CHAPTER FOUR

REMEDIAL MEASURES

4.1 REMEDIAL MEASURES

A large variety of corrective equipment and procedures can be used to minimize flicker. Those most commonly considered are:

4.1.1 Motor Generate Sets

In general, it is probably true that a motor-generator set between the utilization device and the power system gives the maximum possible reduction in flicker, because it is effective in minimizing three of the most undesirable load characteristics: single phase, low power factor, and sudden application. Since the only tie between the motor and the generator is the shaft, the disturbances due to single-phase load or to low power factor are not transferred to the power system. When more than one utilization device causing flicker is involved, the question of a single m-g set versus an m-g set for each such load must be answered. In these cases it is very important to consider the regulation of the generator of the set and how constant a voltage is required by the utilization devices. For example, it frequently happens that a factory is using several electric welders which produce 5 percent voltage dips of very objectionable frequency. This 5 percent drop usually does not affect the performance of the welders, and they could be operated at, random on the power system. If a motor-generator set is to be used, however, the transient reactance of the generator is apt to be as high as 35 percent based on its rated current, and, assuming that the welder reactive current equals the generator rating, a 35 percent drop in voltage would occur. If only one welder is operated at a time, this is quite satisfactory, as the welder tap can be set on the basis of "closed circuit" voltage, that is, the regulation of the generator can be taken into account. If, however, another welder is operated simultaneously, even though on another phase, the additional voltage drop, uncompensated by the welder tap, is enough to spoil the weld. In order to operate several "choppy" loads simultaneously from the same m-g set, it is therefore necessary to use an oversize generator (from a thermal standpoint) to keep the regulation within required limits. Alternate solutions are to interlock utilization devices so that they cannot operate simultaneously or to provide separate m-g sets for each device. Another alternative is to use one common driving motor and several separate generators on the same shaft. The separate m-g set plan has the advantage of permitting operation at partial capacity in case of damage to one set, but is costlier.

4.1.2 Phase Balancers:

In industrial plants a large percentage of the potential causes of flicker are single-phase devices. A discussion of phase balancers is, therefore, of interest, although there have been few commercially installed.

In a single-phase circuit the flow of power pulsates at a frequency twice that of the alternating supply, whereas in a balanced polyphase circuit the flow of power is uniform. Therefore, in order to effect a conversion between a single-phase and a polyphase system, some energy storage necessary. This storage may be made in static devices such as inductances and capacitors, or in rotating equipment with mechanical inertia. Except for small sizes, the static equipment has not yet been found commercially practical. The most familiar type of phase converter is that shown in Fig [4.1] It has been extensively used in railway electrifications to convert single-phase power from the contact system to three-phase power for the locomotive motors; this is merely the converse of the phase-balance. As shown, a rotating two-phase machine is connected to the three- phase power system through the equivalent of a Scott- connected transformer, which also serves as the primary for the single-phase load winding.

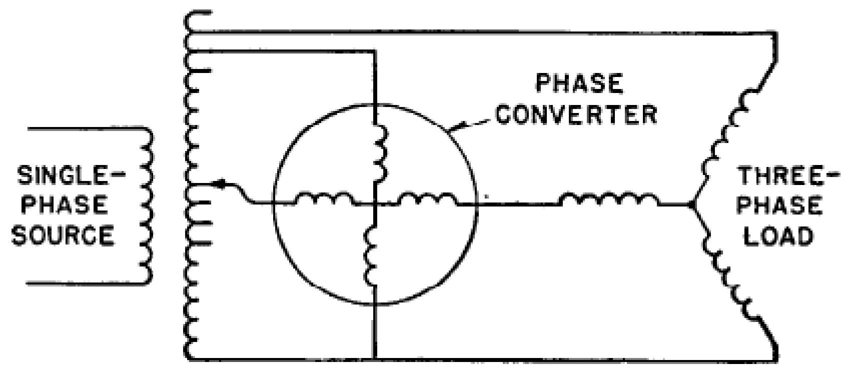

Fig [4.1] Schematic diagram for phase converter used extensively on railway electrifications to convert single-phase power from the trolley to three-phase power for the locomotive motors. A rotating two-phase machine is connected through the equivalent of a Scott-connected transformer to the three-power system.

