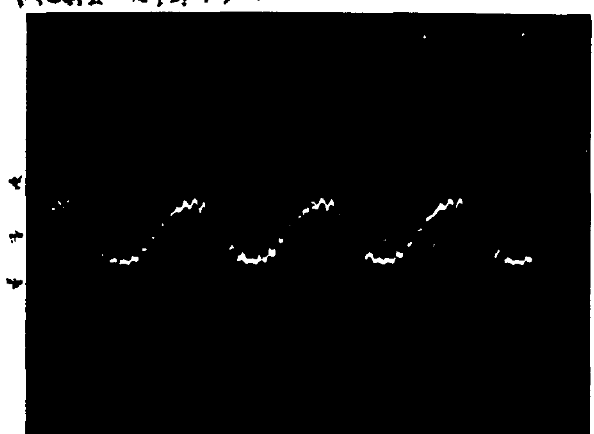
Thursday June 21, 1990, 710 Hz



Input Source 1, 0.2 Volts/div, 5 msec/div, 1/2 sec, full flash

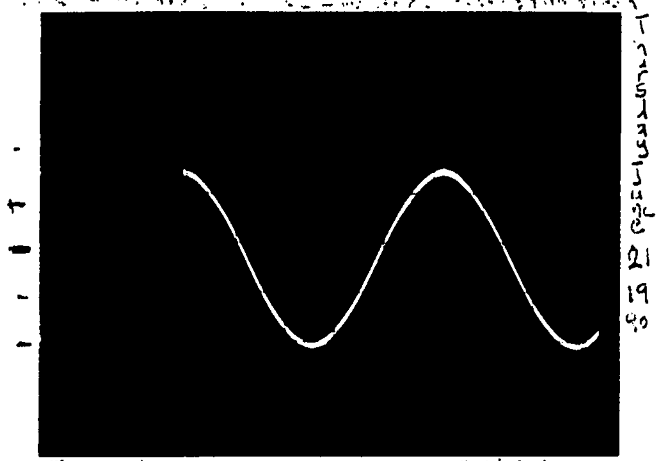
Fig 5-5a Input signal Source 1

710Hz 21/6/90, 710 Hz



Output Source 1, 10mV/div, 5msec/div 21/6/90

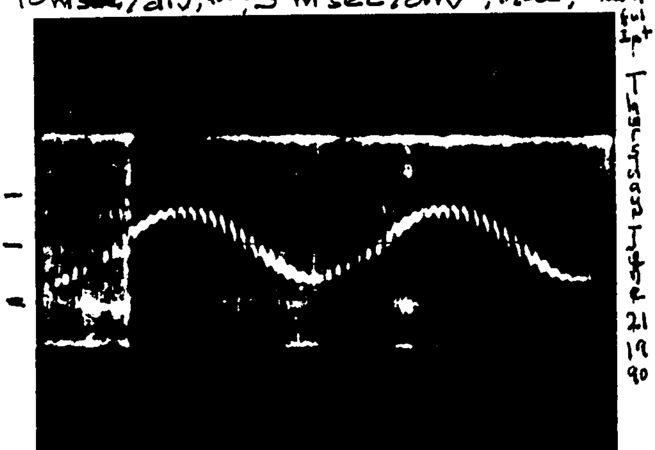
Fig 5-5b QAM output of Source 1



Input Source 2 (0.245 VAC Source Intensity)

Fig 5-6a Input signal Source 2

10 mvolts/div, 400Hz, 5 msec/div, 4½ sec, Flash



Output Source 2 (0.245VAC Source Intensity)

