Transmission System Protection
Voltage Stability, Over/Under Frequency Protection
and Load Shedding

ES 586B
Power System Protection

Instructor:
Dr. T. S. Sidhu

NAME: AHMAD MOSAVI
STUDENT ID: 250441993
Load Shedding and Frequency Relaying

1. Introduction

In a system operating in a normal frequency the power generated by the generators is equal to the sum of all loads connected to the system plus all the losses. When a fault appears one of the consequences could be a frequency change in the system. If the sum of connected loads and losses in the system exceeds the amount of mechanical power provided by the generators, rotors will slow down and therefore the frequency drops. Conversely if the generated energy is more than demand the rotors will speed up and the frequency will rise. As we can see the speed of rotors specifies the frequency of the system.

In different systems we have Unit Governors which will sense small changes in the loads connected, and will adjust the generated (input) power with the power we need to sustain the frequency all the time.

In sudden and large changes like when a system looses a generator the frequency drops rapidly. If the governors cannot response quick enough the system may collapse and cause disastrous consequences.

In these situations a rapid and selective drop of loads may help recovery possible preventing a total system shut down.

2. Rate of Frequency Change

As we know ‘Generation = Loads + Losses’ in a stable system and during a fault the frequency may vary.

The equation we have for the initial rate of frequency change is:

\[ \frac{df}{dt} = \frac{-\Delta P}{2H} \]

\( \Delta P \) is the power difference during a fault in per unit.

\( H \) is the inertia constant (\( \frac{KW - \text{sec}}{KVA} \)).

For instance a generator rated at 100MVA with an inertia constant of 4 has a kinetic energy of 400MW-sec or 400MJ which means the generator can supply its full load for 4 seconds with no input power before its rotor halts.

So the larger the inertia constant the slower the frequency drops for a given overload.
When $\frac{df}{dt}$ is negative it means the frequency is dropping in the system causing a drop in the load power. Studies show a 1% drop in frequency (0.6Hz) will cause a 2% load reduction.

Most 60Hz plants will operate down to 55Hz on a temporary basis but under no circumstances should long-blade turbines be permitted to operate at a frequency below 59.5Hz (58.5Hz for short-blade turbines).

To avoid operation at reduced frequency we have to shed the load and trip the circuit breakers to disconnect some of the load from the source of power.

### 3. Load Shedding

When load increases in a system, unit governors will sense the speed change and increase the power input to the generator. Extra load will be handled by using the unused capacity of all generators operating in the system (spinning reverse).

If all generators are operating at the maximum capacity (spinning reverse is 0) it is necessary to disconnect a portion of the load, equal or greater than the overload, intentionally and rapidly.

As frequency is a reliable indicator of an overload situation, frequency sensitive relays can be used to disconnect a portion of the load automatically.

This arrangement is referred to as Load-Shedding or Load-Saving scheme and is designed to protect system against frequency interruptions.

Under frequency relays are usually installed at distribution substations where selected loads can be disconnected which will balance load and generation.

The first line of these relays is set just below normal operating frequency range (59.4-59.7Hz). When the frequency drops below this level, these relays will drop a significant percentage of system loads. If the frequency stabilizes (or increase), it means the load drop was sufficient, but if the frequency continues dropping (with a slower rate) until it reaches the second line of relays, a second block of load is shed.

This will continue until the overload is relieved or all the frequency relays have tripped.

### 4. Frequency Relays

There are three general classes of frequency relays:

The Induction-Cylinder Relay, the Digital Relay and the Microprocessor Relay.
4.1. Induction – Cylinder Relays

The principle of operation of this relay is based on a circuit in which the phase angle changes as the frequency varies. The phase relation between the current and the reference current produces a torque that changes direction when the set point frequency is reached. This relay is fast and accurate for most applications, but precaution must be taken in designing the device so the phase shift associated with faults does not cause misoperation in the system.

In induction-cylinder relays there is a time delay of six cycles (minimum) until the relay trips. The tripping characteristics are shown in the figure below.

This type of plot is useful to find out the frequency at which the tripping will occur.

The cycles of delay parameter linked to each curve is the intentional time delay setting after the cylinder unit closes the contact.

This graph includes the inherent cylinder operating time.

For example if we take the six cycle delay curve with a 10 Hz/sec frequency decline, the trip contact will close when the frequency is 2Hz below the setting.

Total operation time will be 12 cycles in this case which means the cylinder unit operates in six cycles and the timer adds a six-cycle delay to it.