The two-phase machine may be of the induction type and act as a phase converter only, or it may be synchronous and used for power factor correction as well. Because of the regulation of the machine, the source currents are not balanced during variable- load conditions, unless the taps on the transformer winding are varied. From this point of view, it is not very suitable for “choppy” loads. Where there are several separate single-phase loads to be served, the capacity of a converter of this type must be equal to the sum of the individual loads. The series type of phase converter is shown in Fig [4.2] this is probably most efficient for conversion from three- phase to single-phase, where the single-phase load is not expected to grow, cannot be distributed between phases, and where no power factor correction is required.

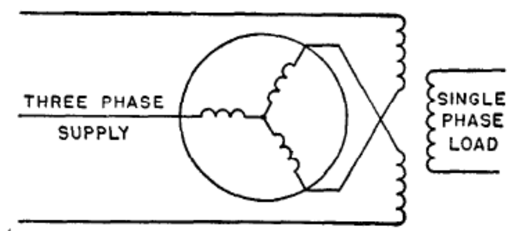

Fig [4.2] Series type of phase converter from three phase to single phase.

It consists of a counter-rotational induction-type series machine, connected through transformers in such a manner as to offer a high impedance to negative-sequence current between the single-phase load and the three-phase supply. When a single-phase load is suddenly applied, a magnetizing transient results, so that part of the negative-sequence component of load current is passed on the source. Although this transient subsides in about 0.1 second, it detracts considerably from the value of the scheme for use with "choppy" loads.The series impedance balancer shown in Fig [4.3] consists of an auxiliary induction-type machine in series with the polyphase supply and with the main shunt machine. The single-phase load is drawn from between the two the series machine rotates oppositely to normal direction for positive-sequence applied voltage, and therefore, offers high impedance to negative-sequence currents and low impedance to positive-sequence currents.

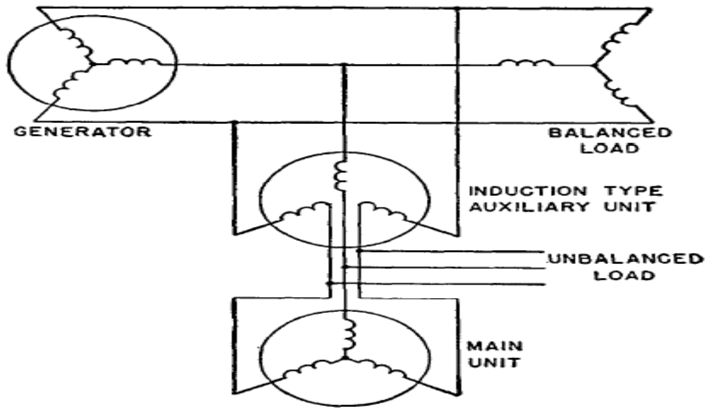

Fig [4.3] Series impedance type of phase balancer.

The shunt machine therefore takes the negative-sequence component of load current. The positive-sequence component of load current is taken by the system if the shunt is an induction type unit. If a synchronous type unit is used for the shunt machine, it can also take the wattless component of load current with suitable control of excitation. As with the series phase converter, the series machine does not immediately respond to load changes, and temporarily (for about 0.1 second) some unbalanced current is drawn from the source. The scheme, like the series phase balancer, is inherent in its action, no regulators being required unless power factor correction is used. This method has one important advantage over the previous two schemes in that the size of the shunt machine need only be enough to take care of the maximum unbalance of Phase balancers, as a class, are not particularly suitable for flicker elimination except perhaps in borderline cases where only a moderate improvement (perhaps a one-half reduction in voltage dip) is required. In this case they may be the cheapest and most efficient remedy.

