POWER SYSTEM OPERATION AND CONTROL (15EE81)

MODULE – 1: Introduction:

Electricity is a converted form of energy and is used extensively in industrial, commercial, residential agricultural and transportation sectors. It can be generated and transmitted in bulk, economically, over long distances. AC systems have become the most popular system for use, over DC, for the following reasons:

1. AC generators are simpler than DC generators.
2. Transformation of voltage levels is simple, providing great flexibility of different voltage levels at generation, transmission and distribution.
3. AC motors, widely used, are simpler and more economical than DC motors.

In modern power systems, the grids are interconnected and vary widely in size and structure. However, they comprise three phase systems, at both generation and transmission. Synchronous generators are used for generation. The prime movers act to convert mechanical energy into electric energy. Thermal plants use coal as the primary fuel and hydel plants use water to run the turbine. The generated power is transmitted over a wide geographical area, at voltage levels higher than the generated voltage. At the consumer end, the voltage is stepped down and distributed to various consumers. Consumers of different types need voltages of different levels.

The transmission system interconnects all major generating stations. Normally, the generated voltage is 11 kV or 22 kV. The transmission voltages are 220 kV and above. The voltage level is stepped down at the distribution substations and transferred to the industrial consumers at voltages between 4kV and 35 kV. The secondary distribution feeders supply to the residential and commercial consumers at 230 V. Thus, the network is really large, consisting of a number of generating stations, several transmission interconnections and the distribution network.

Operating States of Power System:

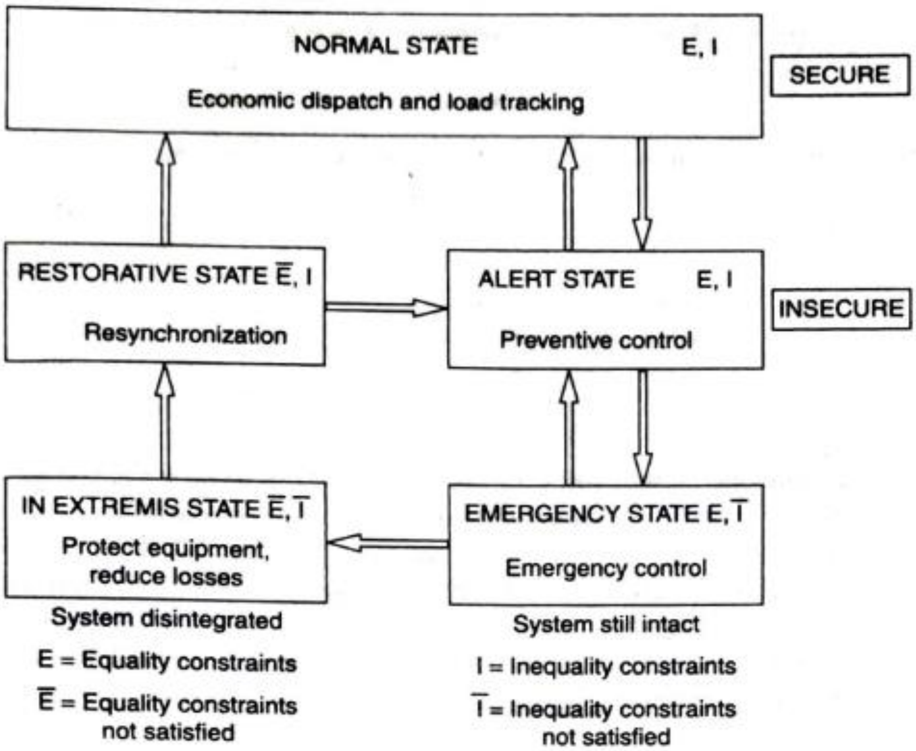

Fig.1 Operating states of a power system

The system operation is governed by equality and inequality constraints. The equality constraints are nothing but the power balance between generation and load. The inequality constraints set the limits on different operating parameters, such as voltage, generation limits, currents, etc.

For purposes of analysing power system security and designing appropriate control systems, it is helpful to conceptually classify the system-operating conditions into five states:

1. Normal operating state: In this state, the equality constraints (E) and inequality constraints (I) are both satisfied. The generation is adequate to meet the demand, without any equipment being overloaded. The system operates in a secure manner and is stable to withstand a contingency without violating any of the constraints.