Fig 5-6b QAM output of Source 2

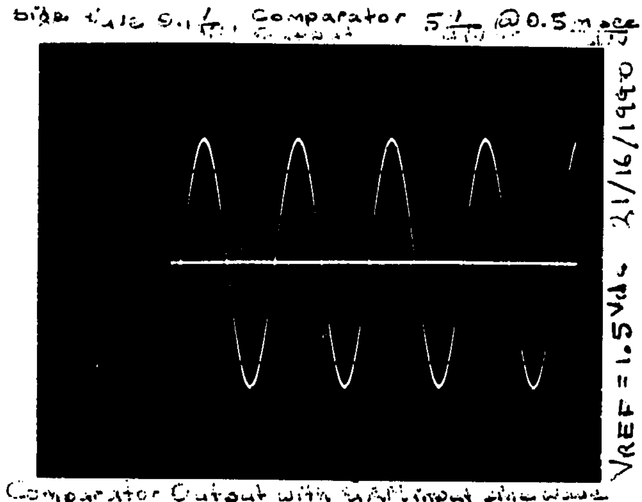


Fig 5-7a Simultaneous input and output waves of the comparator. The reference voltage is below the allowed maximum level resulting in a null output for the comparator.

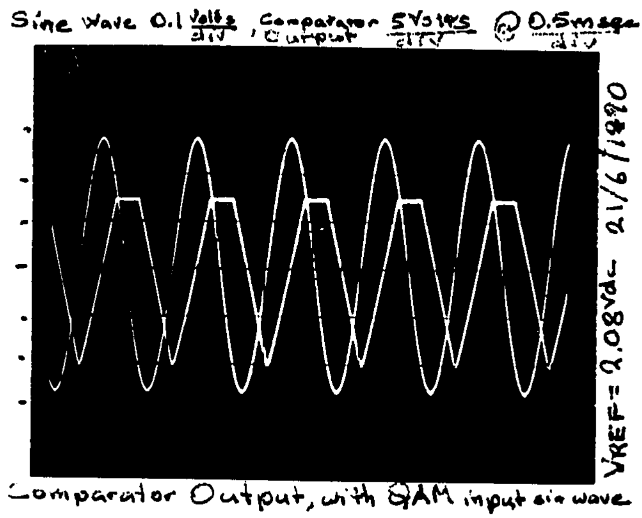


Fig 5-7b Simultaneous input and output waves of the comparator. The reference voltage is above the allowed maximum value resulting in an output from the comparator that will be used to disconnect a power system branch via an oscillator, then a bandpass filter then finally with a silicon controlled rectifier.

VI. RECOMMENDATIONS

There are two recommendations:

A. How to locate Line to Line faults.

B. Automatic throw-over switch implementations.

1. DETECTING LINE TO LINE FAULTS

Line to Line faults will be detected in four steps:

A) A 120° phase difference exists between each of the three phase system. If a point is taken as a reference on one phase, then the relative voltage levels on the other two phases could be calculated, as shown in figure 6-1.

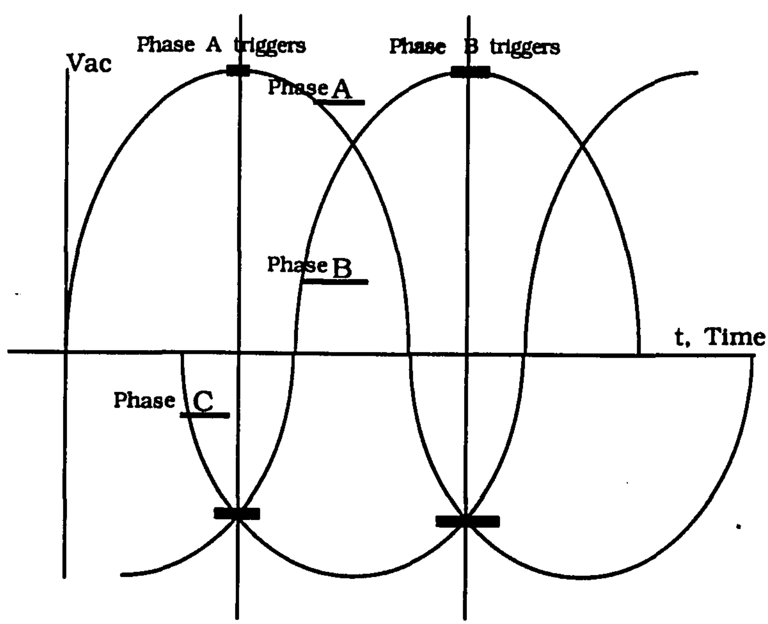


Fig. 6-1 Line to line fault detection scheme.