4.1.3 Synchronous Condensers:

The voltage dip on a power system resulting from a suddenly applied load is equal to the vector product of the current and the system impedance giving proper consideration to vector positions. Consequently, one way of reducing flicker is to reduce the system impedance. Usually, the system impedance is predominantly inductive, and flicker is caused by current of low power factor so that most, of the voltage drop is due to the reactive component of the system impedance.The effectiveness of a synchronous condenser can be much improved by the use of reactors between the power system and the load and operating the condenser from the load bus. This scheme permits greater voltage fluctuations on the condenser and, therefore, causes it to bear a greater proportion of the fluctuating component of current. The customer's bus volt age, of course, undergoes the same voltage fluctuation, and this fact plus the fact that only a limited amount of series reactance can be used without unstable condenser operation, limits the extent of improvement. In most instances, it is likely that a reduction of flicker to one-half its uncompensated value is the economic limit of correction by this means. Where only this amount of correction is sufficient, the synchronous condenser and series reactor scheme may be the best economic solution, considering the power factor correction and control of voltage level afforded by the machine. The suggestion has been made of using a driving motor for the synchronous condenser to permit higher values of series reactance without instability. This arrangement is the equivalent of a motor-generator set with a reactor paralleling the motor and generator ends. This scheme has never been used in practice, but calculations of performance and cost estimates indicate that there is little advantage compared with the straight m-g set or condenser-reactor schemes.

The benefits from the use of synchronous condensers for flicker reduction depends in a large measure upon bon low the subtransient and transient reactances can be made. The modern standard low-speed salient-pole synchronous condenser has been developed primarily for power factor correction and voltage control, and low-cost and low-loss condensers have relatively high reactance. A typical ma chine has subtransient and negative sequence reactances of about 25 percent and a transient reactance of 35 percent. A reduction in these reactances usually results in both higher costs and losses. The high-speed (3600 rpm) cylindrical-rotor type of machine inherently has lower react- antes, perhaps one-half or less, but the cost and losses are both greater. In larger sizes and where other circum stances are favorable, the overall economy may justify the use of outdoor highspeed hydrogen-cooled synchronous condensers of low reactance.

Another way to decrease the reactance of the synchronous condenser is to use capacitors in series with the machine leads. The capacitive reactance partially nullifies the machine's inductive reactance giving a lower net reactance. This scheme theoretically should be quite effective and economical. However, the series capacitors may cause the synchronous condenser to hunt. The boundaries of satisfactory operation have not been fully explored, and predetermination is difficult. It is expected that after an experimental installation of this form of compensation is made that practical information will be available.

4.1.4 Series Capacitors

There are two main uses of series capacitors, depending whether they correct for the inductance of the supply or for that of the load. Their most familiar use is for line drop compensation; the application to equipment correction is more recent and shows much promise, as it improves conditions in the entire system, whereas the line capacitors benefit only those customers beyond the point of capacitor installation. Being in series with the entire power circuit, series capacitors are instantaneous in their corrective effect. This is perhaps their most valuable advantage because any change in line current causes an immediate change in compensating voltage. Another advantage is that they generate lagging reactive kva proportional to the square of the current, thereby improving the power factor.

Series Capacitors Connected in Line

Fig [4.4] shows in (a) a layout ordinarily favorable to the application of series capacitors. The transmission substation is assumed to have bus voltage regulation so that the voltage is fairly constant. The step-down transformer bank and the low- voltage line feed a distribution substation serving the fluctuating load and lighting loads; no loads are served at intermediate points between the substations. The series capacitor may be installed near the transmission substation, as shown in (b), or near the distribution substation. Another alternative is to install the capacitors between the transmission substation bus and the step-down trans former (depending upon which voltage is more suitable for standard capacitors). The voltage along the line is shown by the diagram at (c), Curve A showing the un compensated voltage and B the compensated voltage. The point of interest emphasized by (c) is that the compensating voltage is introduced in one step while the voltage drop along the line is uniform. For this simple case with no intermediate line loads, the voltage gradient along the lint is unimportant, and, subject to limitations outlined later, complete voltage drop compensation at the distribution substation may be secured.

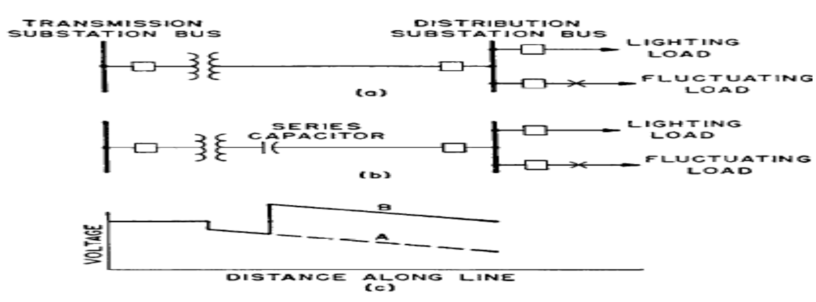

Fig [4.4] Typical application of series capacitors.