4.2. Digital Frequency Relays

In digital frequency relays zero crossing of voltage is detected and a counter starts and continues counting until the next voltage zero or in some cases the next positive going zero crossing (one cycle). This will show us the period of the waveform and the frequency can be calculated.

The accuracy of this relay is 0.005Hz and depending on the condition the relay trips after a specific number of irregular readings occur in three consecutive periods. If the frequency is satisfactory the relay will reset and count to 3(cycles) for the next cycle of reading.
4.3. Microprocessor Relays

The principle of microprocessor relays is the same as digital frequency relays but some additional complexities are included. All the self-checking provisions and examination of various failure modes are built inside these relays. Multiple set points are common among these relays so they can be used for over and under frequency applications. Some of them have restore function which is set at a frequency level which indicates that the power system has recovered and is able to return the load that was shed back to the system.

5. Designing a Load-Shedding Scheme

Many procedures have to be considered for load-shedding schemes in a specific system. We need to anticipate the maximum overload, number of load shedding steps, size of load shed at each step, frequency setting, time delay and location of the relays. A brief explanation of each step has been expressed below.

5.1. Maximum Overload

The relays we use in the system should be able to shed the entire load during overload situations. This is because we don’t have to limit the load shedding to a portion of the load since we have to do anything to avoid the system to collapse. So if it is necessary we have to cut 100% of the load to protect the system. So we have to anticipate the overload and all the losses that might appear in our system. We also have to do stability studies to detect places that if islanded or separated from the rest of system would have severe generation deficiency.

5.2. Load-Shedding Steps

When the relays sense a frequency drop in the system, usually the first step is to drop a prearranged percentage of the load even if it is more than the generating frequency decline (since it can be restored rapidly). Now if we use two groups of relays we can get better results as one group operates at a lower frequency than the other group and we can divide the shedding loads between these two groups of relays. So during overloads the first predetermined loads will drop after a specific frequency drop and if that is not enough and the frequency still decreases the second group of relays will trip cutting off the second group of loads.
Most utilities use between two and five load shedding steps (as it is difficult to coordinate many steps) where three steps is the most common.

5.3. Size of Load Shed Per Step

Depending on the system configuration and load shedding steps the load percentage of each drop will be determined. In a three step load shedding system we can have something as follows:
Step1 Shedding 12% of the total load.
Step2 Shed an additional 8% of the remaining load (20% of total)
Step3 Shed an additional 12% of the remaining load (32% in total)

5.4. Frequency Setting

Setting the frequency at which each load shedding step will occur depends on the system normal frequency range, the accuracy of the relays and the number of load shedding steps.
For instance the solid-state type 81 relays or microprocessor relays may be set from 55 to 59.9 Hz within 0.01Hz of the lowest expected frequency.
For electromechanical relays the highest setting is approximately 0.1 to 0.2Hz below the expected frequency. No matter the type of relay we use, the frequency has to be chosen in way to avoid major disturbances as the system can’t recover on its own in those cases.

5.5. Location of the Frequency Relay

In large systems, the load-shedding relays should be spread throughout the system to avoid heavy power flows and undesirable islanding.
Load-shedding in one area, can cause heavy power flow over transmission lines from the area where the load was shed, to areas of excess load. Because of the original disturbance, these lines may already be operating at high emergency levels, and the uneven load-shedding may cause thermal overload or system instability.
Loss of generation in certain areas of the system will also result in frequency dispersion as the frequency in the overloaded areas will drop faster than elsewhere. The difference in frequencies naturally produces rapidly increasing torque angles on the transmission lines, which may cause the system to go out of step.
That is why load-shedding relays in the area of greatest frequency decline will trip first which alleviates the uneven loading, helps to bring back the system to uniform frequency and avoids the impending loss of synchronism. We have to install some extra load-shedding capability in any portion of the system that is susceptible for overload situations.

6. Voltage Stability

There are two kinds of disturbances that make a power system unstable:
1- Gradual variation of system condition, like a gradual change of load
2- Severe changes of system conditions such as faults or losses of an important generator(s) or bus.
Voltage stability problems usually occur in heavily stressed systems. While the disturbance leading to voltage collapse may be initiated by a variety of causes, the underlying problem is a natural weakness in power system. In addition to the strength of transmission network and power transfer levels, the principle factors contributing to collapse are the generator reactive power/voltage control limits, load characteristics, characteristics of reactive compensation devices and the action of voltage control devices such as transformers.

