46-A

Digital Computer Aided Protection and Automation

46.1. INTRODUCTION TO POWER SYSTEM CONTROL AND OPERATION

Consider the basic variables related with electrical energy :

(*i*) current (*ii*) voltage
(*iii*) frequency (*iv*) power factor, real power, reactive power
(*v*) time.

The energy is generated (infact converted from other forms), transmitted, distributed and finally utilised (in fact converted to some other form such as heat, mechanical drive). At every stage, certain supervision, control and protection are necessary (Fig. 46.1). Until recently (1960's) the system control was carried out exclusively by analogue or digital equipment with fixed wiring. Some functions were automatic (*e.g.* voltage regulation, system protection) and some functions were by more manual interaction between man (supervisor) and machines (equipment). In a small independent generating station, the supervision and co-ordination of various parts can be carried out by the operator with the aid of analogue and digital control systems for the plant. For a large interconnected power system, task of supervisions, operation, co-ordination, control and protection become very complex and the traditional equipment requiring operators skill and judgement are not adequate.

During recent years several new types of process control equipment have come in market. These include : digital computers (large, mini and micro), micro-processors, static control devices, static protective relays. Even the most complex tasks which could not be carried out efficiently by the traditional equipment can be easily performed with the aid of these recently developed (1960-70's) equipment.

During last few years (1970's) programme packages have been developed or carrying out the various duties related with supervision, control and protection. This software enables several functions to be performed automatically from a central system control centre. Extensive monitoring of network operations, load dispatching, load and frequency control (Ch. 45), load shedding (Ch. 45), optimum loading of various plants, remote back-up protection etc. are possible from a Central Grid Control Centres. Whereas many functions should be decentralised and carried out from zonal control centres and control rooms of individual plants. Table 46.1 states the main tasks of control centres at different levels.

* Voltage control is achieved by means of (1) Excitation control (2) Tap-changing (3) Shunt compensation, (4) Series compensation. It is applied in generating stations, sub-stations and near load points. Centralised voltage control of Grid is not possible. Refer Ch. 45-B. Ref. Ch 49 and Ch 50.

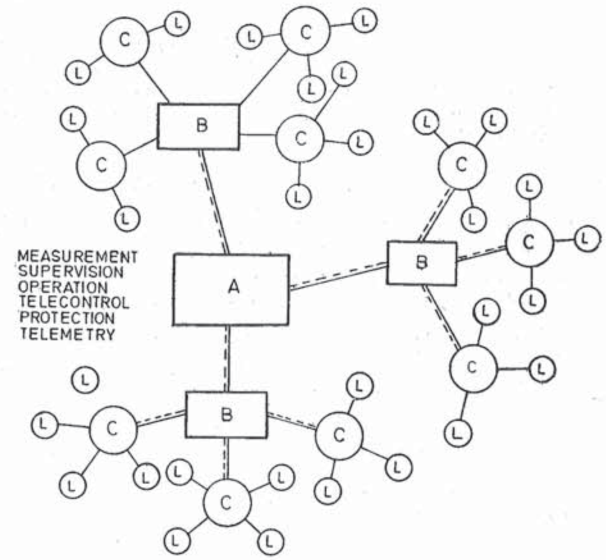


Fig. 46.1. Complex functions of measurement, supervision, operation, control, protection, communication need the team work-of.

Measurement — Telemetry — Switchgear and Power System
Protection — Power System Control Devices aided by Digital Computers
A = Master Control (Grid control) centre ; *B* = Regional Control centre
C = Power Plants ; *L* = Loads.

To assist the work in the control centres, certain functions are automated with the aid of computer based (or microprocessor based) control systems. Such a *Supervisory Control And Data Acquisition system* is intended to facilitate the work the operator (dispatcher) by acquiring and compiling information as well as locating, identifying and reporting faults. On the basis of the information received, the operator makes the necessary decisions *via* the control system he can then perform different control operations in power stations or influence the processing of the information acquired. (Refer Ch. 50 SCADA and AGC system).

The size and topography of the power system as well as the emphasis on generation, transmission or distribution influence the functions which are to be automated in a particular control centre. Finally, the scope is determined by the organisation and policies of the electricity boards.

Different electricity boards impose rather, different demands on their control systems. However, it is quite clear that there is a trend to include more and more planning and following up functions. There is always a need to perform such functions regularly and accurately. Developments have now reached such a stage in the areas of powerful minicomputers, microprocessors, mathematical models and real time programming methods that automation of these functions are possible.

Load Dispatching. Large power system comprise several power stations, load centres, interconnected to form a single grid. The operations of such grid can be controlled from a centralized 'load control centre' or 'load dispatch centre'. The central load control centre is linked with various local dispatching stations, each of which covers certain area the operations concerned with a particular area, which do not affect. The system performance are carried out by persons in the local dispatching stations. The operations concerned with the system, and no limited to a particular area are performed from central load dispatch centre. The central load dispatcher takes decisions about loading of large stations, loading of interconnected lines, etc. Supervisory control is a method of controlling and supervising from a central point, the operations of equipment at one or more remote locations. Carrier signals are used for remote control. Relay settings need a change with major changes in load flow. Refer Ch. 46-*B*.

46.2. TERMS RELATED WITH COMPUTERS AND MICROPROCESSORS

1. Access time. Times interval between the instant at which information is called from storage and the instant at which delivery is completed (read time).

2. **Accumulators.** Parallel storage registers for work-in-process. Some are available for application while some are built-in for internal use within the processor.

3. **Adaptive control system.** A system able to tune itself with a changing environment.

4. **Address.** Lable name or number that designates a register or memory location, generally refers to the number that designates the memory.

5. **Algorithm.** A finite set of well defined rules for the solution of a problem in a finite number of steps. Fixed step-by-step procedure for accomplishing a required result.

Table 46.1. Main tasks of control centre at different levels

Level	*Planning*	*Operation*	*Following up*
National Grid Control Centre	Load prediction and generation schedules, power balance planning co-ordination of overhauls, planning of reverses	Supervision of load generation, power exchange reserves, transmission networks, Tile-line loading and exchange	Reporting and accounting, statics, following up of efficiency, fault analysis
Zonal control centre	Load prediction and generation schedules, power balance planning, coordination of over-hauls, planning reserves	Supervision of load generation, power exchange, reserves, transmission networks	Reporting and accounting, static, following up of efficiency, fault analysis
District control centre	Short-term according to directives	Supervision of load, generation, and power exchange supervision of different components in power system, operation and control of underlying power station and sub-stations	Load generation and water flow reports, accounting data statistics
Power station, substation Control Room	Work planning	Control of power, level, etc., sequential Start/Stop functions, automatic system restoration, protective functions, supervision of process variables.	Sequential events recording

* Courtesy : ASEA, Sweden

** All India National Grid will have five zonal load control centres : Northern zone, Western zone, Eastern zone, Southern zone and Central zone. The National Grid Control Centre will be near Delhi.

Table 46.2. Main Functions of Supervisory Control and Data Acquisition Systems (SCADA)

Operation Supervision	Data acquisition and presentation of quantities such as power, voltage current, temperature, water level as well as fault signals and breaker position.
	Monitoring of limit values. Acquisition of metered energy values. Following up of power balance with interconnected utilities and between own regions. Following up of production and load within different regions. Calculation of spinning reserves.
	The monitoring of limit values can be carried out as function of time and ambient temperature network modelling. Filtering of measured values. Calculation of non-measured values and transmission losses. Contigency analysis of the consequences of disconnection of a lines of generating set. Short-circuit calculations.
Operational Control	Start/Stop of generating sets. On/Off operation of breakers and disconnectors. Hand/Auto for local automation equipment. Increase/Decrease of set-point control for power generation voltages gate positions.
Planning (Time horizon < 1 week)	Power balance planning with operation schedules. Load prediction, Economic production, distribution between generating sets, Planning of power exchange (Purchase-Sales-analysis). Simulation operation schedules with respect to load distribution, economic production distribution and security.
Following up	Daily, weekly and monthly logs for generation, load power exchange and power flow. Even reports in power systems and control centre. Hydrological following up through calculation of head losses, heads, water flow and spillage Statistics. Compilation (calculation) of transmission losses.

6. **Assembly language.** Operator's (source) language composed of brief expressions, usually uneconomic form, it is translated into machine language by *Assembler*.

7. **Autonomous.** Independent.

8. **Architecture.** Preset, physical and logical arrangement of a computer; it determines how a computer operates.

9. **Binary.** Numbering system represented by two digits 0 and 1.

10. **Bipolar.** Most popular fundamental kind of integrated circuit (IC).

11. **Bit.** Abbreviation for binary digit, the fundamental unit of information.

12. **Bootstrap.** Short sequence of instructions, which when executed by the computer, will operate a device to automatically load the programmable memory with a large programme.

13. **Branch.** To depart from normal sequence of executing programme instructions, done by one or more branching instructions in the programme.

14. **Buffer.** Device which stores information temporarily during data transfer.

15. **Bus.** Channel along which the data is sent. Often refers to physical connections as contrast to channel of logical path.

16. **Byte.** Sequence of binary digits usually operated as a unit. A byte is commonly 8 bits long.

17. **CMOS.** Complementary MOS and refers to combination of P-channel and N-channel transistors. CMOS is faster than MOS but consume lesser power.

18. **Computer.** (Digital) a device which can perform substantial computations including numerous arithmetic, logical operations without interventions of human operator during the run. It needs a stores programme.

19. **Computer system.** A system comprising *software* system (programmes) and hardware system (computer, memories etc.)

20. **Core memory.** A magnetic storage in which data are stored by elective polarisation of magnetic cores.

* *Courtesy* : ASEA, Sweden. Ref. Ch. 49 and Ch. 50.

21. **CPU (Central Processing Unit).** A portion of computer that includes three main sections Arithmetic, Control, Logic elements. It directs functions such as I/O.

22. **CRT.** Cathode Ray Tube.

23. **Channel.** Path along which electrical signals can travel. That portion of computer memory to which particular output station has access.

24. **Code.** To prepare a set of computer instructions.

25. **Compiler.** Built-in system that permits the compute to generate its own machine readable (object) programme from the programmers instructions written in one or several languages more easily understood by human.

26. **Compiler language.** Computer language more humanly readable than assembly language, which instruct the compiler to translate the source language into machine language.

27. **Control Unit.** Portion of a computer that directs the operation of computer, interprets computer instructions and initiates proper signals to other computer circuits to execute instructions.

28. **Counter.** Device or location which can be set to an initial number and increased or decreased by a number.

29. **Clock.** Device contained within computer which times events or keeps events co-ordinated.

30. **CROM.** Control read only memory a ROM which has been microprogrammed to decode control logic.

31. **Cycle.** Sequence of operation that respects regularly.

32. **Data.** Information, facts.

33. **Data processing.** The recording and handling of data (information) by means of electrical, electronic equipment.

34. **Data logger.** The equipment which makes a 'log' (record) of the reading of instruments.

35. **Digitise.** To convert an analogue form to digital form.

36. **Discrete.** Pertaining to distinct electronic elements (resistors, transistors, capacitors etc.)

37. **Dual computer system.** A computer system containing two computers where one computer is generally a back-up for the other.

38. **Driver.** Small programme which controls peripheral devices and their interface with the central processor.

39. **Executive control programme.** Main system programme designed to establish priorities and to process and control other programmes. Also called Monitor.

40. **FETCH.** To bring a portion of main memory - in case of microprocessor, the instruction resister-for execution.

41. **FORTRAN.** A specific problem oriented language for numerical computation by digital computer.

42. **Hardware.** Mechanical, magnetic, electrical and electronic devices which make the computer.

43. **Firmware.** Programmed loaded in read Only Memory (ROM or PROM). Firmware is often fundamental part of the system, system, hardware design, as contrasted to software, which is not fundamental to hardware operation.

44. **Hardwired.** Physically connected.

45. **Hexadecimal.** Number notation in the base 16.

46. **IC.** Integrated circuit.

47. **Index.** Integer uses to specify the location of information with a table or a programme.

48. **Instructions.** Set of bits cause computer to perform certain prescribed operations.