(a) Layout ordinarily favorable to application of series capacitors

(b) Location of series capacitor

(c) (A) without capacitors; (B) with capacitors.

Where there are distributed loads along a line, it is necessary to consider the location of the capacitors. The capacitor gives its full voltage boost at the point of its installation, and therefore loads immediately ahead and behind the capacitor differ in voltage by the amount of boost in the capacitor.. In general, the best capacitor location is one-third the electrical distance between the source and the flicker-producing load, as shown by Fig [4.5]

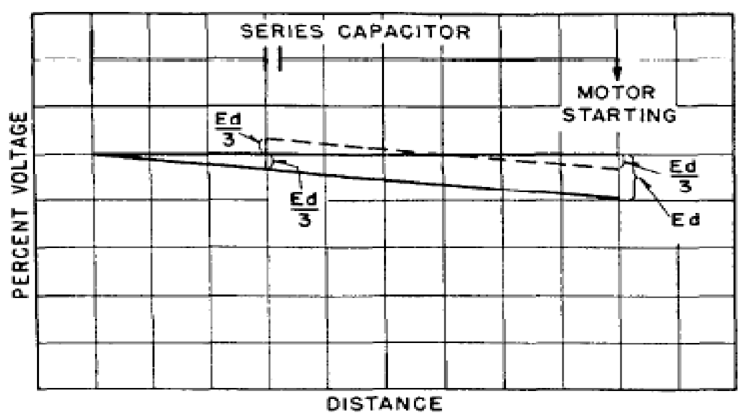

Fig [4.5] Percent voltage regulation-in general, by placing the series capacitor about */3 of the electrical distance between the source and the load, the voltage on both sides of it are kept within plus or minus limits in which flicker is not objectionable.

In principle series capacitors are effective in reducing flicker caused by practically all types of fluctuating loads. However, their effect is only beyond their point of installation; hence they do not correct the system as a whole. For example, a series capacitor installed just ahead of substation B in Fig [4.11] may remove most of the voltage fluctuation on that bus. However, at Station A, there may still be considerable voltage fluctuation, as the series capacitors do not correct the supply circuits. Another point to be noted from Fig [4.6] is that the series capacitor must be large enough to carry all loads beyond its point of installation.

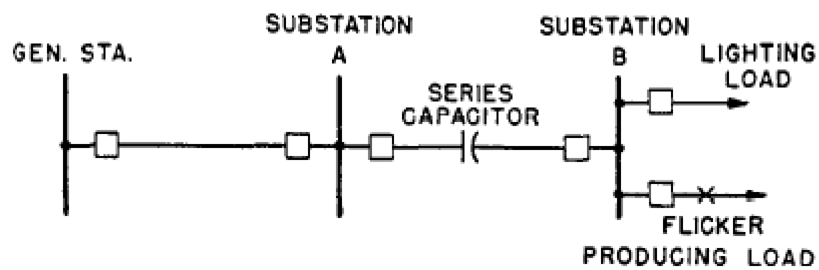

Fig [4.6] Series capacitor must be large enough to carry total substation load.

Consequently, if the flicker-producing load is small as compared with normal load, the cost of the series capacitor is too high for the correction obtained. Series capacitors are therefore economical primarily where the flicker load is a large portion of the total, where the circuit resistance is equal or lower than the reactance, where the flicker-producing load is of low power factor, and where the supply circuits are fairly long.

Under certain circumstances series capacitors will produce, in conjunction with other apparatus, voltage or current surges in the line. The magnetizing inrush current of transformer banks, and the self-excitation of synchronous or induction motors are some of the factors causing this phenomenon, which is too involved for treatment here.

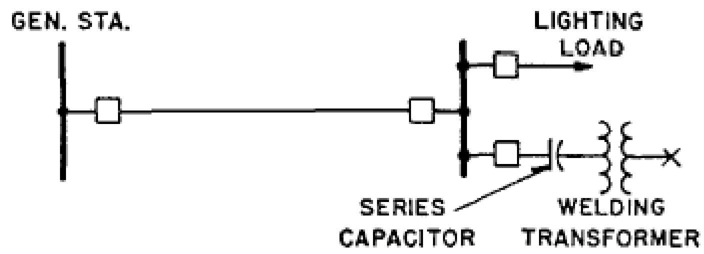

Fig [4.7] Series capacitor installed with a welding load to reduce kilovolt ampere demand and improve power factor.