6.1. Small-Disturbance Instability

A power system stability point is composed of independent voltages and currents. When the situation changes (like a load change) system stability will change accordingly. If the changes are small the transition is instantaneous the system wont lose stability, but at certain conditions when maximum power point and power angle changes we will lose stability. This point is called ‘Bifurcation’ point and it results small disturbance instability.
Small disturbance instability can be classified into angle and voltage stability. If the bifurcation point occurs because generator angles has been increased to their limits, the stability is called SD angle instability and if it appears because bus voltages are decreasing to their limits it is called Voltage instability.

6.2. Large-Disturbance Instability

Large disturbance move a system far away from the stable point. After the disturbance if the system recovers to its equilibrium point, it is stable otherwise it is instable.
The large disturbance instability studies are based on whether the system is able to return to its stable condition or remains instable.
Based on the dynamic system theory, there is a region around any stable equilibrium. If the system’s initial transient states fall in this region, the system will recover to the stable point. If the initial states are outside of this region, the system will be unstable. This region is defined as the field of attraction of the stability point.

Finding this stability point is easier in linear systems as they remain stable after a large disturbance.

The figures below show the concept of linear system stability. In figure (a) the ball is in its stable point. In figure (b) the ball is away from its stable point but it will eventually return to the stable point.

In nonlinear systems, the situation is quite different, as shown in the next figures. Depending on the disturbances or its initial positions, the ball may not return to its previous stable point and may never return to any stable point. When the ball falls inside the domain of a stable equilibrium it will become stable and return to the stable point eventually.

Under large disturbances such as short circuits or loss of important lines or generators, a power system cannot be described by a linear model. This is mainly because the real and reactive power terms include sine functions and multiplications of voltages.

Figure (a) shows a nonlinear system with two balanced areas with two equilibrium points.
When a disturbance occurs at time T the ball might stay in area 1 or as we can see in figure (b) if the disturbance is large enough it will be shifted to the second area or sometimes to an unbalanced area with no equilibrium point.

7. Voltage Instability Protection

The index of voltage instability has to be simplified for protective relaying applications as they require extensive computation and information. This will guide us in designing more practical voltage instability protection tools. So to come up with a protection design we have to identify and predict the occurrence of voltage instability in the system.

7.1. Reactive Power Control

Voltage instability is mainly caused by system failure in providing sufficient reactive power. Control of the reactive power sources is one of the effective methods in preventing voltage collapses. Capacitors can deliver reactive power to the power system and keep system voltage within acceptable limits. To ensure that capacitor banks are activated only during voltage collapse conditions (not during fault conditions) capacitor banks switching is sometimes supervised by zero sequence over-voltage relays or over-current relays.

The other way to achieve this purpose is by delaying switching actions, provided that faults can be cleared within a short period of time. Therefore it can be controlled by delaying the capacitor banks to distinguish faults. This method is applied to subtransmission systems at 161kV and distribution systems at 46kV, but for transmission systems over 230kV fast capacitor switching is required because of the potential impact of extended low voltage conditions. For this purpose Programmable-Logic-Controller (PLC) high speed capacitor control schemes have been used for fast switching. (A time delay of 0.2sec is used to avoid switching during fault conditions)

Other than mechanically switching capacitors, there are other reactive power sources which can prevent voltage collapses. The reactive sources include static var compensators (SVCs), static condensers (STATCONs), synchronous condensers, and generators. They are usually controlled by solid-state switches so they provide varied reactive power in a continuous manner. When the reactive power sources reach their maximum limits and voltages at main buses are still in a dangerous state, other solutions such as load shedding has to be used.
3.2. Load Tap Changer (LTC) Blocking Schemes

During normal conditions load tap changers will adjust the tap to a lower level if the controlled voltage is higher than a desired upper limit; similarly LTCs will adjust the tap to a higher level whenever the controlled voltage is lower than the desired lower limit. Under low-voltage conditions, the LTCs will make the situation worse, especially when load reactive power demand is very sensitive to voltage levels. Under such a situation, the voltage rise by LTCs will cause a significant increase in reactive power demand and thus widen the gap between reactive power supply and demand. It is recommended that LTCs be blocked from trying to raise voltages whenever there is a clue that there is an upcoming system voltage collapse.

3.3. Load Shedding

Load shedding is applied when all other options have been executed but there is still voltage drop in the system. As described previously in this article undervoltage load shedding is implemented in stages and a time-delayed fashion. We have to determine the amount of load to be shed, verify time steps of load shedding and select the loads that have to be shed.

References:

1. Power system voltage stability / Carson W. Taylor; edited by Neal J. Balu, Dominic Maratukulam


4. Power system stability and control, Kundur