49. **I/O.** Input-output.

50. **Interface.** Refers to machining or interconnecting of system or devices having different functions.

51. **Loader.** Programme that operates to input devices to transfer information from off-line memory or storage to on-line memory.

52. **MOS.** Metal oxide semiconductor. MOS circuits have higher component densities.

53. **Machine language.** Language that can be understood by the computer without need of translation.

54. **MNEMONIC CODE.** Group of symbols that can be easily understood by humans, *e.g.*, MPY means multiply.

55. **Main memory.** Programme addressable storage from which instructions and other data can be loaded directly into registers for subsequent execution.

56. **PLA.** Programmable logic array. It uses a standard logic network programmed to perform a specific function.

57. **PROM.** Programmable read only memory, a type of can be programmed after it is packaged.

58. **Programme.** Sequential instructions that direct the computer to perform a specific task.

59. **RAM.** Random access memory, generally understood to mean memory with both read and write capability and in which the location can be accessed in any (random) sequence.

60. **ROM.** Read only memory, a memory which cannot be erased and reprogrammed.

61. **Real Time.** Actual time during which physical process transpires (outside the computer). It pertains to processing the data by a computer in connection with another process outside the computer, according to time requirements imposed by outside process and requiring immediate utility and the immediate access to the data relevant to the process.

62. **Sampling.** The process of obtaining a sequence of values at regular or irregular intervals.

63. **Scanning.** To examine in sequence to check automatically (the values or states) with scanning devices that may then act upon the information so received.

64. **Software.** Programmes or routines and supporting documents.

65. **Software systems.** Collective name for all programmes in a specific computer system.

66. **Subroutine.** Series of computer instructions which perform a specific task apart from main routine.

67. **Throughput.** Speed with which problems are performed.

68. **TTL.** Transistor-Transistor logic.

69. **Word.** Set of bits comprising smallest addressable unit of information in memory.

70. **Word length.** Number of bits in a word.

46.3. SUPERVISORY CONTROL AND DATA ACQUISITION SYSTEM FOR POWER-SYSTEM OPERATION AND CONTROL

This includes :

— data collection equipment
— data transmission telemetric equipment
— data monitoring equipment
— man/machine interface.

Table 46.3. Data Regarding Generating Units

System data	*Units*	*Input form*			*Input internal and/or check interval*
		Remote control	*Programme*	*Manual*	
Operating condition (on/off, load frequency control)	0/1			×	during variation
Based load	MW		×		2 min
Based load				×	If no connected to ELD*
Gradient of power	MW/min		×		20 sec
Power set point	MW		×		20 sec
Active power	MW	×			20 sec
Reactive power	MVA	×			20 sec
Minimum active power	MW		×		1 hr, 4 hr
Generated voltage	kV	×			20 sec if selected
Emergency generated	MWh		×		1 hr, 0.5 hr, 5 min
Power generated	MW				1 min (with integration)
Breaker condition	0/1	×			If changed
Isolator position	0/1	×			If changed
Protection signal	0/1	×			On occurrence
Alarm signals from auxiliaries	0/1	×			On occurrence
Limiting value of MW, MVAr, MW/min				×	1 min, 1 min, 20 sec

** Courtesy : Brown Boveri, Switzerland.
* ELD : Economic load dispatcher

The data (information) regarding various power-system variables is necessary for effective supervision, operation and control. This data can be broadly classified as :

— data regarding generating plants and power station
— data regarding transmission stations (sub-stations)
— data regarding conditions of supply region, receiving stations.

(Refer Table 46.3, 46.4, 46.5) (Ref. Ch. 50)

Table 46.4. Power Station Data**

System data	*Units*	*Input form*			*Input internal and/or check interval*
		Remote control	*Programme*	*Manual*	
Power set point	MW		×		1 min
Spinning reserve (target)	MW			×	1 min
Spinning reserve (actual)	MW		×		1 min
Voltage at main bus	kV	×			1 min
Voltage at aux bus	kV	×			20 sec
Ambient temperature	°C				1 hr
Fuel consumption	100 kg	×			1 hr
Water level	cm	×			1 hr
Volume flow	m^3	×			1 hr
Output	MWhr	×			1 hr
Limiting value of voltage at busbar	kV	×			1 min

** *Courtesy* : Brown Boveri, Switzerland.

46.4. DATA COLLECTION EQUIPMENT, DATA LOGGERS (Refer sec. 46.2 - 34)

This collects the primary data from the data sources and converts it into suitable form for information transmitting and processing.

For successful operation of any plant, it is necessary to record (*log*) the readings of variables from different locations in the plant. This is done automatically by *Data Logger.*

In addition to presenting data for a large number of points at regular intervals of time, the data can be *scanned* and recorded very quickly under fault condition by automatic initiation.

Data logger can be designed for plant performance computation for logical analysis of alarm conditions, thus minimising the possible confusion during emergency.

The intervals of readings (scanning) can be selected by setting of a dial of a push button on the data logger.

The basic parts of a data logger and interface are shown in Fig. 46.2. The input scanner is an automatic sequence switch which selects each signal in turn. Transducers are used to convert original variable to suitable electrical form for the input scanner. The signal amplifies low level signals (say 10 mV) to higher level (say 5 V). *The analogue signals are converted into digital signals.* The programmer is used to control the sequence operations of the logger.

Table 46.5. Transformer Station Data**

Data system	*Units*	*Input forms*			*Input Interval and/or check interval*
		Remote control	*Programme*	*Manual*	
Load on line					
Active power	MW	*			20 sec
Reactive power	MVAr	*			20 sec
Apparent power	MVA				1 min if required
Load at transformers					
Active power	MW	*			20 sec
Reactive power	MVAr	*			20 sec
Apparent power	MVA				20 sec
Limiting values of					
Min. bus bar voltage	kV			*	1 min
Max. load at transformer	MVA			*	1 min
Max. load at station	MVA			*	1 min
Voltage at main bus	kV	*			20 sec
Voltage at aux. bus	kV	*			20 sec if required
Temp. at windings	°C	*			15 min
Ambient temperature	°C	*			If changed
Breaker condition	0/1	*			If changed
Isolator condition	0/1	*			If changed
Protection signal	0/1	*			If occurs

**Courtesy : Brown Boveri, Switzerland.

The signals are fed to the input interface of the input scanner. The input scanner selects each signal in turn. The rate of scanning has to match with the requirements (Refer Tables 46.3, 4.5). Mixed scan rates are generally preferred.

The data logger supplies the digitized data to microprocessor.

Scanning and Indication. The automatic control necessitates a series of scans and checks at regular intervals which provide indication whether and when appropriate action can be initiated. For example consider change in power supplied to a mesh point. An initial indication should be obtained as to how large the change in power must be counteract the overload (drop in frequency). The scanning gives the necessary data regarding the value of various input variables. The decision regarding the follow up action (change in input in this case) can be taken according to the programmes. The logic operations and computations can be performed rapidly by on line microcomputer.

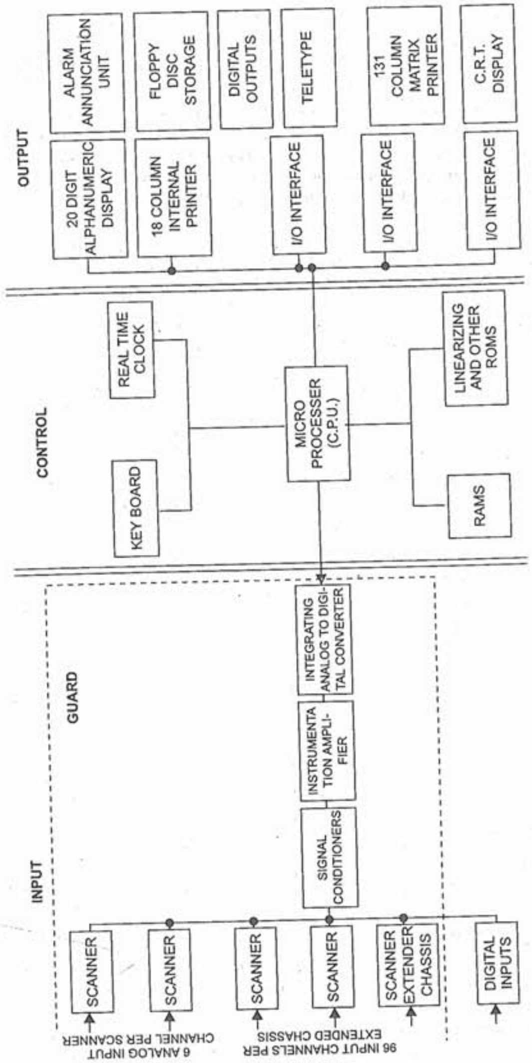


Fig. 46.2. Data logger with interface.

Based on the results of computer calculations, the decision can be taken about follow-up action (say switching of a remote distribution line to reduce load or opening of a faulty line).

CRT Display. (Refer Sec. 46.2-22) (Ref. Ch. 50)

The operator in the control room needs information regarding parameters and network configurations. CRT display provides the operator with these informations whenever he wants. (When he processes an appropriate button on control desk) two types of displays include :

— Tabulated values of parameters, measured values and computed characteristic.

— Symbolic representation of equipment status usually in form of mimic diagrams of sub-stations or synoptic displays of parts of network.

Alarm System. Alarm can be divided into group according to the nature of their occurrence. The first group comprises signals regarding abnormal (generally undesirable) conditions in the network which are detected at the place they occur and are passed to the central control room *via* the *telemetry system.* These are alarms in the conventional sense.

Another group of alarms is initiated by computer programmes when some computed quantity exceeds the present limit. These can be quite complex parameters. Registering alarms of this kind provides valuable supplementary information, but it is not possible to get and process such information without the aid of computers. As digital computer/microprocessors are able to respond very fast, there is a danger of overwhelming the operator with certain transient alarms. Therefore, he must have the facility for suppressing short-lived but repetitive transient alarms for a set period (about 30 sec) and then have them brought to his attention only if they are still present after this interval.

46.5. DATA TRANSMISSION EQUIPMENT (TELEMETRY)

Tele means remote. Telemetry refers to the science of measurement from a remote location. Telecontrol refers to remote control of equipment. Telemetering and telecontrol equipment necessary for control of a power plan from the control centre. The telemetering system comprises electronic equipment which converts the data received from transducers into analogue or digital signals and transmits it to the control room for the use of computers.

(Telemetering systems have been used with space-craft which sends data to earth control station).

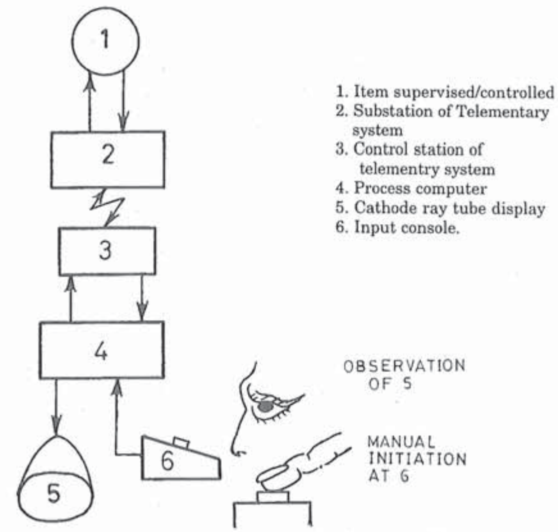


Fig. 46.3. Telemetry for supervisions and controls.

The instructions from control centre should be sent to the remote power stations for necessary action. This two-way interaction is illustrated in Figs. 46.3 and 46.4.

Method of Data Transmission. Different types of data transmission system can be used depending upon the network conditions and requirements. These include :

(*a*) Use of telephone lines (cables)

(*b*) Use of separate cables

(c) Power line carrier (PLC) ;

(d) Radio wave (microwave) channels.

For large systems power line carrier (PLC) is used for data transmission. (Ref. Ch. 30).

The choice of telecontrol equipment depends upon the following :

— kind of information to be transmitted.

— quantity of information to be transmitted, rate of increase.

— available transmission channels, lines.