Capacitors in Series with the Equipment

This application is limited to utilization equipment with a constant inductive reactance, for which it is possible to compensate with a series capacitor, so that the load drawn from the supply circuit is practically at unity power factor at all times. Thus, although the power drawn from the line is still fluctuating, the resultant flicker voltage is great11 reduced. Figure [4.7] shows such compensation applied to n melding transformer. Inasmuch as the load itself is corrected, the benefits are felt all over the supply system. Several such applications have been successfully made to spot and seam welders.

4.1.5 Shunt Capacitors

Contrary to frequent misconceptions, permanently connected shunt capacitors are of no benefit whatever in minimizing flicker; in fact, they may make it slightly worse. An example shows the reason readily. A system with 10 percent inductive reactance in the supply leads, serving an intermittent load having an inductive reactance of 100 percent is shown in Fig.[4.8](a). Resistance in both line and load will be neglected to simplify the example, but the same general effect will be observed if resistance were present.

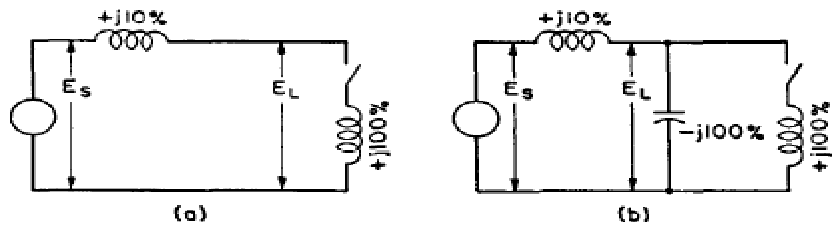

Fig [4.8] Shunt capacitors are not effective in reducing voltage dips.

When the switch is open $E_L = E_s$. When the switch is closed, the voltage at

$E_L = (+j100/(+j10+j100))E_s = 91$percent E_s.

Fig.[4.8] (b) shows a similar circuit except a capacitor having a reactance equal and opposite to that of the load is permanently connected in the circuit. When the switch is open, the voltage

$$E_L = \left(-\frac{j100}{+j10 - j100}\right) E_s = 111 percent\ E_s.$$

When the switch is closed, the net load impedance is

$$\frac{(-j100)(+j100)}{-j100 + j100} = \infty.$$

This means that the combination of the capacitor and reactor draws no current from the source, and $E_L = E_s$. Thus, comparing the two cases, without the capacitor the voltage drops from 100 percent to 91 percent, a change of 9 percent. With capacitors, the voltage drops from 111 percent to 100 percent, a change of 11 percent.

Shunt capacitors connected to utilization equipment so that they are switched in accordance with load, reduce voltage drop. To be effective, the utilization device must draw a current that is substantially constant in magnitude and power factor during the “on” period, as, for example, some forms of resistance welders on which long runs are made without change of set-up. Motor starting is one example of an application to which shunt capacitors cannot be used effectively in this manner for flicker reduction. Motor inrush current approximates six times full load. If this is neutralized by a shunt capacitor, the initial voltage dip is greatly reduced. However, when the motor comes up to speed, the voltage rises above the initial voltage.

4.1.6 Voltage Regulators

Voltage regulators are also totally unsuited to correcting flicker. This statement applies both to generator voltage regulators , or to step- or induction-type feeder regulators. These devices operate only when the voltage changes; furthermore there is a time lag before voltage is restored to normal. Changes in voltage, the ones that voltage regulators cannot eliminate, are the very ones to which the human eye is most sensitive. Consequently, the flicker is perceived before the regulator can even start. It is sometimes thought that an electronic regulator and exciter can eliminate this difficulty and pre vent voltage dips. However, the field time constant of the generator which in large units is as high as 10 seconds and even in very small machines may be one second, makes correction by this means impossible.