2. Alert state: In this state also, the equality and inequality constraints are satisfied. However, the reserve margins are reduced. Therefore, there is a possibility that some inequality constraints may be violated in the event of disturbances that places the system in an emergency state. If the disturbance is very severe, the in extremis (or extreme emergency) state may result directly from the alert state. Preventive action, such as generation shifting (security dispatch) or increased reserve, can be taken to restore the system from the alert state to the normal state.

3. Emergency state: Due to severe disturbances, the system may enter an emergency state. This could be because of imbalance between generation and loads, either at the system level or at the local level. This could also be because of instability due to energy built-up in the system after a fault. Some strong control measures, such as direct or indirect load shedding, generation shedding, shunt capacitor or reactor switching, network splitting, fault clearing, excitation control, fast-valving, called emergency control measures are to be taken. If these measures are not taken on time, the system stability may be under threat and the system may eventually break down and go to the In Extremis state.

4. In Extremis state: In this state, both the equality and the inequality constraints are violated. The violation of the equality constraints implies that the generation and the load demand do not match. This means that some part of the system load is lost. Emergency measures must be taken to prevent cascading outages, total grid collapse and widespread blackout.

5. Restorative state: This is a transitional state, where the inequality constraints are satisfied by the emergency control actions taken, i.e., reconnect all the facilities and to restore system load, but the system has still not come to normalcy in terms of the equality constraints. We can have a transition either to the alert state or to the normal state.

Objectives of Control:

The fundamental requirements of a power system irrespective of its size are the following:

1. The system must be able to meet the continually changing load demand for active and reactive power. Unlike other types of energy, electricity cannot be conveniently stored in sufficient quantities. Therefore, adequate spinning reserve of active and reactive power should be maintained to take care of sudden variation in the load demand.
2. The power quality should meet certain standards with regard to frequency, amplitude and wave shape of generated voltage and level of reliability.
3. The system should supply energy at a minimum cost.

To achieve the above objectives, we have several levels of controls that are integrated in a complex way. Some of the controls act exclusively on individual components as described below:

1. The generators are provided essentially with excitation control, to keep the voltage and reactive power at the desired levels, and with prime mover control, to maintain the frequency and real power at the desired levels.
2. The prime mover control is concerned with regulation of the speed, and the controls are for the associated parameters such as water discharge quantity, boiler pressure, temperature, flows, etc.
3. Power system stabilizers are used to damp oscillations of the generator following a disturbance. A stabilizing signal is injected into the exciter system to damp the oscillations. Some of the commonly used feedback signals are frequency and real power.
4. The system generation control maintains the required active power balance in the system. The Automatic Generation Control (AGC) is responsible for maintaining this balance, which in turn is required to hold the frequency around the nominal value. The AGC also maintains the scheduled power flows in tie-lines, which are responsible for power transfer between different control areas.

5. The transmission controls include power and voltage control devices, which help maintain the voltage levels within limits, maintain system stability, protect the system and result in reliable operation of the system. The control devices are tap changing transformers, Flexible AC Transmission (FACTS) controllers, shunt reactors, shunt capacitors, phase-shifting transformers and HVDC controls.
6. Distribution level controls such as capacitors, wave shaping circuits, etc., are used to provide quality power to the consumer. These devices maintain the system voltage at the correct frequency and amplitude, and also help in removing harmonics injected into the load or the system. ·