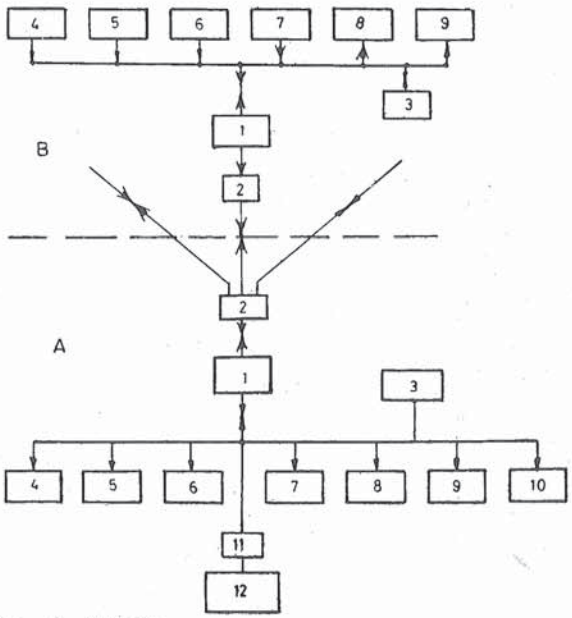
— degree of security demanded against error or loss of information.

The kind of *Traffic* means how the information is transmitted communication systems. It is necessary to send different data. It should be possible to distinguish between the data received.

It is a general practice in communication system to distinguish between lines and networks.

Line traffic is characterized by the fact that the transmission of information between two points is able to take place without having to pay any attention or transmission from other stations using other channels of the same system.

Network traffic, on the other hand, enables information to be transmitted between two or more stations of the network but the transmission is dependent on information being transmitted by



A = Master Station B = Outstation
1. Logic 2. Transmitter 3. Test Unit 4. Measured value (analogue)
5. Data and incremental input/output 6. Meter readings 7. Signal
8. Command output for *A*, input for *B* 9. Setting (analogue and digital)
10. Digital Display (for measured values and matter readings)
11. Computer adapter 12. Computer.

Fig. 46.4. Arrangement of Telecontrol of power system.
Courtesy : Brown Boveri, Switzerland.

other channel of system. The difference is not in the geographical location of the stations nor the properties of the transmission channel.

Point-to-point Traffic. Simple line traffic between two stations.

Simplex Traffic. Traffic in one direction at a time.

Duplex Traffic. Traffic in both directions at the same time.

Multiplex Traffic. Several data transmitted at the same time in both directions between different stations.

Time-division Multiplex. Traffic staggered in time.

One way line traffic is typical of telemetering. In complex, two-way networks, depending upon the quantity of information to be transmitted and the specified transmission time, the signals are transmitted either one-way line traffic or staggered one way traffic.

A typical *one-way telemetering equipment* employs continuous, analogue transmission of measured value. It operates on frequency shift principle. The frequency range of 1500-3300 Hz is used with the bandwidth of 60 Hz at a spacing of 120 Hz. Its short time constant is 0.2 sec, and makes it suitable for transmission of measurement signals and positional signals for control devices (*e.g.* Load-frequency control Ch. 45). (Refer Fig. 46.6).

A typical two-way telemetering equipment employs two one-way equipments, one command channel for direction and the other feedback channel for one transmitting the measured value. A frequency range of 420-3300 Hz may be used. (Refer Table 46.6).

Equipment for *Radial Traffic* enables Telemetering, remote indication remote control and data transmission (Fig. 46.4). A central station serves either one out-station in semi-duplex traffic (with arbitrary division of the information capacity). In the command direction, commands sustained commands and general commands can be transmitted to all out-stations in the independent signalling directions, status indications, plus indications and measured values.

A central logic system in each stations controls various functional units. The master station controls the flow of information by cascaded scanning cycles for signals and data.

The telemetering equipment is used in conjunction with process control computer. The computer with its peripherals performs various tasks.

46.6. APPLICATIONS OF POWER LINE CARRIER

Power line carrier equipment (described in Chapter 30) is used for the following applications :

— *Carrier Communication*

The person in power stations and receiving stations can communicate with each other by using this facility.

— *Carrier Protective Relaying. (Ch. 30)*

— *Carrier Telemetering*

Telemetering is the indicating or recording of quantities at a location remote from the point. The quantities telemetered on power systems are electrical quantities like kilowatts, kilovars, voltage, tap-changer position, circuit breaker position, and many other quantities. In carrier telemetry by impulse-rate system, frequency or rate of pulses varies according to the magnitude of telemetered quantity. In impulse-duration system the duration impulses is proportional to the magnitude of the telemetered quantity. The pulse telemetering system is telemetered by suitable for carrier channels.

— *Load Control and Frequency Control*

Load-frequency control is the control of outputs of group of generators on the system in such a way as to maintain the system frequency and regulate the interchange of power between parts of the system according to a predetermined plan. The carrier signals are used for load and frequency control in a similar way to telemetering of two quantities. The two types of impulses to be transmitted one for increase in power and the other for decrease.

— *Carrier supervisory control*

Controlling the operations of the equipment from a central location.

Table 46.6. Technical Data Regarding Some Telecontrol System

Type of designs	*Electrical with discrete components or IC*
Tasks	Telemetering (Analogue) Telemetering (Digital) Positioning signals for Load-frequency control Remote control Indication (Digital) Protection Remote back-up
System capacity	Number of outstations : 1/1 — 10/1 — 16 Number Control Commands : 1 — 25 Number of pulse commands : 25/100/180 Number of signals : 25/2500/1000/3000 Number of measured values : 20/0/300
Data Transmission Features	Method — Frequency Multiplex — Time div. Multiplies Kind — Point to point — Single Direction, staggered Frequency Range : — 1500 — 3000 Hz — 400 — 3000 Hz — 30 — 500 kHz Transmission Medium : — Cable/Power Line Carrier Time of Measured value : Continuous/9.00s/4.5 s/cycle

46.7. MAN-MACHINE INTERFACE

The data monitoring and processing system (scanners, data loggers, microprocessor, display, permit statistical processing, control regulation and optimization). The data processing equipment are based on either of fixed type of adaptive models.

The interaction between man and machine is illustrated in Fig. 46.3. The facilities of display of process condition through (5) CRT enables the operator to initiate manual instructions (*P*).

Many large systems need a process computer to perform the multifarious tasks which are very difficult for human.

46.8. APPLICATION OF COMPUTERS IN NETWORK AUTOMATION

In traditional equipment for network automation, equipment such as teleoperation, load frequency controllers, protection equipment etc. are fixed-wire type. The nature of the equipment is determined by the fixed wiring. Consequently, the flexibility of the operation is restricted. It is possible for this equipment to be provided with programming units or setting potentiometers to facilitate matching to the given applications.

Process computers are freely programmable and are capable of carrying out the tasks of the fixed wired equipment. The process computer can be adapted to a given problem without involving design modification on the hardware. It would be, therefore, an ideal instrument for solving various problems. The computer may be classified in three groups :

— equipment computers

— freely programmable process computers

— process computers with developed programme packages.

'Equipment' Computers. When the process computer takes the place of fixed-wire equipment, it stimulates central functions. The readily developed programmes are available and may take form of ROM's (Refer Sec. 46.2/60).

Process Computers for Free Programming. Where the process computers are used as units for free programming, the initial computer software can be based on the final application. Basic software packages are available with assembling, compiler, operating and debugging systems and other programmes for communication between the central unit and peripheral.

Process Computers with Predeveloped Programme Packages. General programmes for network automation have been developed and are generally available in the form of software packages as a marketed product. Such packages include automatic generator controls, load-frequency regulation, real time load flow programme.

The software system is divided into modules which perform different tasks. Certain system modules perform basic functions such as process communication, man machine communication, data base management, alarm and event processing.

Large digital computers may not be necessary for performing specific tasks of power protection and control. These specific tasks may be performed more economically and conveniently by microprocessor based minicomputer. Though these applications are very recent, they gaining rapid popularity and are likely to change the art of power-system protection and control with increasing use of digital techniques.

Super, Mini, Micro Computing Machines. Various manufacturers of computers, computer systems, research workers etc., use new terminologies in the field of computers. As a result many words like super computer, large computer, minicomputer, microcomputer, parallel processor, array process etc. are introduced. Firstly the words large, super, mini and micro describe the size and capacity of computers.

The characteristic of any computing machine is its floating point word length. The word length determines the precision by which the number can be represented and is fixed for a given machine, *e.g.* a 32 bit single precision floating point world may be adequate for simpler computing techniques.

Super-computer class has arithmetic unit in which arithmetic functions can be broken down into number of segments (*e.g.,* fetch normalize, add, etc.). This process is known as pipelining. Super-computers have multiple pipes which operate in parallel and assist in achieving high rate of computing speeds. Supercomputers are costlier (50 to 150 million rupees - 1978).

Array processor carry out high speed signal processing. These machines have low or no pipelining. They achieve their high speed by use of efficient use of parallel arithmetic elements and memory.

Parallel processor type computing machines contain several processors which operate on multiple instructions multiple data mode MDM. The parallel processing means ability to achieve higher computation rates in a computer by dividing arithmetical work among several distinct arithmetic processors are in experimental stage.

Micro-computer and minicomputers generally are of smaller physical size, hence the names. Their computing capability may not be limited by size. Basically, microcomputers is classified by the number of binary digits (bits) it can handle at one time. The smallest and cheapest microcomputer system can handle 4-bit block (words). Eight bit micro-computers are most popular for general control applications. Sixteen and 32 bit micro-processor may be suitable for simple programmes.

Micro-computers based on microprocessor system are of almost half price than minicomputers, require less power (fraction of a watt).

46.9. MICROPROCESSORS

One of the most recent (1980) advances in solid-state technology which is gaining rapid popularity in power system protection and control is the microprocessor.

A microprocessor has one or more semiconductor chips (IC's) containing several transistors and other solid state components. The device is programmable and functions similar to the central processing unit (CPU) of a computer in that it performs both arithmetical and logic functions. The CPU in the microprocessor system is called microprocessor.

Adding memory and interface circuitry for connections to external devices converts the microprocessor to a microcomputer. Two types of memory can be used. Read only memory (ROM) has a fixed content and contains the operating programme of the microcomputer. A programmable read-only memory (PROM) can be programmed in the field.

The second type of memory used with microprocessor is Random- Access Memory (RAM). RAM's are generally used to store continually changing data used by the microcomputer. Frequently changing programs can also be stored by RAM.

When a microprocessor system requires clocks, control logic, interface buffers to sensors, actuators, displays and data terminals trade-offs must be examined between using microprocessors and hard-wave (random) logic. As thumb-rule, when a digital system requires 50 or more hard wired logic IC's, a microprocessor should be considered.

Microprocessors are now being used in controllers for generating station, power system, control systems, protective relaying systems.

Microprocessors is based on the technology which allows many elements on a single chip with low energy consumption. This leads to the microprocessor having low cost but a slower speed and shorter word length than its big brother minicomputer.

A complete microprocessor system (called microprocessor or μP for convenience) was also called microcomputer earlier. It consists of :

— central processing unit (CPU) microprocessor
— random access memory (RAM)
— read only memory (ROM)
— input/output parts (I/O).

The ROM serves as a bank or a store-house of instructions to control the operations of CPU.

The instructions stored sequentially in ROM are referred as programme. The RAM serves as a data bank I/O parts give the device communication with the outside world.

As mentioned earlier, a microprocessor contains several diodes, transistors, flip-flops etc. on a single or several chips. These logic elements are grouped into various functional blocks, each having a specific capability. The basic blocks re-memory, Arithmetic Logic Unit (ALU), input/output (I/O) and control section.

Memory. The programme that a microprocessor executes is stored in read only memory (ROM). Other parts of the systems can read information held by this memory, but the information can be further removed nor replaced. A separate memory is used both accepting information for storage and for transmitting information to other digital circuits. Thus it is called read-write or random-access memory (RAM). And because this type of memory is handy for temporary storage during the manipulation of digital data, it is also called Scratch-pad memory.