4.1.7 Compensating Transformers:

As illustrated is similar in effect to a line drop compensator used in voltage regulator control except that the size of the elements is that of a power device rather than that of an instrument. The current drawn by the flicker-producing load passes through a resistance and reactance branch, and the voltage drop thus created is added to the lighting-load voltage by means of a series transformer. By proper selection of the resistance, reactance, and series-transformer ratio, the flicker in the lighting circuit may be eliminated almost completely. Satisfactory results can often be obtained by omitting the resistor, and in such cases, the apparatus becomes simply a transformer with an air gap in its magnetic circuit.

Despite the technical simplicity of this scheme, it has practical and economic limitations. It is apparent that the improvement in the lighting circuit is obtained at the expense of the flicker-producing load. This limits the application to cases where the lighting load is only a small proportion of the total. In general, the equipment must be individually designed for a specific set of conditions since the proportions and size are affected by the line volt: age, line drop, total current, and ratio of loads. Should system changes necessitate its removal, there is small likelihood of being able to use the compensating transformer elsewhere. The cost of the apparatus is rather high because it is not standard.

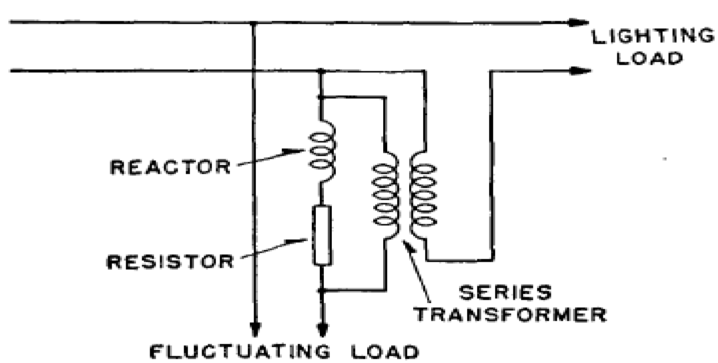

Fig [4.9] Compensating transformer can be used in very special cases to reduce voltag dips.

4.1.8 Motor Starters:

As pointed out under "Utilization Equipment," most motors can be started directly across the line because even the larger sizes are usually supplied from heavy feeders compared to the size of the motor. Where this is not the case, a starter may be required if the starting is frequent. It is difficult to generalize on the question of motor starting, because individual cases vary with the motor size, type, and the starting torque of both motor and load. Starting "compensators" are now being used much less than formerly. This is due largely to the acceptance of across-the-line starting, but also to the realization that the two voltage dips caused by the compensator may be as objectionable as one larger dip when starting across the line. In this respect reactor starting is superior, because the circuit is not opened at transition, and the reactor- short-circuiting operation may not result in a noticeable voltage dip if the motor is substantially up to speed. A reactor starter causes a greater initial voltage drop than a compensator, because the starting kva is decreased only directly as the starting voltage and not as the square of the voltage. When the continuous-load rating of the feeder is the same as of the motor, the use of wound-rotor motors with stepped-resistance starters in the rotor circuits usually avoids annoying flicker. The cost of that motor and control is greater, but where the motor is near the end of a long line and is started frequently, this may be the most economical choice. Where motors are started infrequently, but where the resultant voltage dip is still objectionable, some form of increment starter may be warranted. In a starter of this type, the stator current is increased in steps until the motor rotates, and the remaining impedance is cut out of the circuit after the motor has reached full speed. There are no standard starters of this type on the market, and the few that have been built have been specially designed for- the particular service. In general, they represent a combination of auto-transformer and reactor starting, the switching being done without opening t&-circuit during the entire sequence. Resistance starters in the stator circuits have been employed. On small integral horsepower motors the simplest and cheapest of these is a single-step resistor which is cut out after the motor comes up to speed. Xs with reactor starting used on larger motors, the short-circuiting of the resistor does not usually cause a noticeable voltage dip, and the initial dip of course is considerably reduced. Resistance starters should be adjustable for individual requirements; in extreme conditions a variable resistor may be desirable. These starters are in general more expensive and more difficult to maintain by unskilled attendants.