If a positive peak point is selected as a reference on line A, then the relative voltage level on line B and C could be figured out. Phase B and C will be exactly at the same voltage level because B=sin(90+120)=C=sin(90+240)=-0.5. A peak detector on line A, detects when wave A reaches a positive peak, where sin(90)=1, then simultaneously triggers a separate voltage reading on all three phases. Under normal operating conditions -if none of the lines are touching each other or if none of the lines are grounded- line B and C would have a relative voltage difference with respect to line A. This guarantees that line A is not touching line B or C.

B) Phase B and C voltage levels are at the same level when A reaches the positive peak. Then phases B and C should also be checked to assure that they are not in physical contact. This is done in a similar way as step 1. This time a positive peak point is selected on phase B, and a separate peak detector will trigger the separate voltage meters connected to all three phases. This time, under normal operating conditions, line B would have a different voltage level than line A and line C. This will confirm that line B and C are not touching each other.

So far this procedure has verified that:

1) The voltage level on line A is different than B and C, but line B and C are at the same voltage level.

2) At a different point on the same waveform, the voltage level on line B is different than A and C, but line A and C are at the same level.

This will verify that line A line B line C are not touching each other. If necessary this can be simplified if all voltage meters are triggered when phase A is at zero volts. In this case all three phases are at different voltage levels. As can be seen from figure 5-1, when line A is zero, first line B is negative and line C is positive, and the next time when line A is zero, Line B is positive and line C is negative. In this case, all three lines are checked twice during one cycle of the wave, compared to being checked once as explained in the above sections.

Once the three phase voltage relations are known, then the voltage difference can be verified by the use of comparators. Voltage on line A will be one input of the comparator, line B (or C) will be the other input, and this difference must continuously be true, and fixed, -or must not change- for all three phases during the normal operation of the AC wave. If the expected voltage difference does not happen, then this would clearly indicate a fault condition.

A clock will start counting time as soon as a fault condition is detected on any one line of the power distribution system. A separate clock will be used for each branch of the power system. This time would register the length of the time line to line error would be detected on that specific power system branch. In other words, a different clock on each branch of the power system starts counting the length of the time line to line error is detected on that specific branch. The branch with the longest time is where the line to line fault has occurred. Then the controller can be programmed to turn that branch off. If the fault is still persisting, then the controller will go to the next longest clock reading.

This technique uses wave propagation time delay to detect and then single out where a line to line fault has occurred. Imagine that there are two wires, one ground and the other a voltage line, and they are parallel to each other as shown in figure 6-2.

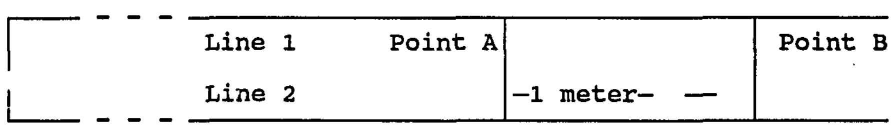


Figure 6-2 Explanation of Wave Propagation Time Delay.

If the two lines touch each other at point A, ($V_{a1}=V_{b1}$) at time t=0, it would take some time to detect the line to line fault at point B ($V_{a2}=V_{b2}$). Assuming that the wave propagates with the speed of light on a copper wire, 3×10^8 meter/second, -actual wave propagation on a copper wire is much slower- then it would take approximately -t= 1(meter) / 3×10^8(meter/second) = 3.33×10^{-9} seconds- 3.5 nanoseconds to detect the fault at point B. By using a fast clock, such as DM74S03, TTL[44], where the propagation delay time is listed as Min=2ns, Typ=3ns, Max=4.5ns, a line to line error can be detected within a distance of 1 meter. Considering A) ECL gates are much faster than TTL gates, B) this data is from 1976, compared to 1990, line to line fault locations can be easily and accurately detected.