Arithmetic Logic Unit (ALU). The section contains decisions making elements of the microprocessor, such as AND, OR, NOR, NAND, exclusive OR. The ALU also has digital circuits which can perform addition, subtraction, multiplication and division of binary numbers.

Input/output Circuits. A microprocessor communicates with external devices through arrays of flip-flops called registers. Input registers receive logic signals from limit switches, thumb wheel switches, relay contacts or any TTL compatible device and store them until the microprocessor is ready to receive them output register operates in reverse.

Control Section. The various building blocks of microprocessor are connected together by common set of lines called data bus. The control section contains timing circuits that synchronise. The starting and stopping of data flow between building blocks. The entire system is kept in-step by a pulse generating clock.

A microprocessor is similar to central processing unit (CPU) of a computer in that it manipulates digital information by interpreting and executing coded program instructions. Alone, however, a microprocessor (CPU) cannot be anything. It needs interface devices to link, it to the outside world.

Besides power supply for operating power, a microprocessor needs. Switches for human inputs, digital to analogue converters to energize read out devices, and relays to convert logic signals to electrical signals.

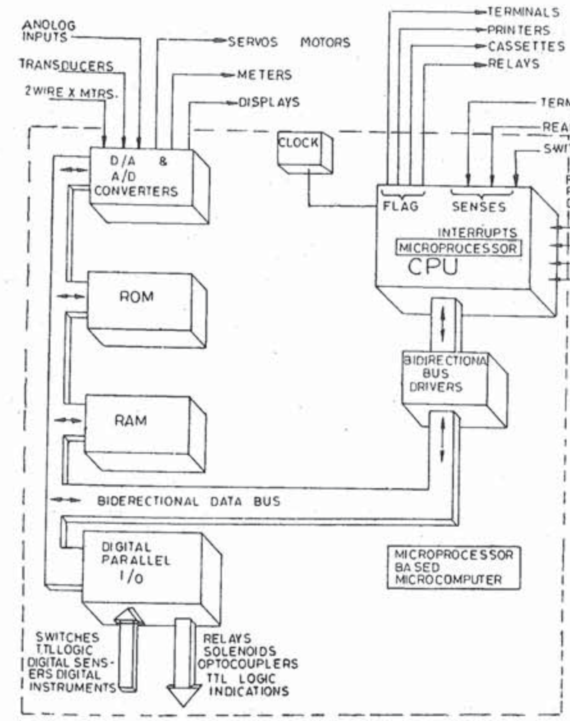
When a *microprocessor* is used as CPU in a system containing the extra memory and the required I/O circuitry, it becomes a *microcomputer.*

46.10. MICRO-PROCESSOR BASED MICRO-COMPUTER

(*Courtesy* : National Semiconductors, USA)

Fig. 46.5 illustrates a typical microprocessor based microcomputer. Microprocessors forms the heart of a sophisticated digital control system. The central processing unit (CPU) contains the logic and arithmetic circuits. There circuits interpret and route incoming instructions from digital peripheral devices such as data readers and switches to appropriate data- processing station in the micro-computer. Incoming interrupt signals order the computer to stop main programme routines contained in the memory and execute subroutines also contained in the memory.

Information flows between the computer and digital devices such as relays, switches, indicators, sensors and instruments pass through digital Input/Output (I/O) circuits. Information flows be-



CPU = Central Processing Unit RAD = Random Access Memor ROM = Read Only Memory

Fig. 46.5. Simplified Block Diagram of a Microprocessor Based Microcomputer
(*Courtesy* : National Semiconductor)

tween the computer and analogue devices passes through analogue-to-digital and digital to analogue (A/D and D/A) converts.

All this information travels on a common data bus, typical consisting of eight lines for machine control.

To prevent garbling of data, information transfer between building blocks in synchronized by a block.

Thus, basis control-process sequences are contained in memory as digitally coded instructions. The micro-processor turns the controlled process elements (motors, solenoids, valves) on and off through power-module interface devices as per programme stored in memory. As a microprocessor ticks off the basis sequence from its memory, it constantly receives updated data on process status from sensor inputs, and it awaits special instructions from the machine operators *via* panel switches and keyboards.

These inputs are constantly analyzed by microprocessor logic circuits. When these inputs form certain combinations as determined by conditional logic circuits, the microprocessor switches off from main programme to subroutine that alters controlled-process operation, to meet new requirements. Through it all, arithmetic logic circuits make the necessary conversions on incoming numerical data for display on record on external devices. Refer Sec. 43.28 for details.

46.11. APPLICATIONS OF DIGITAL COMPUTER AND MICRO-PROCESSORS IN POWER SYSTEM PROTECTION.

During the recent past there is increasing trend towards use of one line digital computers and micro-processor in power system protection. Many new areas in which conventional protection systems (incorporating individual electromagnetic or state relays) are now being explored for use of digital static relays and protection system based on microprocessors. This trend is likely to grow rapidly as the cost of single chip micro-processor is low.

In classical centralized control, about sixty per cent of operating time of the computer is used for data processing and for reading signals from remote regional load centres. Thus much time is taken by conveying of each data to some distance through telemetric equipment. Thus with large number of power plants and controlled variables the limitation is the time required for data reading and processing. A costly digital computer cannot be effectively utilized for data collecting, data processing and computation purposes. The recent trend is to separate the functions of computer into three hierarchical levels.

Level 1. National load control centre which co-ordinates regional load control centres and is relieved of the direct supervision and data processing of individual plants.

Level 2. Regional control centre controlling several power stations in the region.

Level 3. Control rooms of individual power stations.

The distribution of functions in three levels presents the following advantages :

— higher computation efficiency due to optimum utilization of computer time at every level.

— supervisory programmes of level (3) are simpler and identical for all power plants of similar types. These programmes supervise *more data* than the levels (2) and (3). This ensures better control quality.

— higher reliability due to independence of computing systems.

— lower cost.

The types of computers and microprocessors at three levels can be economically selected. The commercial computers for business purposes have to perform multifarious functions such as accounts, material control, personal data design calculations, management aid. Hence it has more memories and peripherals. Such a computer cannot be economically used for the power system control. The process control computes for the three levels are selected to perform specific functions and

can have only required architecture to suit the functional requirement. Thus several functions can be performed by microprocessor based microcomputer giving economic and operational advantages.

The central functions (level 1) are performed by minicomputer. The regional control function (level 1) are performed by microcomputer. The total control of individual power plants is performed by microcomputer based microcomputers.

46.12. MICROPROCESSOR BASED INVERSE TIME OVERCURRENT (IOT) RELAY

Fig. 46.6 illustrates a schematic diagram of an experimental system. The output of line CT's is given to the signal processing block. The signal processing block containing auxiliary CT's surge suppressors, rectifiers, filters etc. depending upon design. The processed signals are given to A/D converters. The digitized inputs are given to microprocessor. The microprocessor processes the data and determines the condition for tripping the circuit-breaker.

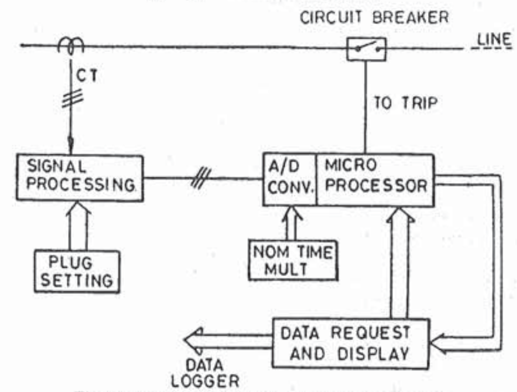


Fig. 46.6. Microprocessor based overcurrent relay.

46.13. DIGITAL COMPUTERS FOR POWER SYSTEM OPERATION

Digital computers (Refer Ch. 27) are taking over several important functions in today power systems. These functions include data acquisition, determining sequence of events monitoring automatic control, voltage regulation, determining, loading on generators, switching of lines, transformers, shunt reactors/capacitors, recording of events etc. This method of using Digital computer for power protection has been outlined in the paper "Fault Protection with a Digital Computer", by G.D. Rockefeller, IEEE Trans, PAS, Vol. 88, April, 1969.

The merits of digital computers in power protection include :

— faster main and back-up protection.

— greater reliability as continuous on line feature (convention relays remain idle till fault occurs)

— economical for large systems, as a single computer performs protection of several equipment. (Refer Sec. 46.12)

Protection of power systems has become to be very much complex. Digital computers will play diverse role in the protection of power system. Computering power system protection in a broad sense, the digital computers will be used for the following purposes :

1. Checking fault levels.
2. Loading of plants to ensure reliable supply and avoid outages.
3. Relaying analysis, setting of trip levels to suit loading conditions.
4. Determine switching sequence.

5. Main protection : Computer will judge whether the system is healthy of faulty. It will give instructions to circuit-breaker.

6. Back up protection and main protection of system element by Digital Computers.

7. Protective relaying management.

46.14. ON LINE DIGITAL COMPUTER FOR PROTECTION OF LINE

In a protection of transmission line by means of digital computer carrier signals are sent over the transmission line. The computer compares the signals cycle by cycle. Each sample is compared with the corresponding sample of the previous cycle. If the values differ in excess of permitted tolerance, the counter of that phase is incremented. The counter decides by means of logic circuits which sub-routine to follow. Thereby the fault is determined in the corresponding sub-routine. Thus in the protection scheme, the disturbance is detected, the fault is classified and trip signal is sent to the corresponding circuit-breaker by the digital computer.

In conventional protective relaying, the following principles are used for sensing the abnormal condition.

— Level detection : Overcurrent, low voltage, low frequency etc.

— Comparison of Magnitudes ; current/current, voltage/current etc.

— Comparison of phase angles.

For use of digital computer, the analogue, data should be converted into digital form. (Refer Definitions, Sec. 46.2).

Consider protective relaying of a power station comprising several equipment such as buses, transforms, circuit-breakers, incoming and outgoing lines. For protective relaying purposes several a.c. quantities (say v_n and i_n voltages and currents are assessed. These are derived from secondaries of CT's and PT's. These quantities are first converted into digital form. Raw a.c. information passes through a.c. signal conditioning to Analogue to Digital Conversion(A/D) sub-system. In A/D unit the information is sampled, converted and under control of the Data Buffer (Scratch Pad Memory or SPM) control circuits and is then transferred to the memory of computer sub-system for processing. The type-writer and programmers console provides facility for logging of desired data by the computers as well as convenient means of executive control, software generation, loading modification, programme check-out.

The Analogue-to-digital conversion unit converts the instantaneous values of a.c. quantities into samples in a sequence with time interval of the order of 0.5 milliseconds. The various sub-routines are called at a definite interval. For example, sub-routines MA (Memory action), CPD (Line current peak determination). VED (Voltage fault detector) are called at an interval of every 0.5 milliseconds, while **TFD** (Transformer Differential Protection) is called at every 32 milliseconds. Depending upon sub-routine, certain method is used for detection of abnormal condition. One of the method which compares current reading with previous computed predictions is illustrated in Fig. 46.7(a) shows current samples yielding predictions. During normal conditions the predictions match with current samples within adaptive limits. The adaptive limit follows variation in load current, up or down. A fault causes an abrupt aberration in the waveform is illustrated in the figure. As a result the predicted sample diverges from corresponding actual sample beyond permissible limit. This difference is used for fault detection.

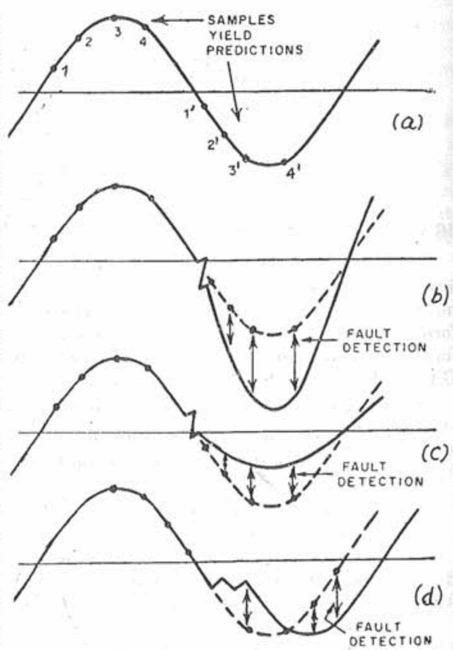


Fig. 46.7. Phase fault detector (PFD) compares reading with previously computed predictions.
Courtesy : Westinghouse Electric Corporation, U.S.A.