4.1.9 Excitation Control:

This involves single-step increments of the field excitation of synchronous motors by switches actuated by the equipment causing the flicker. This method is generally ineffective in eliminating flicker caused by abrupt voltage dips as explained under "Voltage Regulators." However, it can reduce considerably the width of the band of voltage regulation, which annoys power-supply companies by causing too frequent operation of feeder-voltage regulators as they attempt to compensate for the voltage swings. Such swings are caused by continuous strip rolling mills, large electric shovels, etc., where the variations of load are large, but where the rates of application and removal are moderate, say 10 to 30 percent per second.

4.1.10 Load Control:

In some cases it is possible to minimize lamp flicker by controlling manufacturing processes. For example, in a plant operating two or three resistance welders, it may be possible to provide interlocks so that not more than one is operated at the same instant. A remedy of this kind is only possible if the "on" time is short compared to the "off" time, otherwise the production rate would be slowed up considerably. Similarly in arc-furnace work the violence of the current swings during melting can be reduced by lowering production rate during this phase of the cycle. It is also possible to perform flicker-producing operations at a time when the lighting load is low. Control of load is not a very general solution to reduction of flicker, and it is employed in but few cases.

4.1.11 Flywheels:

A general discussion of the effect of flywheels is given under "Motor-Generator Sets," but the same principles apply to direct-driven apparatus. This method has considerable value for mechanical loads having short durations with long "off" periods, such as shears, punch presses, etc.

4.1.12 System Changes:

In practically all cases of flicker caused by utilization equipment, there is a direct relationship between the amount of the flicker and the size of the power supply system. For example, assume that a welder causes a three-percent voltage flicker on a residential substation, where only one percent is acceptable. Tripling the size of the supply to the substation would reduce the flicker to the required level, and this would constitute one way of eliminating the flicker. If this were done by multiplying the number of incoming lines and transformer banks by three it would probably be the most costly of all possible corrective measures. Usually more economical system changes can be made. A common form of substation supply with two or more feeders from the generating station paralleled to a single bus is shown in Fig [4.10](a). With this arrangement, all loads fed from the substation are subjected to any flicker produced on the outgoing feeders. Fig [4.10](b) shows a low voltage bus divided into two sections, one for residential and commercial loads, the other for industrial loads. This layout is based on the fact that voltage fluctuations objectionable to residential customers are acceptable to industrial users. There is probably a greater flicker tolerance in shop work than in residence lighting, and industrial plants are usually willing to accept flicker when it is caused by their own operation.

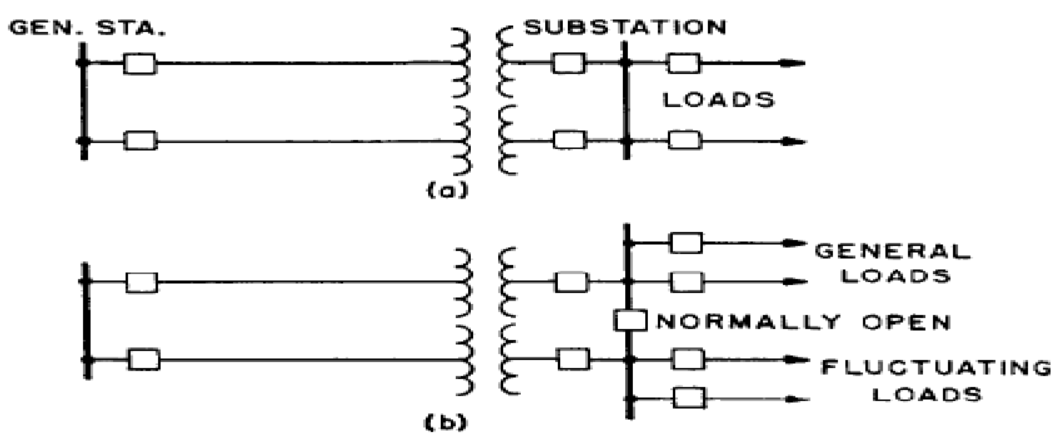

Fig [4.10] System layout.

(a) Fluctuating load on substation bus affected all loads fed from bus.

(b) Fluctuating load feeders separated from rest of the load.

Other methods of stiffening the power system involve changing the voltage of the supply line, tapping nearby high-voltage, high-capacity lines, adding more transformer capacity, or running a separate line to the flicker-producing load. Local conditions determine what remedial measures are most suitable in a particular case. Occasionally system increases are justified if the additional capacity may be needed later anyway.