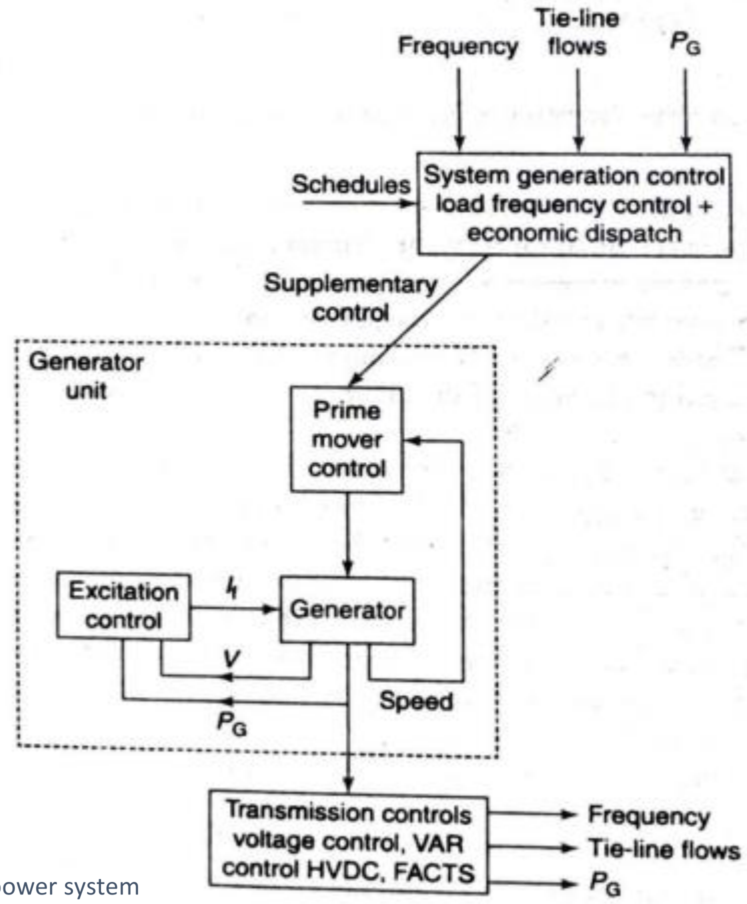

Fig.2 Various controls in a power system

The control objectives need to be defined properly. They are different under normal conditions and disturbances. Under normal operating conditions, we just need to keep tracking the load to match with the required generation, to maintain the frequency around the nominal value and regulate the voltage. However, under a disturbance, we need to take suitable control actions to prevent catastrophic collapse of the system. The control action depends on the state of the system.

The operation and control of the system should ultimately maintain the following:

1. **Stability:** Continued intact operation of the system, following a disturbance. This depends on the operating condition and the nature of the disturbance.
2. **Security:** It is the degree of risk in the power system's ability to survive contingencies without interruption to the customer. It is related to the robustness of the system.
3. **Reliability:** It is the probability of satisfactory operation over a long period. It denotes the ability of the system to supply adequate service on a nearly continuous basis, with a few intermittent interruptions over an extended time period.

Key Concepts of Reliable Operation:

The North American Electric Reliability Corporation (NERC) has proposed seven key concepts for reliable operation of the power system. These are:

1. **Balance the generation and the load:** The load on the power system is dynamic and changing all the time. The production by the generators must be scheduled to meet this constantly changing load. The AGCs are used to match the generation with the demand. The demand, though dynamic, is predictable and a load prediction is done, to keep the appropriate generation and reserve on hand. Failure to match the generation with the demand will cause frequency deviation from the nominal value. The frequency increases if the generation exceeds the demand and drops if the demand exceeds the generation. Large deviations in frequency are detrimental to the life of the equipment. Over-frequency and under-frequency relays operate when the frequency deviations cross the preset values.

2. **Balance reactive power generation and demand:** This balance is required to maintain the scheduled voltages. Reactive power sources are generators and capacitor banks. They must be constantly adjusted to maintain the voltages at all levels, within permissible range, to protect the equipment. The generator automatic voltage regulators control the voltage level of the generators. FACTS controllers are commonly used for reactive power control.
3. **Ensure thermal limits are not exceeded:** The heating limits of the overhead lines must not be exceeded; otherwise, the lines will sag into the objects given below. There are many critical blackouts which have resulted due to sagging of lines, leading to short circuits, relay tripping and ultimately grid collapse.
4. **Maintain system stability:** The IEEE/CIGRE has defined the stability as follows: Power system stability is the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact. If a system loses stability, the grid may face a total collapse. The stability limits will specify the maximum power that can be transferred over the lines. Angle stability is the ability of the generators connected to the grid to remain in synchronism. Voltage stability is the ability of the system to maintain steady acceptable voltages at all buses in the system under normal operating conditions and also after a disturbance. Both are vital for the health of the system.
5. **Meet N – 1 reliability criteria:** This means that the system should remain operational and secure even after the loss of the largest generator in the system. (N is the number of generators, N - 1 indicates loss of one generator). Further after a contingency, the operators must assess the health of the system in the eventuality of another contingency, and take suitable control actions to maintain system security, if it were to occur.
6. **Plan, design and maintain to operate reliably:** The planning, design and maintenance should be such that the system should be operated reliably and within safe limits at all times. Planning involves both short-term and long-term planning.
7. **Prepare for emergencies:** In spite of thorough planning and good design, emergencies such as weather fluctuations, operator error, software failure, equipment failure, etc., can occur. Operators must be trained to prepare for such emergencies.