Fault Programme of Prodar 70 system is described in Fig. 46.8.

(*Courtesy* : Westinghouse, USA).

The key purpose of the fault programme is the calculation of apparent line impedance for directional distance checking. These calculations require considerable execution time relative to required speed, so the programme can only make them repetitively for one potential/current data pair at a time. There are six pairs to choose from - the three phase-to-ground voltage with corresponding compensated phase currents, and three data voltage with corresponding delta currents. To choose the faulted pair as quickly as possible, it is necessary to being the fault programme with an analysis of symptoms.

Referring to Fig. 46.8, a fault-type analysis (FTA) routine attempts to find characteristic of the fault which can aid processing. It looks for : (a) severe instantaneous overcurrent - this result causes an immediate output to the SL card for fast tripping; (b) low-line to ground or line-to-line voltage, indicating faulted phase(s) for a distance check : (c) high phase and/or residual currents, also indicating faulted phases and type of fault, and (d) voltage phase reversal due to capacitive faults.

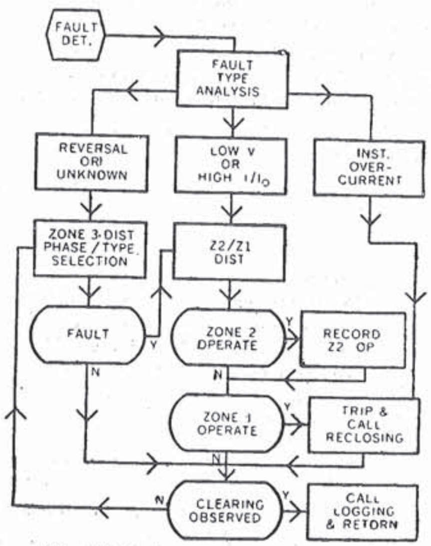


Fig. 46.8. Fault programme, Flow Diagram.
Courtesy : Westinghouse Electric Corporation, USA.

If none of these severe conditions are found or if the result (a), ground distance (Using phase-to-ground voltage and compensated phase current) and phase distance (using data voltage and current) checks are made on all phases, using the zone 3 reach characteristic. For either result (b) or (d) a memory voltage (software generated from prefault data) must be used for current directional is made strictly on the most severely faulted phase(s), with either ground or phase distance logic, using the zone 2 and zone 1 reach characteristics. The location of a fault in zone 2 results in recording of pertinent data for later logging; zone 1 location causes a trip output as well. If memory voltage directional sensing was used in zone 3 check, it is continued for zones 2 and 1.

If the fault-type analysis results in (b) or (c), the logic proceeds directly to a zone 2/1 check on the apparently faulted phase(s), using ground or phase distance as appropriate. In the case of (b), memory voltage is again used, this time to mitigate the effects of the poor signal to-noise ratio which results from severe voltage collapse.

For a distance check, the fault programme finds the apparent impedance from calculated peaks of voltage and current, using integer numerical approximation techniques.

The apparent impedance is subtracted from the magnitude of the reach at the calculated angle. A positive sign on the result indicates, of course, that this impedance is inside the zone. Mathematical integration techniques and repetitive result requirements render the logic secure against noise and transients which may cause error in specific impedance calculations.

After a trip output the reclosing task is initiated. In any case, there follows a fault clearing check. Hence, the computer performs non-directional distance calculations on all phases, using both ground and phase distance logic. If all checks do not confirm clearing of the fault, whether internal or external, after a reasonable period of time, the zone 3 distance check logic is re-entered. If an internal fault was not found during the first instance check, it can be located now. Whatever the result of this second pass, the fault programme again makes the clearing check, with the same action. It two returns to zone 3 distance. Yield no clearing, the fault programme is exited, with the failure to see clearing noted as a breaker failure where tripping was attempted; otherwise, a failure of external relays is recorded.

With prompt fault clearing, the logic will exit after the first clearing check. During the exit, logging tasks are bid for and the data-store-and-process logic are reset for normal operation. A reservation is made for a table of fault clearing data.

Throughout the fault programme are points where sequence-of-events recording takes place. Software events codes, times, involved phase, etc. are stored for logging at a less busy time.

Microprocessor based protective and control systems have proved economical in complex power systems.

QUESTIONS

1. Explain the tasks of Grid Control Centre and its interaction with individual power plants.
2. Describe the functions Telemetry and Telecontrol in operation of a large power system.
3. Explain with the help of neat block diagram the various functions of a Data Logger used in a power plant.
4. Explain the terms in brief :
   (*i*) Data Log (*ii*) Scanning
   (*iii*) Display (*iv*) Data processing
   (*v*) Telemetry
5. Explain the techniques of transmitting the data from Load Control Centre to individual power plants and *vice versa*.
6. Explain the architecture of a microprocessor based microcomputer. State **clearly** the function of
   RAM, ROM, CPU, I/O
   State applications of microprocessor in power system protection.
7. Explain the principle of a digital computer (or microprocessor) aided power system protective scheme.
8. Write detailed notes (any two) :
   — Microprocessor and its application in power system.
   — Automatic control of power system operation and control
   — Data logger
9. Fill in the blanks :
   1. Load-frequency control is achieved by matching ... with the prevailing ....
   2. Frequency of power system depends upon the balance between ... and ....
   3. Voltage control is achieved by means of ...., ..., ...
   4. the total grid is controlled by joint efforts at following levels :
   ......, ..., ...
   5. Digital computers are used for following on-line functions in power system operation and protection :
   ......, ..., ...

46-B

Economic Operation of Power System and Automatic Economic Load Dispatch

INTRODUCTION

As seen in Ch. 44-A and Ch. 45-A, the generation of power is always matched to meet prevailing load conditions so as to maintain constant frequency (*f*) and stability of the network. Besides this technical requirement ; *the energy should be supplied to the consumers at the lowest possible cost; i.e.* the cost of power delivered should be minimum for any load conditions.

Load conditions change from time to time. *The basic object of economic operation of power system is "the distribution of total generation of power (P) in the network between various regional zone; various power stations in respective zones and various units in respective power stations such that the cost of power delivered is minimum".* The cost of *power delivered* takes into consideration : the cost of *power generation* and the cost of *transmission losses.* It means for every load conditions, the load control centre should decide.

1. How much power to be generated to meet the prevailing load condition to maintain constant frequency.

2. How much should each 'Region' generate ?

3. What should be the exchange of power between the Regions (Areas) ?

This aspect can be decided by regional control centre.

Exchange of power should be decided by considering *technical aspects plus economic aspects.* The economic aspect include cost of generation plus cost of transmission losses for inter region exchange *e.g.*. If hydro-electric power is cheaper and at shorter distance and is available in surplus this should be used by neighbouring region.

(4) As the regional control centre gets a command from the load control centre, the regional control centre has to decide the total power generation in its jurisdiction in various Generating stations based on technical and economic criteria. The economic criteria include cost of generation of various plants and cost of transmission losses.

The criterion usually applied is *equal incremental fuel costs for various and various units therein.* (And not the minimum cost of generation of units as will be seen in subsequent paragraphs).

If F_n = R/shr ..... operating cost of a unit '*n*'

P_b = MW ..... output of *n*th unit.

Incremental operating cost of the nth unit is defined as λ_n

$$\lambda_n = \frac{dF_n}{d\lambda_n}$$

The units in a power station are operated economically when their incremental operating cost are equal, *i.e.*

$$\lambda_1 = \lambda_2 = \lambda_3 = ... \lambda_n$$

i.e.

$$\frac{dF_1}{dP_1} = \frac{dF_2}{dP_2} = \frac{dF_3}{dP_n} ... \frac{dF_n}{dP_n}$$

where F_1, F_2 ... operating costs ... Rs/hr of unit 1, 2, ...

P_1, P_2 ... Power shared ... MW

λ_1, λ_2, ... Intermental operating costs Rs/MWhr

This criterion should be understood to know the method of economic load distribution between units in the same plant or between different plants in the same region. The *transmission losses* are taken into consideration by modifying the basic equations of economic plant loading.

The functional assignments for economic power system operation are as follows :

National Load Control Centre. To decide generation allocation to various regions and to decide exchange between regions on overall economy and energy policy/reserves.

Regional Load Control Centre. To decide generation allocation to various generating stations within the region on the basis of equal incremental operating considering line losses are equal.

Plant Load Control Room. To decide allocation of generation for various units of the plant on the basis of equal incremental operating costs of various units.

To minimise reactive power flow through lines so as to minimise line losses and maintain voltage levels. (Ch. 44-B).

Sub-station Control Room. To minimise reactive power through transmission lines by compensation to minimise line losses and to maintain voltage levels.

46.15. CLASSICAL METHOD OF LOADING THE UNITS IN A PLANT

The ancient method was to load the most efficient plant to deliver the power during low loads first. When the most efficient plant is fully loaded, then bring the next efficient plant, as so on.

Thus, the steps were as follows :

Suppose A, B, C, D is the order of efficiency of units

— Load most efficient unit *A*.

Increase its input to meet higher loads when unit A is loaded fully, bring-in the next efficient unit *B*.

— Increase input to unit *B* to increase power shared by *B* till *B* is also loaded fully. Then bring-in the next efficient unit *C*.

— Follow the same for unit *D*.

While reducing the load,

— Reduce loading on unit *D* first.

— Then take out unit *D* and reduce load of unit *C*.

— Further, reduce load on unit *B* and finally keep the low loads supplied by unit *A*.

The classical method of economic load *distribution* between *generating units in the order of efficiencies, i.e.*, "Load most efficient unit first and less efficient unit later *fail to give minimum cost of generation.*

The same method was applied to loading of various generating plants in the region, *i.e.* load most efficient plant first : then less efficient, and subsequently in the *order of efficiencies of plants, transmission losses were totally neglected.*

The classical method of loading the plants in the order of efficiencies does not give the *economic loading* because

— The operating cost of a unit or a power station varies with load. The variation of operating cost with respect to variation in load (dF/dP) is not considered in the classical method.

— line losses are neglected in the classical method.

Hence, the *modern method of economic loading of units in the plant* and economic loading of various plant in the region was evolved. This method was further modified to take into account the line losses.

46.16. ECONOMIC LOAD DISTRIBUTION WITHIN A GENERATING STATION BY MODERN METHOD

(*a*) **The Problem Definition.** Suppose a generating station (G_A) has n generating units. Each unit comprises a generator, turbine, boiler and auxiliaries. Suppose the power generation of the stations (G_A) is P_R : and corresponding operating cost of the n units is F_R : what should be the criterion for distribution of total power P_R within the n units ?

(*b*) **Data.** Let G_A be the generating station having n units.

F_1, F_2, F_n = Input cost of respective units, Rs/hr

P_1, P_2, P_n = Output power of respective unit, MW

Each unit 1 to n will have respective curves (Figs. 46.9 and 46.10). A typical curve of operating cost (Rs/hr) against output (MW) is shown in Fig. 46.9. The slope of this curve at any point would have the units.

$$\text{Slope} = \frac{\Delta Y}{\Delta X} = \frac{\text{Rs}}{\text{hr}} \times \frac{1}{\text{MW}} = \frac{\text{Rs}}{\text{MWhr}}$$

This is called Incremental operating cost and has units Rs/MWhr.

Let F_n = Input to nth unit in Rs/hr.

Pn = Output of nth unit in MW

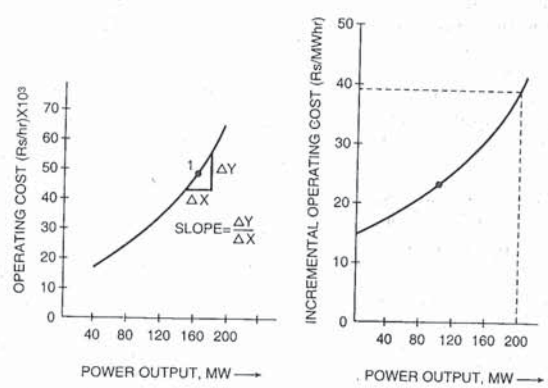


Fig. 46.9. Operating Cost and Incremental Cost Curves.