2. AUTOMATIC THROW-OVER SWITCH IMPLEMENTATION

Due to survivability of a navy ship, it is important to keep the maximum number of branches alive. This could be further accomplished on a power system by connecting one branch, skipping one bus line and connecting it to the next lower bus line, if necessary by using a transformer as shown in figure 6-3. If a fault occurs on a skipped line, and due to a fault the new design disconnects that particular branch, then with the use of this system, the lower level branches can be energized by the use of a secondary wiring as shown in figure 6-3. In our power system, the programmable logic controller must be accordingly programmed to accommodate and respond for this convenience. In today's power distribution systems this is accomplished by the use of an automatic throw-over switch.

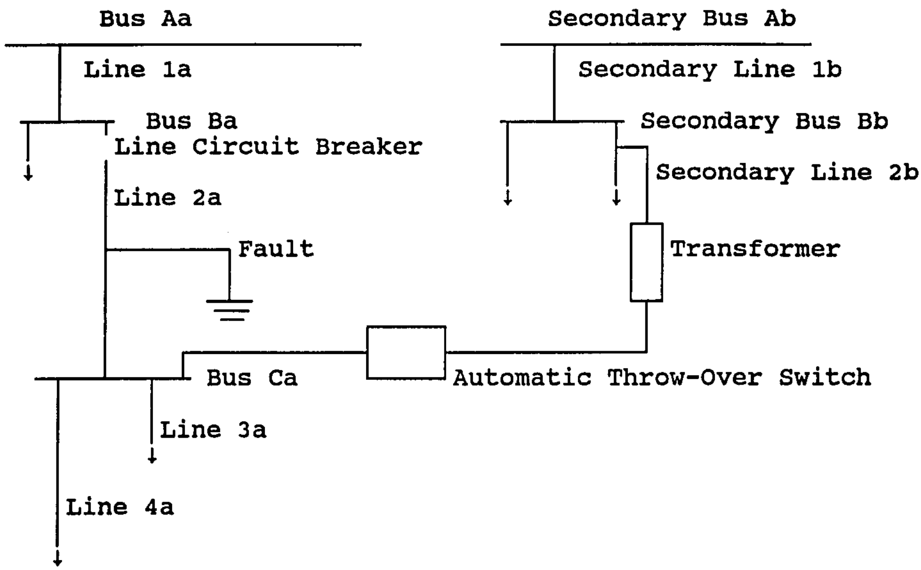


Figure 6-3 Implementation of Automatic Throw-Over Switch.

SUMMARY AND CONCLUSIONS

This thesis demonstrates a reliable, fast acting knowledge based design for early detection of disturbances on power distribution systems. This design is proved to be capable for discrimination, coordination and isolation of faults for all major cases of failures from power distribution systems. The basic idea of the design is applicable to all power distribution systems with any configuration provided that the controller program can be modified to suit the distribution system.

The basic parts of the design is built in the laboratory to prove the proper functioning of the system. Building the design concept did prove some real life difficulties, such as noise in the system which was overcome with the use of simple low pass filters. Thus, small deviations from the theory should be expected for real life applications. Overall, the design concept does prove to work under real life conditions, and it does function as the theory predicted.

There is more room for improvements on the thesis idea, as mentioned on the recommendations section of the thesis. Some of these improvements may be luxury for some distribution systems and a necessity for others, such as the navy vessels under attack where their survivability may solely depend on the optimum proper functioning of their power systems.

As the author, the originator of this system and idea, it would be my dream to see such or even better systems to be used regularly on our power distribution systems.

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