Preventive and Emergency Controls:

Preventive control is meant to keep the system in the normal state or bring it back to the normal state from the alert state. Automatic controls are provided for frequency and voltage control. Preventive control measures commonly used are as follows:

1. Rescheduling of active power generated by various units, to match the changing load.
2. Scan-up of generation units and providing adequate spinning reserve.
3. Switching of shunt elements for reactive power control. This will help maintain the voltage within desired limits.
4. Change of reference points of controllable devices such as FACTs controllers, phase-shifting transformers, etc.
5. Change in the voltage reference points of generators and voltage control devices.
6. Change of substation configuration, like bus-bar splitting, etc.

Emergency control measures are taken to stop worsening of the situation, prevent degradation of the system and cascading failure effects and to bring back the system to the alert state. Under-frequency and under-voltage load shedding schemes are used. Some of the common emergency control measures are as follows:

1. Tripping of generators.
2. Load shedding.
3. Fast valving or fast water diversion which leads to a fast reduction in generation.
4. Controlled disconnection of interconnected systems to prevent spreading of frequency problems.
5. Controlled islanding to create local generation-load balance.
6. Blocking of tap changers of transformers.
7. Fast HVDC power transfer control.
8. Application of braking resistors.

Energy Management Centres:

It can be seen that the control of the modern power system is extremely complex. Modern energy management centres are embedded a number of functions. They comprise both hardware and software to monitor and control the system. Monitoring is fully automated. Controlling is a combination of automated and manual operations. Sophisticated computing machines have enhanced the system operation and control facilities. A hierarchical structure is used for control. The functions of energy centre can be divided into three subsystem blocks as follows:

1. The dispatch subsystem: This subsystem would involve the functions of unit commitment, economic dispatch, automatic generation control and demand forecasting.
2. Data subsystem: This subsystem is essentially for data acquisition and processing. It contains the units of SCADA, state estimation and all the associated alarms and displays.
3. Security subsystem: This subsystem is basically to oversee the secure operation of the power system. The functions included are security monitoring, contingency analysis, decision on control actions based on the state of the system, such as preventive control / emergency control / restorative control, etc., and decision on the VAR support to be provided in the system for the voltage profile to be maintained.

The hierarchical control can be broadly classified into three levels:
Level 1: Load forecasting, unit commitment and trading (longer duration)
Level 2: Economic dispatch, optimal power flow, Interchange evaluation (duration 5 -10 min)
Level 3: Automatic generation control, voltage control, state estimation (time in seconds)

Level 1 functions require statistical data and hence probabilistic methods are used. The results of level 1 are used in level 2 and level 3 functions. These are mainly deterministic in nature.

Major components of Energy Centres

The four major components of the energy management centres are as follows:

1. SCADA: The SCADA system consists of two subsystems - the supervisory control and the data acquisition. The supervisory subsystem is responsible for: (a) display at the central location, the status of circuit breakers and other devices such as tap changers, capacitor switching, generator voltage regulators; and (b) facilitating remote tripping of breakers, tap changing of transformers, etc. The dispatcher at the control centre will initiate actions to switch circuit breakers, change taps, etc. The data acquisition subsystem consists of the Remote Terminal Units (RTUs) to interface the power system instrumentation with the control devices and interface communication channels (wireless communication and Power Line Carrier Communication (PLCC) systems) and control centre.

2. Computers: Modern computers are having immense capabilities in terms of memory and speed. The structure of energy management centres has changed with advent of fast computing facilities. Since the applications are crucial, redundancy is built in the hardware. Different schemes are available for backup. The main functions of the computing facilities at the control centre are as follows:

- Real-time monitoring and control
- User interface
- Operating studies
- Maintenance and testing
- Simulation studies

3. User interface (with extensive GUI and display facilities): The user interface consists of consoles, data loggers, display units and screen projections to alert operators. Since there is extensive interaction with human beings, modern interfaces use techniques of animation and extensive graphics to make it more user friendly.