Incremental operating cost at a given point.

L on the P *vs*. F curve is defined as the slope dF/dP at that points thus

$$\lambda \frac{dF_n}{dP_n} = \text{Incremental operating cost.}$$

Likewise from calculated values of $\lambda = \dfrac{dF}{dn}$

for various output values P, the curve of output P *vs*. incremental operating cost is/drawn (*e.g.* Fig. 46.10).

(*c*) **Criterion for Economic Loading**

Let F_T = Total operating cost of power station Rs/hr

P_T = Total output of power station, MW.

$$F_T = F_1 + F_2 + F_3 \ldots + F_n$$

$$P_T = P_1 + P_2 + P_3 \ldots + P_n$$

where n = number of units.

$P_1, P_2, P_3 \ldots P_n$ = loading of respective units.

$F_1, F_2, F_3, \ldots F_n$ = Operating costs of respective units.

Minimum operating cost of generating station is obtained when Incremental operating cost (λ) of each unit is equal *i.e.*

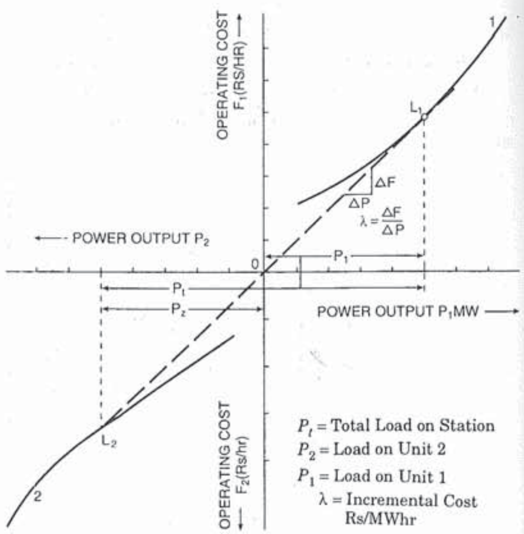
$$\lambda = \frac{dF_1}{dP_1} = \frac{dF_2}{dP_2} = \frac{dF_3}{dP_3} = \frac{dF_n}{dP_n}$$

or $$\lambda = \frac{dF_n}{dP_n} \text{ where } n = 1, 2, 3, 4, \ldots n,$$

In practice, each unit has certain minimum and maximum loading. A curve of λ *vs*. power output is drawn for each unit indicating maximum and minimum loading. For each *power output of plant,* the load distribution should be such that, the incremental operating costs of units should be equal ($\lambda_1 = \lambda_2 \ldots = \lambda_n$) and sum of loading of units should be equal to total power output of the power station. ($P_T = P_1 + P_2 + \ldots + P_n$) since maximum and minimum outputs of each units are specified, for lower loads, some units whose incremental operating cost is *higher* will not be operated on low loads.

Refer Fig. 46.10 illustrating economic load distribution P_1 and P_2 for total P_t in a generating station having two units 1 and 2.

The F *vs*. P curves are drawn for unit 1 and 2 as in Fig. 46.10. For various points on curve (I), tangents are drawn to curve L and a corresponding parallel tangent is drawn to curve 2 also. Thus there will be two points L_1 and L_2 having equal



ECONOMIC LOAD DISTRIBUTION

Fig. 46.10.

slopes dF_1/dP_1 and dF_2/dP_2. Let P_1 and P_2 be powers corresponding to L_1 and L_2. Thus PT = Total power of stations = $P_1 + P_2$ and $\lambda = dF_1/dP_2$ is equal for 1 and 2.

Fig. 46.10 shows only one pair of points L_1, L_2 likewise for different points on curve 1, corresponding points having some slope can be obtained on curve 2 and corresponding powers P_1 and P_2 can be computed. Thus, for various points the following can be tabulated.

Total Power Output of Power Station $P_t = P_1 + P_2$	*Power output of Unit 1* P_1	*Power output of Unit 2* P_2	*Incremental Operating cost* λ

Putting limiting conditions P_1-maximum and P_2 maximum. P_1-minimum and P_2 minimum in the table, the power shared P_1 and P_2 should be held its *limiting value.*

For more than 2 units, a similar method may be used. The table of Total P ; P_1, P_2, P_3, P_4, P_n and λ is drawn for various slopes of F *vs* P curves. $P = P_1 + P_2 + \ldots P_n$. Thus, for various table loads P, the economic loading $P_1, P_2, P_3 \ldots Pn$ are known. Each unit operates at same incremental operating cost λ such that

$$dF_1/dP_1 = dF_2/dP_2 = dF_3/dP_3 = \lambda$$

46.17. MODERN METHOD OF ECONOMIC LOAD DISTRIBUTION BETWEEN VARIOUS GENERATING STATIONS IN A REGION

The method of loading based on equal incremental operating cost (Refer Sec. 46.17) is applicable for deciding economic load distribution between Generating Units in a Region.

Thus :
$$F_T = F_1 + F_2 + F_3 \ldots . F_n$$
$$P_T = P_1 + P_2 + P_3 \ldots P_n$$

For economic loading, incremental operating cost should be equal, *i.e.*,

$$\lambda = \frac{dF_1}{dP_1} = \frac{dF_2}{dP_2} = \ldots \frac{dF_n}{dP_n}$$

where F_T = Total operating cost of 'n' stations, Rs/hr

P_T = Total power generation of n stations, MW

$F_1, P_2, \ldots P_n$ Power generation by individual stations MW

$F_1, F_2, \ldots F_n$ Operating costs of individual station Rs/hr.

λ = Incremental operating cost

Thus the various generating stations are loaded such that the incremental operating cost $\lambda = dF/dP$, R_s/MWhr of the generating stations are equal and total power of the region is equal to the sum of power output of generating units.

Example 46.1. Economic Load Distribution :

A 250 MW generating station has two 125 MW units. The incremental operating costs of the two units are as follow :

$$\lambda_1 = \frac{dF_1}{dP_2} = \text{Incremental operating cost of Unit 1} = \frac{R_s}{\text{MWhr}}$$

$$\lambda_2 = \frac{dF_2}{dP_2} = \text{Incremental operating cost of Unit 2} = \frac{R_s}{\text{MWhr}}$$

P_1 = Output of Unit 1 MW

P_2 = Output of Unit 2 MW.

$$\lambda_1 = 0.1\, P_1 + 20 \ldots \frac{R_s}{\text{MWhr}}$$

$$\lambda_2 = 0.12\, P_2 + 16 \ldots \frac{R_s}{\text{MWhr}}$$

Limits of loading of P_1, P_2 are maximum 125 MW and minimum 20 MW (same for both)

Determine load allocation for each unit for various loads on generating station from 50 to 250 MW. Also determine incremental operating costs for these load values.

Solution. There are only two units in the generating station. The total load is increasing from 50 to 250 MW. Minimum and maximum load of each units 20 MW and 125 MW respectively. Unit 1 will have high incremental cost for lower loads, hence it should be operated in its lowest limit of 20 MW for low loads (light loads), and Unit 2 will share 50—20 = 30 MW.

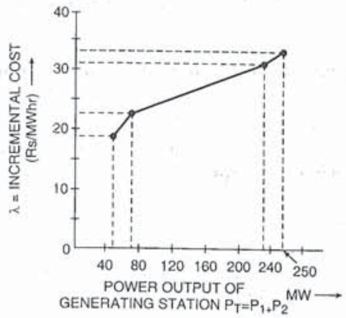


Fig. 46.11. λv/s Plant Output Solution to Example 46.1

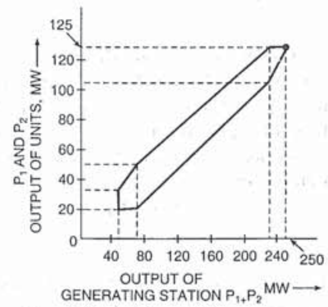


Fig. 46.12. Loading of Units For Economic Operation Solution to (Ex. 46.1)

For low loads. For low loads, unit 1 will be loaded to 20 MW and unit 2 will share 30 MW.

$$\lambda_1 = \frac{dF_1}{dP_1} = 0.1\,P_1 + 20$$

$$= 0.1 \times 20 + 20 = 22 \ldots R_s/\text{MWhr}$$

$$\lambda_2 = \frac{dF_2}{dP_2} = 0.12 \times 30 + 16 = 19.6\,R_s/\text{MWhr}.$$

Further increase in load. The loading on unit (1) to remain at its minimum 20 MW and further increase in load to be shared by unit (2) till the incremental operating costs of unit (2) and unit (1) become equal, *i.e.* when dF_2/dP_2 increases to 22 R_2/MWhr, *i.e.*

$$\frac{dF_2}{dP_2} = 0.12\,P + 16 = 22$$

Hence $\qquad P_2 = \dfrac{22-16}{0.12} = \dfrac{6}{0.12} = 50$ MW

Thus at $\qquad P_2 = 50$ MW, $P_1 = 20$ MW

and $\qquad \lambda_1 = \lambda_2 = 22\,R_s/\text{MWhr}$.

After this, the loading P_1 and P_2 is allocated for equal values of incremental operating cost λ till upper limit of 125 MW of individual unit is reached.

Thus the values of P_1, P_2 are calculated for various values of λ such as 24 R_s/MWhr, 26 R_s/MWhr, 28 R_s/MWhr, 30 R_s/MWhr and 31 R_s/MWhr.

$P_T = P_1 + P_2$ is calculated by adding P_1 and P_2

Upper Limit 125 MW

Substituting $\qquad P_2 = 125$ MW in Eq.

$$\frac{df_2}{dP_2} = 1.12\,P_2 + 16 = 0.12 \times 125 + 16 = 31\,R_s/\text{MWhr}.$$

For this, λ_2, λ_1, P_1 are calculated :

$$31 = 0.1\,P_1 + 20$$

$$P_1 = 110 \text{ MW}$$

$$P_T = P_1 + P_2 = 110 + 125 \text{ MW} = 335 \text{ MW}.$$

Above 335 MW Total Load :

Unit 2 is loaded upto 125 MW

Unit 1 is loaded to take $PT - 125 = P_1$

Finally both units share 125 MW each to give total 250 MW.

Thus the allocation of loads P_1 and P_2 for various values of incremental operating costs λ are as follows :

Incremental Operating costs λ Rs. / MWhr.	*Loading of Unit 1 P_1 MW*	*Loading of Unit 2 P_2 MW*	*Total load on Generating station $P_1 + P_2$ MW*
19.6	20	30	50
20	20	33.3	53.3
21	20	41.7	61.7
32	120	125	245
32.5	125	125	250

Note. $\qquad \lambda_1 = 0.1\,P_1 + 20$

$$\lambda_2 = 0.12\,P_2 + 16$$

P_1 and P_2 max = 125, min = 20

Example 46.2. *Incremental Operating Cost for Economic Loading*

A generating station has two units (1) and (2). The incremental operating cost of the two units are as follows :

Unit : 1 $\qquad \lambda_1 = 0.1\,P_1 + 20\ \ R_s/\text{MWhr}$

Unit 2 : $\qquad \lambda_2 = 0.12\,P_2 + 16\ \ R_s/\text{MWhr}$

where P_1 = Load on Unit (1) MW, P_2 = Load on (2) in MW.

Calculate (*A*) the load distribution based on economic loading of the two generating stations for total equal to 180 MW.

(*B*) Corresponding value of incremental costs.

Solution. P_t = Total load $P_1 + P_2$ = 180 MW ... given. For economic load distribution, the incremental operating costs are equal.

Hence, $\qquad \lambda_1 = \lambda_2 = \lambda$

i.e. $\qquad 0.1\,P_1 + 20 = 0.12\,P_2 + 16$

Expressing P_1 in terms of P_2,

$$0.1\,P_1 = 0.12\,P_2 + 16 - 20$$

$$0.1\,(180 - P_2) = 0.12\,P_2 - 4$$

$$18 - 0.1\,P_2 = 0.12\,P_2 - 4$$

$$22 = 0.22\,P_2\,;\ P_2 = 100 \text{ MW}$$

$$P_1 + P_2 = 180$$

$$P_1 = 180 - 100 = 80\ MW$$

$$\lambda_1 = 0.1\,P_1 + 20$$

$= 0.1 \times 80 + 20 = 28\ _s/\text{MWhr}$

$\lambda_2 = 0.12\, P_2 + 16$

$= 0.12 \times 100 + 16 = 28\, R_s/\text{MWhr}$

Check :D $\lambda_1 = \lambda_2$ for economic loading

Answers : $P_1 = 80$ MW

$P_2 = 100$ MW

$\lambda = 28\, R_s/\text{MWhr}$.

Example 46.3. *Comparison-Economy Loading and Equal Loading.*

In a generating station having two units, the incremental operating costs of units as follows :

Unit 1 : $$\frac{dF_1}{dP_1} = \lambda_1 = 0.1\, P_1 + 20\, R_s/\text{MWhr}$$

Units 2 : $$\frac{dF_2}{dP_2} = \lambda_2 = 0.12\, P_2 + 16\, R_s/\text{MWhr}$$

Total load on the station is 180 MW.

Find difference in operating cost per hour between economy loading and equal loading for

(*A*) Unit 1 (*B*) Unit 2 (*C*) Total Power Station.

Also detemine annual saving for the station for economy loading instead of equal loading.

where P_2 = Transmission loss total

P_1 = Loading of plant 1

P_2 = Loading of plant 2

B_{11} = Loss formula co-efficient for plant 1

B_2 = Load formula co-efficient for plant 2.

$$B_{11} = \frac{R_1}{|V_1|^2\,(P\,F_1)}$$

$$B_{32} = \frac{R_2}{|V_2|^2\,(PF_2)}$$

46.18. DISTRIBUTION OF LOAD BETWEEN GENERATING STATIONS BY TAKING INTO ACCOUNT THE TRANSMISSION LOSSES : PENALTY FACTOR

If transmission losses are neglected, the economic loading of generating is such that the Incremental Operating Costs and equal,

i.e. $$\frac{dF_1}{dP_1} = \frac{dF_2}{dP_2} = \frac{dF_3}{dP_3} = \ldots \lambda = \frac{dF_n}{dP_n}$$

When transmission losses are considered as functions of respective plant loadings, the above criterion gets modified as follows :

$$\frac{dF_n}{dP_n} + \lambda\,\frac{dF_L}{dP_n} = \lambda \ldots \textit{i.e.}\ \frac{\partial F_n}{\partial P_n}\left[\frac{1}{1 - \dfrac{\partial P_2}{\partial P_n}}\right] = \lambda$$

i.e. $$\frac{dF_n}{dP_n}\,L_n = \lambda.$$

where L_n is a multiplier for incremental operating cost dF_n/dP_n for nth plant is called 'Penalty factors'. *Penalty Factor* L_n is obtained from the transmission loss P_L and power delivered P_n by nth plant, *i.e.*

$$L_n = \frac{1}{1 - \lambda\, P_L/\partial P_n}$$

where L_n = Penalty factor for nth plant

P_L = Transmission loss

P_n = Power delivered by nth plant.

Thus for economic loading of plants considering respective transmission losses, the total incremental cost should be equal for all the plants, *i.e.*

$$\frac{dF_n}{dP_n} \cdot L_n = \lambda$$

should be equal for n plants in the system

Summarising for economic load distribution between various n number of plants, considering transmission loss P_L, the minimum operating cost of entire system is obtained for equal λ for each plant, *i.e.*

$$\frac{dF_n}{dP_n} \cdot L_n = \lambda \ldots \text{ equal for all } n \text{ plant.}$$

For economic load distribution,

$$\frac{dF_1}{dP_1}\,L_1 = \frac{dF_2}{dP_2}\,L_2 = \ldots \frac{dF_n}{dP_n} \cdot L_n$$

where $\dfrac{dF_1}{dF_2}, \dfrac{dF_2}{dP_2}$ ... incremental operating costs of plant

$L_1, L_2, L_3, \ldots$ penalty factors of plants

$$L_n = \frac{1}{1 - \dfrac{\partial P_L}{\partial P_n}}$$

where L_n = Penalty factor for nth plant

P_L = Total transmission loss

P_n = Output of nth plant.

46.19. AUTOMATIC LOAD DISPATCH INCORPORATING LOAD FREQUENCY CONTROL AND ECONOMIC LOAD DISPATCH

Refer Sec. 45.11. Load Dispatching and Network Controller. This topic will be elaborated in this section.

The *Load Control Centre* determines the allocation of generation by various plants on the basis of economic load distribution considering incremental operating costs λ and penalty factors for transmission losses (Ln) for each plants. The *load centre sends* commands to *Power Station* control room periodically by telemetric data transmission. The automatic load-frequency control in the control system of Generator-Turbine-Governor basically aims at maintaining constant frequency/speed as a primary control (Secs. 45.3 and 45.4). But the setting of governor to turbines (Secondary Load-Frequency Control) is changed according to the instructions of Central Load Control Centre. *Thus the input to turbines of generators gets automatically adjusted by primary load-frequency control and the frequency is maintained. And the governor setting is determined by economy load dispatch instructions.*

Fig. 46.13 illustrates the basis functional scheme of *Automatic load-frequency control and economic load dispatch.*

The total control is achieved jointly by :

(*A*) Load Control Centre

(*B*) Telemetry and Telecontrol Equipment and

(*C*) Power Station Control Room.

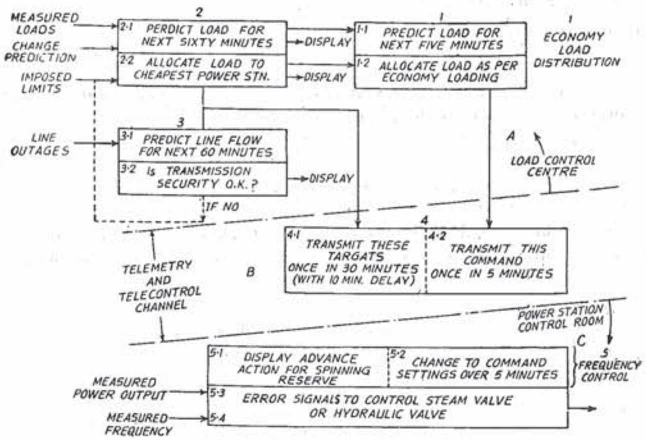


Fig. 46.13.

Function of Load Control Centre (A). The load control centre (Load Dispatch Centre) A has a central micro-processor (Refer Sec. 46.9) which performs the following functions :

— Functional Block 2 in Fig. 46.13.

Calculate the estimated load on the network for the next one hour ahead; display it, calculate economy loading for that load and allocate for the next one hour the load of each power station ... Functional Block (2) Display for next one hour the allocated loading for each power station in the region. These predictions and instructions are telemetered by B to power station (C).

Functional Block (1) in Fig. 46.13 located in the Load Control Centre.

— Calculate Economic Load Distribution for say every next five minutes ahead (slower control than load frequency central) and allocates the economic loading to each generating station (C) *via* telemetric channels (B).

— Load Control Centre (A) may also instruct certain power stations to control the *output* to control system frequency without considering economic loading. This for higher priority to frequency control overriding the economy control.

Function of Telemetry and Telecontrol B. Telemetry and Telecontrol Channels (B) transmit instructions from load control centre (A) to power Station Control Room (C). These instructions are for :

— Targets for next half hour ahead for advance action for spinning reserves in power station (4.1).

— Commands regarding plant outputs for achieving economic loading. These commands are transmitted once in five minutes (or two minutes) (Block 4.2).

Functions of Generating Station Control Room (C). The generating station control room has machine controllers for each generator unit. These controllers provide basic load-frequency control. The frequency of generator bus is taken as a reference. The input to turbines is changed to achieve desired electrical output to maintain the desired frequency. The setting to governor valve determines the range between which the input to turbines can be varied automatically be the primary load frequency control Refer Block (1) and Block (5) in Fig. 46.13. The setting of governor valve itself is changed in accordance with the command of load control centre once in five minutes. Thereby the input to turbines is adjusted once in five minutes in accordance with economy loading

command by block 1. Thus the load frequency control (5) in the power station (C) receives data regarding.

5.1.... Measured power output of the generating station.

5.2.... Measured Frequency.

5.0....Instructions for setting of power output from load control centre.

The control system for frequency control adjusted the turbine valve setting an accordance with the error signal based on 5.0, 5.1, 5.2 above.

Solution.

Refer Ex. 43.2 for Economy Loading Incremental Operating Cost

$$\text{Cost} = \frac{dF}{dP}$$

$$\text{Operating Cost of } F = \int \frac{dF}{dP}\, dP$$

Difference in operating costs with different loadings say P economy and equal will be

$$\int_{P\text{ economy}}^{P\text{ equal}} \frac{dF}{dP} \cdot dP = \text{Difference in operating cost.}$$

For Unit 1

Refer Ex. 46.3. For economy loading

$$P_1 = 80 \text{ MW}$$

For equating loading $\quad P_1 = 90$ MW

Difference in operating cost would be

$$\int_{80}^{90} \frac{dF}{dP} \cdot dP = \int_{80}^{90} (0.1\, P_1 + 20)\, dP$$

$$= [0.05\, P_1^2 + 20\, P_1]_{80}^{90}$$

$$= 0.05\,[90^2 - 80^2] + 20\,[90 - 80] = 0.05\,(1700) + 20\,(10)$$

$$= 85 + 200 = \mathbf{285 \text{ Rs./hr.}} \quad \text{Answer to } (A)$$

Similarly, for Unit 2

Economy loading from Ex. 43.3 = 100 MW

Difference in operating cost would be

$$\int_{P\text{ economy}}^{P\text{ equal}} \frac{dF_2}{dP_2} \cdot dP_2$$

$$= \int_{P\text{ economy}}^{P\text{ equal}} [0.12\, P_2 + 16]\, dP_2$$

$$= [0.06\, P_2^2 + 16\, P_2]_{100}^{90}$$

$$= [0.06\,(8100 - 10{,}000) + 16\,(90 - 1000)]$$

$$= -[190 + 160] = -\mathbf{250 \text{ Rs. hr.}} \quad \text{Answer to } (B)$$

Note. Negative sign indicates increase in operating cost of operating cost of unit 2 for economy loading.

$$285 - 250 = 35 \text{ Rs./hr.}$$

Annual saving = Hourly saving × Annual Hours

$$= 35 \times 8760 = 306{,}600 \text{ Rs/year}$$

Annual saving = **306,600 Rs.** **Ans**

Note. This figure indicates the probable magnitude saving due to economy loading in one small power station.

46.20. TRANSMISSION LOSS AS A FUNCTION OF OUTPUT POWER OF GENERATING STATION

In earlier analysis, the transmission losses have been neglected. These are generally considered as multiple of power generation of generating stations. The transmission losses from a power plant having lower incremental operating cost may be higher due to longer distance from the load and it may be more economical to load a generating station at a lesser distance considering lower transmission losses.

In the economic loading of power stations, the transmission losses are taken into account as functions of respective generating stations outputs.

Consider a simple system having two generating stations G_1 and G_2 feeding power P_1 and P_2 to a load *via* transmission lines 1 and 2 respectively.

$$\text{Power loss in line } 1 = 3/\,|I_1|^2 R_1 \quad \text{...(1)}$$

$$\text{Power loss in line } 2 = 3\,|I_2|^2 R_2 \quad \text{...(2)}$$

where R_1 and R_2 are resistance of conductors.

$$I_1 = \frac{P_1}{\sqrt{3}\,|V_1|\,(PF_1)} \quad \text{...(3)}$$

$$I_2 = \frac{P}{\sqrt{3}\,|V_2|\,(PF_2)} \quad \text{...(4)}$$

Total transmission loss P_L watts

$$P_L = 3\,|I_1|^2 R_1 + 3\,|I_2|^2 R_2 \quad \text{...(5)}$$

$$= \frac{3P_1^2 R_1}{\sqrt{3}\,|V_1|^2\,(PF_1)^2} + 3\,\frac{P_3^2 R_2}{3\,|V_1|^2\,(PF_2)^2}$$

$$= P_2^2\,\frac{R_1}{|V_1|^2\,(PF_1)^2} + P_2^2\,\frac{R_2}{|V_2|^2\,(PF_3)^2} \quad \text{...(6)}$$

(PF_1), (PF_2) are power factors.