4. Application software: This section is to implement the various functions discussed, namely, Unit Commitment (UC), economic dispatch, state estimation, optimal power flow, contingency analysis, etc.

Supervisory Control and Data Acquisition (SCADA)

Introduction to SCADA and its Components: Supervisory control and data acquisition (SCADA) is a combination of supervisory control and data acquisition, along with the associated telemetry. They are used to control equipment which is geographically dispersed. It consists of both hardware and software. SCADA systems have made substantial progress in the past decade in terms of their performance, functionality, scalability and utility. SCADA is only for supervisory control and does not include a full control system. In electric power systems, most supervisory systems are meant to provide operators with sufficient information and control capabilities to operate the power system in a safe and secure manner.

- **Supervisory Control System:** The intention of supervisory control is to control a specific device to make it perform in accordance with a directed action. Some typical supervisory systems used in power systems are:

1. **SCADA:** A SCADA system performs traditional operations of data acquisition and control functions, including a limited amount of record keeping and data reporting.
2. **SCADA / AGC:** It is similar to SCADA, except that AGC capabilities are included to calculate the area control error, monitor system frequency and tie-line interchanges, and perform economic dispatch.
3. **EMS:** Energy management systems incorporate all features of SCADA and also includes other computations, such as load flows, state estimation, contingency analysis, etc. It includes extensive capabilities of record keeping and data exchange.
4. **DMS:** Distribution management systems are meant to monitor and control distribution feeder loads. DMS today includes topology analysis and load flow programs that allow identification of problems and restoration of services.
5. **LMS:** Load management system is meant to manage the peak load and is useful for, demand-side management. It can be a stand-alone program or integrated into EMS or DMS.
6. **AMR:** Automatic meter reading is incorporated into LM systems.

- **Telemetry:** Telemetry refers to the technique used in transmitting and receiving information or data over a medium. Typical data in a power system are the measurements of voltage, power flows, circuit breaker status, etc. The information is transmitted over a medium, such as cable, telephone, internet or radio. The information can come from multiple locations.
- **Data Acquisition:** It refers to the method used to access and control the information or data from the equipment that is being controlled or monitored. The data are then forwarded via the telemetry system. The information can be either in an analog or in a digital form. It is the data obtained from sensors, meters, actuators, control equipment like relays, valves, etc.

With the above definitions, we can now define SCADA as a collection of equipment that will provide an operator at a remote location with enough information to determine the status of a particular piece of equipment or an entire substation/power system, and cause actions to take place regarding that equipment or facility without being physically present at the location of the fault.

Components of SCADA System: The major components of a SCADA system are classified as:

1. **Field instrumentation** --- sensors and actuators generate the analog and digital signals that are monitored by the remote station.
2. **Remote stations** --- Remote Terminal Unit (RTU) is a computer with good interfacing for communication and flexible programmability, Programmable Logic Controller (PLC), which controls local actuators and monitor sensors with good programmability.
3. **Communication network** --- RS-232/RS-442/RS-485, dial-up telephone lines or dedicated landline, microwave, satellite, X.25 packet protocols and radio via trunked/VHF/UHF and Ethernet
4. **Central Monitoring Station (CMS)** --- the master unit of a SCADA system with a man-machine interface (MMI) or human-machine interface (HMI) program, mimic diagram of the whole system or plant displayed on screen for the operator, display of RTUs with present I/O reading, window for alarms and trending display
5. **Software** --- Proprietary and open types based on real-time database (RTDB).

Standard SCADA Configurations:

We have two distinct layers in a SCADA system: the client layer that caters to the MMI and the data server layer that handles most of the data control activities. The data servers communicate with the RTUs and are connected to them either directly or via networks or field buses that are proprietary or non-proprietary. Data servers are connected to each other and to client stations via LAN. The master station and the RTUs can be connected in a number of different ways. They are:

1**. Single Master Station Configurations**
a. Single master station and single RTU
b. Single master station and multiple RTUs
c. Single master station with multiple RTUs in multidrop circuit.

2. Multiple Master Station Configurations
a. Single dual ported RTU, radial circuit
b. Multiple RTUs, multidrop circuit
c. Multiple master stations, multiple single ported RTUs
d. Multiple master stations, multiple dual ported RTUs.