In the above expression the transmission loss PL is expressed in terms of plant loads P_1 and P_2. Rewriting eq. (6) in terms of Loss Formula Co-efficients B_{11} and B_{22} as

$$P_L = P_1^2 B_{11} + P_2^2 B_{22}$$

46.21. NETWORK CONTROLLER IN LOAD CONTROL CENTRE (Refer Sec. 45.11)

Consider the power generation in an area (Region). The tasks of the power system network controller in the load control centre is to maintain the power exchange through the tie-lines with neighbouring regions at the desired values, and simultaneously to control the system frequency f.

The network controller compares the action sum of Tie-line Power P_1 with Scheduled sum of Tie-line Power P_{io} : to calculate the Deviation ΔP

$$\Delta P = \sum_{1}^{n} (P_i - P_{i0}) \quad \text{...(1)}$$

where ΔP = Deviation of actual power transfer through tie-lines from targeted values

1, ... n = No. of Tie-Lines with neighbouring regions

P_i = Tie-line Power Flow, MW

P_{i0} = Scheduled Tie-line Power Flow, MW

Thus, $$\Delta P = \sum_{1}^{n} (P_i - P_{i0})$$

gives total deviation of power exchange with interconnected areas from the scheduled exchange.

It means, the generation in the area under the control of the network controller should be changed by ΔP to meet targeted exchange.

Next, the network controller has to control the system frequency. Let ΔP be the frequency deviation *i.e.*

$$\Delta F = f - f_o$$

where Δf = frequency deviation

f_0 = target frequency .... Hz

f = actual frequency ... Hz

A factor K called *System Frequency Bias* is introduced.

The system frequency bias K is *amount of power generation required to change the system frequency by one cycle.* Thus,

K = System Frequency Bias MW/hz

Thus to correct the frequency deviation Δf, the amount of power change would be

$$K\,\Delta F \text{ ... (MW)} \quad \text{...(2)}$$

Combining (1) and (2), the *Area Requirement e* is given by

$$e = \Delta P + K\,\Delta F$$

Thus the network controller determines Area Requirements (e), where

$$\boxed{e = \Delta P + K\,\Delta f}$$

e = Area Requirement Correction MW

ΔP = Deviation in Power Exchange through Tie-Lines ... MW

K = System Frequency Bias

Δf = System Frequency Deviation

Kf = Power change required to achieve target frequency ... MW

This area requirement correction is transformed into output signals by the network controller. These output signals for *correcting conditions* are set to various generating stations under automatic control. (Block 1.2 in Fig. 46.13).

The primary load frequency control in response to automatic governor action to achieve target frequency is faster (a few seconds). This corrects the input to turbines within set limits of turbine to control the frequency.

The secondary load-frequency control (in response to instructions from network controller) is slower (once in say 5 minutes). It adjusts the governor settings.

Refer Fig. 46.14 illustrating load frequency control of generating unit.

The output of the turbo-generator P and the frequency f is controlled by the load frequency control system as follows. The frequency of generator output is measured by frequency measurement (F) and is fed into operational amplifier OM in the form of $K_m\,\Delta f$. The output power of the generator P_m is measured by Power Measuring Convertor MC and its equivalent d.c. P_m is fed into the operational amplifier. Thirdly, the area requirement correction e computed by the network controller is converted into equivalent proportional- integral signal called Y which is an analogue d.c. signal (d.c. voltage or current) and is given as input to the operational amplifier. Thus the operational amplifier OA gets three inputs (1) P_m, (2) $K_m\,\Delta f$ and (3) $Y_m \propto e$. The operational amplifier OA processes these three inputs and gives an output ΔG.

$$\Delta G = \frac{P_m + K_m\,\Delta f}{P_{m-\max}}\,100\% - Y_m\ (\%)$$

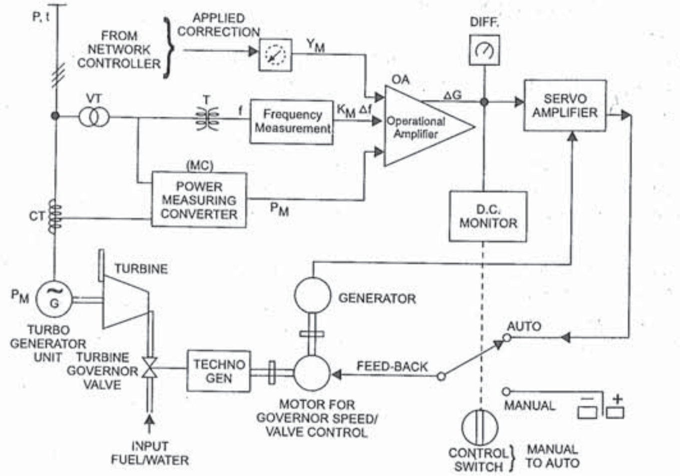


Fig. 46.14. Load-frequency control of a unit.

The value of ΔG passes through the servo amplifier to the two phase servo motor such that the speed of the servo motor is proportional to ΔG. A techo-generator coupled to the motor produces a feedback voltage which is fed-back to the servo-amplifier and the speed of the motor is made independent of the torque. The difference ΔG is monitored by d.c. monitor DCM and is shown on the control desk by the indicating instrument difference.

The servo-motor rotates in required direction by required number of turns in response to ΔG and the setting of turbine-governor-valve is changed. Thereby the input to turbine is changed and generator output is changed.

The running time of the motor for governor valve control is of the order of 20 to 100 seconds. In order to avoid-regulation, hunting etc. the stopping time is short of the order of 0.5 second.

The centrifugal governor should have dead-band of less than ± 0.5%. There is a provision of changing-over from automatic to annual as shown in Fig. 46.14 when difference ΔG is higher than present limit the change-over from automatic to manual takes place and an alarm is sounded.

Thus the load frequency control system of turbine-generator unit serves the function of maintaining target frequency and scheduled generation for economic loading.

SUMMARY

The load-frequency control and the economic loading of generators is achieved by a combined action of network controller in the load control centre and the frequency control system in the generator control rooms.

For economic loading of the *unit the plant,* there incremental operating costs are equal, *i.e.*

$$\lambda = \frac{dF_1}{dP_1} = \frac{dF_2}{dP_2} = \dots = \frac{dF_n}{dP_n} \cdots \frac{R_s}{\text{MWhr}}$$

Some principle is applied to the loading of power stations in the area economically neglecting line losses.

$$\lambda = \frac{dF_1}{dP_1} = \frac{dF_2}{dP_2} = \frac{dF_3}{dP_3} = \cdots \frac{dF_n}{dP_n}$$

However lines losses should be considered and they are generally expresses as a function of plant loading. The incremental operating cost of each plant is multiplied by its penalty factor. Penalty factor for nth plant is

$$\text{Penalty Factor } L_n = \frac{1}{1 - \partial P_1/\partial P_n}$$

For economic loading of power stations in an area considering line losses is given by

$$\frac{dF_1}{dP_1} L_1 = \frac{dF_2}{dP_2} L_2 = \dots \frac{dF_n}{dP_r} L_n = \lambda$$

The load Frequency Control is achieved by combination of

— Primary load frequency control by the control action of generator frequency control in the control room of the generator.

— Secondary frequency control according to the instructions of network controller situated in the load control centre.

The network controller calculates

Deviation ΔP give by

$$\Delta P = \sum_{1^n} (P_i - P_{i0})$$

and $$K\Delta F$$

where K = System Frequency Bias.

Network controller gives the error

$$e = \Delta P + K\Delta F$$

This error transmitted to the generating station control room.

The operational amplifier in the frequency control system gets signal (e) from network controller and produces output G.

$$\Delta G = \frac{P_m + K_m \, \Delta f}{P_{m-max}} 100\% - Y_m \ (\%)$$

where $y_m\%$ is proportional to (e).

Turbine Governor Gate valve is adjusted by the servo-motor in the closed loop system of frequency control system. The turbine input gets adjusted to maintain required frequency and to give economic loading.

QUESTIONS

1. Explain the following terms related with economic loading :
   — Incremental operating cost of power station
   — Penalty Factors
   — Loss formula coefficients

   Explain the modern criterion for economic load distribution between generating stations.
2. Explain the function of network controller and generator control room in frequency control and economic loading by a suitable block diagram.
3. Explain the function of a typical control system for frequency control of a synchronous generator stating the function of each component and the control action.
4. Explain the following equation :

   $e = \Delta P + K\Delta F$

   where e = Area requirement correction
   ΔP = Deviation in power exchange
   K = System Frequency Bias
   ΔF = Deviation in frequency.

5. Explain the co-relation between load-frequency control and economic loading of power stations. How are both of these achieved simultaneously ?

6. Fill in the blanks :

1. For economic loading of generating stations, the ... should be equal.
2. The unit of incremental operating cost of generating cost is ....
3. Incremental operating cost for a particular load is given by ... curves.
4. Loss formula coefficient is expressed as

Ch. 49 Covers interconnected power systems.

Ch. 50 Covers further details about SCADA systems used in todays Power System Operation and Control.

47

HVDC Transmission Systems

Introduction — Choice — Merits — Economy — Limitations — Bipolar/Mono polar/Homopolar — Arrangements — Thyristor Convertor — Convector Operation — Control of Thyristors and D.C. Line-Layout — Components — Control, Measurement, Protection — Operation — Maintenance — HVDC Simulators — Typical HVDC Line — Summary

47.1. INTRODUCTION CHOICE OF HVDC TRANSMISSION

In India, 400 kV a.c. transmission lines have been introduced during 1970's. 4 HVDC transmission links have been executed (1997). By the year 2000, about six HVDC transmission links are expected to be commissioned in India. HVDC transmission systems are selected as an alternative to extra high voltage a.c. transmission systems for any one or more of the following reasons :

1. **For long distance high power transmission lines.**

2. **For interconnection (Tie-lines) between two or more a.c. systems having their own load frequency control.**

3. **For back-to-back asynchronous-tie sub-stations.** Where two a.c. systems are interconnected by a convertor-sub station without any a.c. transmission line in between. Such a tie-link gives an asynchronous interconnection between two a.c. systems.

4. **For underground or submarine-cable transmission over long distance at high voltage.**

At present 40 HVDC links have been installed in the world and by the year 2000, about 55 links are expected with a total transfer capacity of 70,000 MW. *The choice between 400 kV a.c., 765 kV a.c., 1100 kV a.c. and HVDC transmission alternatives is made on the basis of technical and economic studies for each particular line and associated a.c. systems. Alternating current continues to be used for generation, transmission, distribution and utilization of electrical energy.*

47.2. HVDC TRANSMISSION SYSTEMS

47.2.1. Applications of HVDC Transmission Systems

For generation, transmission, distribution, and utilization of electrical energy, 3-phase AC systems are used universally and have a definite superiority over HVDC.

However in following particular applications, High Voltage, Direct Current Transmission (HVDC) is a strong alternative to EHV-AC transmission and HVDC lines are preferred.

— Long distance high power transmission by overhead lines.

— Medium high power submarine or underground cables.

— System interconnection by means of overhead lines, or underground/submarine cables, or back-to-back HVDC coupling stations, or Multi-Terminal DC systems (MTDC).

— Frequency conversion links (*e.g.* 60 Hz/50Hz)

— Incoming lines in mega-cities.

In HVDC link AC power is converted by thyristor-convertor valves at one end. The energy is transmitted in HVDC form to the other end. At the other end, the DC power is inverted to AC and fed into the receiving AC system. Fig. 47.1 illustrates a typical bipolar HVDC link.