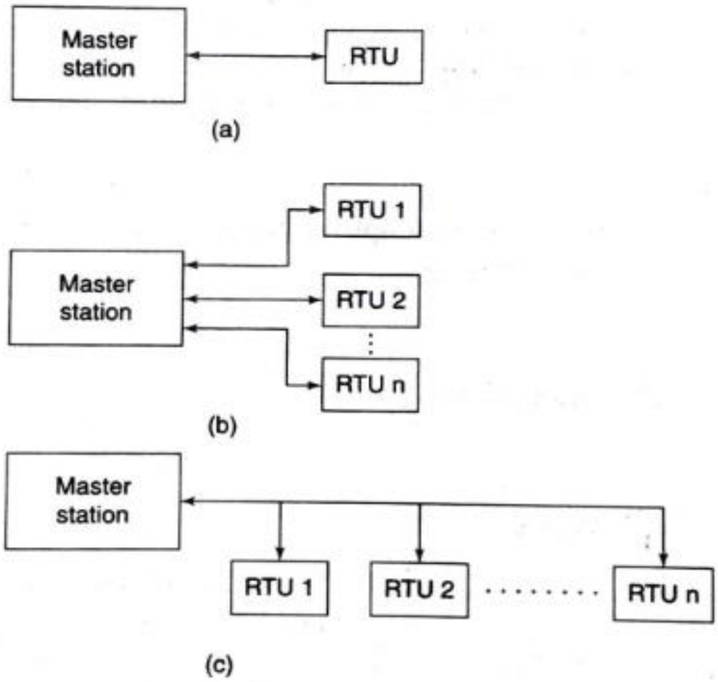

Fig.3 Single Master Station Configurations

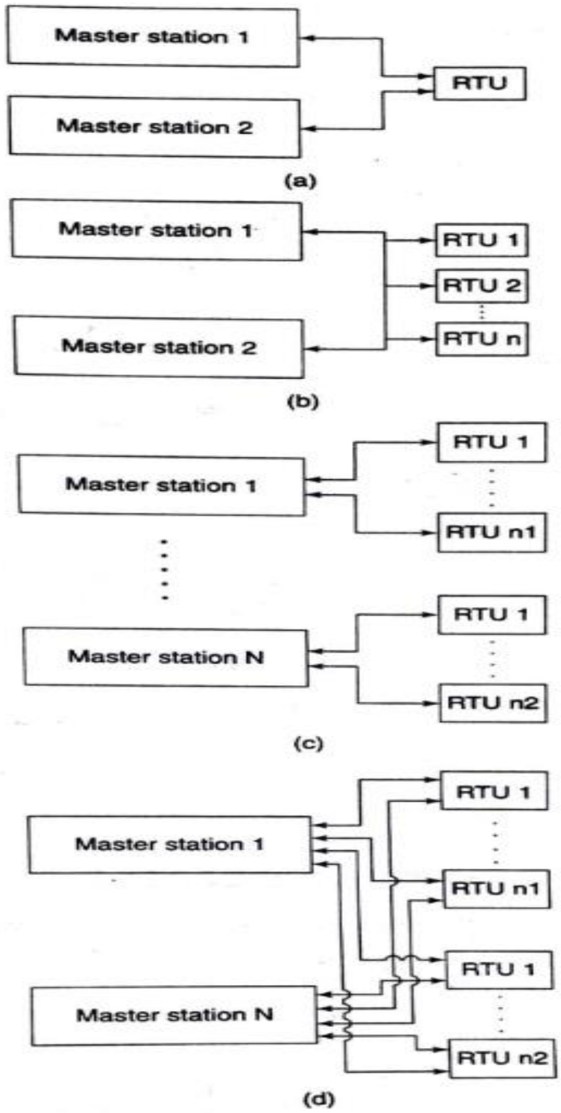

Fig.4 Multiple Master Station Configurations

3. Combination Systems
These are a combination of master stations and sub-master stations.

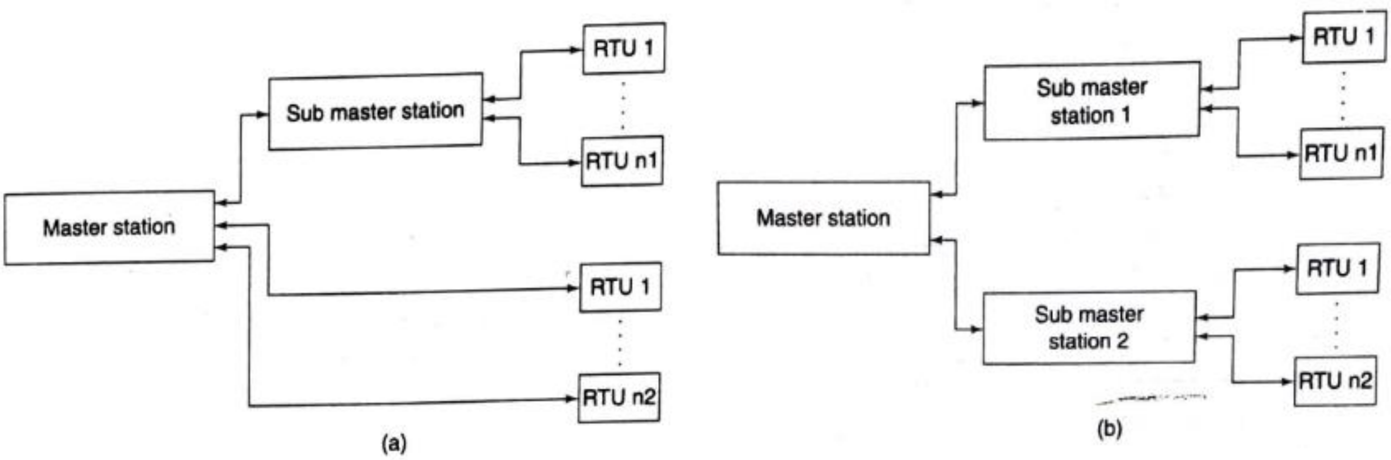

Fig.5 Combination systems

4. Systems with Gateway Connections

With the prolific use of Ethernet, gateway connections have become popular.

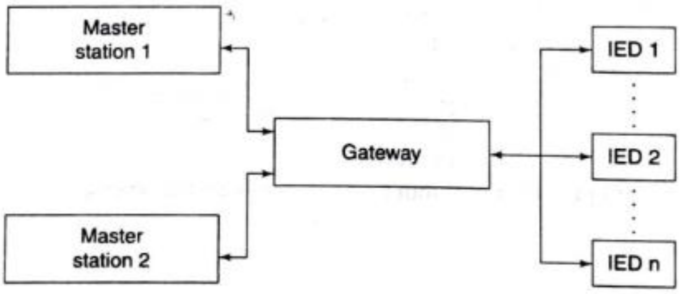

Fig.6 Multiple master stations with substation gateway connection

5. Networked Systems

Drastic technological advancements in networking have made such systems popular. They use WAN/LAN for networking, through routers.

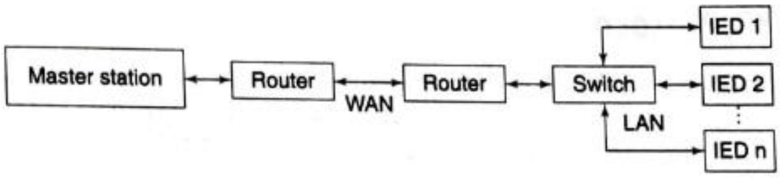

Fig.7 Networked systems with LAN connection via routers

Users of Power Systems SCADA:

The SCADA is useful to a number of people in the power utilities. Some of them are:

1. **System operators:** SCADA is meant to alert the operator to an event and help to initiate a control action in a timely manner.
2. **Relay operation:** To determine the operation of relays for faults. The time-stamping and sequence of events record helps the operator to analyse the operations and detect any maloperation if it has occurred.
3. **Maintenance department:** To determine the maintenance schedule of breakers or relays.
4. **Production department:** Use centralized data collection relating to unit and plant generation, station service, fuel use, efficiency, etc., to indicate how the power system has performed.

Thus, all the departments, in general, would be using the data and it is very essential to plan completely all the requirements, before designing the SCADA system.

Remote Terminal Unit (RTU) for Power System SCADA:

The RTUs used for SCADA in power systems collect data of analog quantities acquired from transducers, status of equipment and perform analog/digital conversions, check data, perform pre-processing tasks and send/receive messages from/to master station via interfaces. The parameters required are active power, reactive power, voltage, frequency, on load tap, status of circuit breakers, switches and isolators, sequence of events. The protocols commonly used are TN101 and DNP3.

The RTU mainly consists of:

1. **Analog input card:** This module accepts analog voltage and current inputs for transmission through the A/D converter to the main processor. Analog input interface up to 32 bipolar or unipolar inputs is available.
2. **Status input card:** This is responsible for collection, processing and reporting of various types of contact inputs for the RTU. The module should be capable of reading a number of discrete digital inputs. All digital inputs are bipolar and optically isolated.
3. **Control input card:** RTU control commands are handled by this module. Reliability and security are of utmost importance in issuing controls. Some functions available are master trip/close relay, select check - execute functions to provide security, local/remote switch to manually disable relay coil power and contact wetting during maintenance, etc.
4. **Central processing unit:** This contains a powerful processor to handle data collection and delivery to host computers, run local automation algorithms and maintain reliability in a substation. Serial ports are available for communication to master station, other RTUs and IEDs such as relays and meters. The RTU firmware resides on the main processor and it has to support all required system function applications.

Functions of RTUs:

Some of the functions of RTUs are briefly described below:

1. Time synchronisation: Events occurring in the power system have to be updated and recorded in the main server in the same chronological order in which they have occurred. This requires that the time of the clocks of all RTUs of all the substations is same and RTU time is synchronised with the standard time acquired from their GPS at predefined short periodic intervals. This ensures data integrity.

2. Select before execute: When a control function such as opening or closing of a circuit breaker/isolator is to be performed by the operator, the select before execute sequence is performed. (A select message is first sent from the master station to the RTU to ensure selection of the correct equipment. The RTU reciprocates with a positive or negative acknowledgment signal for confirmation by the operator. The master station then sends an execute command to the RTU to complete the control cycle.)

3. Reports by exception: This function is provided to reduce the number of data transfers to the master station from the RTU, thereby reducing the load on the communication channel. (A dead band is defined for each analog signal such as voltage, current, power, etc. The RTU calculates the difference at every scan cycle and the analog value is transmitted to the MCC only when the difference is greater than the defined dead band. With respect to digital data such as status of circuit breakers, isolators, etc., the data are sent whenever there is a change.)

Other important functions of the RTU are:

1. Scanning of data from the field continuously
2. Sending data to FEP (Front End Processor) without interruption
3. Sequencing of event (SOE) recording with time-stamping
4. Display of data to local systems
5. Logging of data
6. Executing control commands
7. Self-diagnostics
8. Configuration of data from host and vice versa
9. Time synchronization with host computer.

Common Communication Channels for SCADA in Power Systems:

SCADA in power systems use different communication channels. These are:

1. **Power Line Carrier Communication:** The power lines are used to carry the communication. This channel is common, has a simple technique, is easy to maintain and cheap. It is used for speech and data transmission. The speed of data transmission is limited and long distance, point-to-point communication is not easy. Modems are used at the sending as well as at the receiving end to modulate and demodulate power and data, respectively. In this system, since the conductor acts as a medium of transmission there is attenuation in the transmitted signal.

2. **Microwave Communication:** The frequency range is from 1 GHz to 1000 GHz. A choice of 10 GHz would limit the transmission distance to 5 miles. The main advantage is that the data carrying capacity is high due to the large bandwidth and the data are totally protected from noise.

3. **Fiber-Optic Communication:** This is becoming very popular in the power sector because of the wide bandwidth and high transmission rate over long distances. It produces no emission outside the cable and is nor affected by external radiation, and hence preferred where security is an issue. Further, it is totally not affected by (immune to) electromagnetic interferences, corrosion and noise.

4. **Satellite Communication:** Satellite communications for SCADA networks form a reliable alternative to traditional methods. The benefits include broadcast networks (wherein multiple stations can receive a single message), cost effectiveness when compared to landlines or radio towers, highly reliable with world-wide coverage and easy to integrate with RTUs.

Challenges for Implementation of SCADA:

Though they are widely used, there are a number of challenges in applications of SCADA to power systems. Some are:

1. Ensuring fail safe system functionalities on a 24 x 7 basis.
2. Implementation of innovative techniques to ensure situational awareness for the grid operator.
3. Ensuring total observability of the system in real time.
4. Ensuring availability of correct data.
5. Integration of EMS functions to predict grid behaviour.