CHAPTER 2

OVERVOLTAGE DUE TO SELF-EXCITATION AND INRUSH CURRENT DUE TO CAPACITOR SWITCHING

2.1 INTRODUCTION

It is becoming more common to find use of shunt capacitors for the application of powerfactor corrections and the starting of induction motors. Should the utility power fail during powerfactor corrections or while the motor is accelerating, the capacitors may cause severe motor overvoltage due to self-excitation. This chapter deals with the review of phenomenon of self-excitation. Various protection schemes against overvoltage due to self-excitation are given. A simple protection scheme using series resistance is also proposed. Momentary current rating of switching devices associated with capacitor energizing are also reviewed.

2.2 PHENOMENON OF SELF-EXCITATION

The phenomenon of self-excitation in electrical machines has been well documented in literature (J.E.Barkle 1954; D.B.Watson 1979). In its simplest form, self-excitation is the interaction between a machine and a capacitive reactance connected in parallel to the machine terminals. A single phase representation of this situation is shown in Figure 2.1 where,

\[ I_C = +j \frac{V}{X_C} \]  \hspace{1cm} (2.1)

and \[ I_M = -j \frac{V}{X_m} \] \hspace{1cm} (2.2)

Upon opening of the switch,

\[ I_C + I_M = 0 \]
FIGURE 21 SIMPLE SELF-EXCITED SYSTEM
and if
\[ X_C < X_m \]

the voltage will increase without limit unless saturation of the machine occurs. This is shown in the V-I characteristic of Figure 2.2 where the capacitive reactance is a straight line and the inductive reactance shows the typical saturation characteristic. Initially the system voltage is \( V_1 \) with motor and capacitor currents being \( I_{ML} \) and \( I_{CL} \). On opening the switch \( I_M \) must equal \(-I_{CL}\), which increases the machine terminal voltage to \( V_2 \). At \( V_2 \) \( I_C \) would increase to \( I_{C2} \) and the cycle would repeat until the terminal voltage reaches \( V_F \).

### 2.3 OVERVOLTAGE DUE TO SELF-EXCITATION

The magnitude of the generated voltage will depend upon the value of the capacitor current and the motor speed. The Figure 2.3 shows a typical motor excitation curve and the magnitude of voltage due to self-excitation for various capacitor readings. Point A indicates the percent magnetizing current at no-load and normal voltage. Curves R1, R2, R3 and R4 show the volt-ampere characteristics of capacitors having various ratings. Capacitor curves falling to the right of the motor characteristic curve indicate that the capacitor var is larger than the motor magnetizing var and the motor will self-excite. The final voltage of self-excitation, assuming that the speed remains constant, occurs when the capacitor curve intersects the motor characteristic curve at points A, B and C as given in the report (R.Nailen 1982).

The capacitor curves to the left of the motor such as curve R1 indicate that the motor kvar is less than the motor magnetizing requirements and hence the motor will not self-excite. Curve R3 applies where the capacitor kvar is sufficient to improve this specific motor full load power factor to 100 percent. It should be observed that the voltage of self-excitation in this case is 143 percent. This percentage will vary considerably depending upon the speed and the type motor and its saturation curve.
FIGURE 2.2 VOLT-AMPERE CHARACTERISTIC
FIGURE 2-3 TYPICAL CHARACTERISTIC DATA SHOWING HOW MOTOR VOLTAGE DUE TO SELF-EXCITATION IS INFLUENCED BY CAPACITOR RATING

$R_4$ - Volt-ampere characteristic of capacitor to give maximum voltage

$M$ - Motor excitation curve
In the usual motor application, the motor slows down rapidly after the switch is opened and the voltage rapidly decreases. If more capacitor kvar are applied to the motor than is required to meet the magnetizing requirements, then the windings of the motor will be subjected to overvoltages until the speed declines and the energy in the load capacitor circuit is dissipated. Essentially what is happening is that the addition of capacitors on the motor terminals is lengthening the time constant of the motor. These longer time constants mean that the motor insulation will be subjected to high levels of voltage for longer durations.

2.4 PROTECTION AGAINST Oerveoltage

2.4.1 Zinc oxide limiters

The voltage rise due to the tuned circuit condition is extremely fast (William H. Nichols 1984) and will peak in approximately in one cycle. A total of four to six cycles is required for the voltage relays to detect the overvoltage condition and for the breakers to clear the motor and capacitors. Because of the possible damage that could occur during these four to six cycles, zinc oxide limiters are connected between the lines to clamp the voltage at a safe level. Figure 2.4 shows the pictorial representation for the motor bus voltage as limited by zinc oxide limiters during capacitor starting. The zinc oxide limiters must be sized to absorb some of the stored energy in the rotating motor and starting capacitors for approximately ten cycles, allowing some safety margin for breaker clearing time.

2.4.2 U-frame and T-frame motors

Instead of using Pre-U-frame motors as shown in Figure 2.5(a) U-frame and T-frame motors as in Figure 2.5(b) can be used to limit the overvoltage. These motors use materials that saturate intensively even at low
FIGURE 2-4 MOTOR BUS VOLTAGE AS LIMITED BY ZINC OXIDE LIMITERS
FIGURE 2.5a PRE-U-FRAME MOTORS

FIGURE 2.5b U-FRAME AND T-FRAME MOTORS
enough levels, so that the voltage developed is usually acceptable, as per report (Myron Zucker 1985).

2.4.3 Series resistances

Resistance can be added in series with stator coil of induction machine to limit the overvoltage due to self-excitation as per papers (C.F. Desience 1965, C.Chellamuthu 1991). The value of series resistance has been found experimentally. Capacitors can be connected to the induction machine which has been driven by a dc motor. Since capacitance can only be changed in steps, self-excitation has been obtained by connecting a particular C at some high speed. Then the machine speed can be gradually decreased till self-excitation ceased. The capacitance at that speed would be Cmin to cause self-excitation. Above procedure has been repeated with different series resistances. It is found that when total value of series resistance and stator resistance is greater than \( r_C \) the self-excitation is lost. To take into account the above fact, the terminal voltage of induction machine-capacitor combination when the supply is cut off, (C.F. Desience 1965) can be modified as

\[
V = \left( V_0 / w \right) e^{\alpha t} \left[ \alpha \sin wt + w \cos wt \right]
\]  

(2.3)

where

\[
w = \left[ 1/LC_T - R^2/4L^2 \right]^{1/4} \\
\alpha = R/2L \\
R = [(r_s + r_e) - r_C]
\]

In the above Equation (2.3), the terminal voltage of induction machine-capacitor combination may decay if,

\[ R = [(r_s + r_e) - r_C] \]

is positive. Thus by adding series resistance, the overvoltage due to self-excitation can be prevented.
2.5 CAPACITOR SWITCHING

2.5.1 Momentary rating of a switching device

Although power circuit breakers are designed primarily to interrupt heavy inductive short circuit currents there is no direct relationship between the ability of a circuit breaker to interrupt short circuit currents and its ability to switch capacitor currents. It is widely recognized that high frequency voltage and current oscillations may occur with capacitor switching which, if uncontrolled, may result in damage to apparatus or system outages. The following paragraphs outline the most common conditions encountered in switching and provide information on available switching devices as per reports (J.A. Sainz 1968; Donald F. Miller 1976).

2.5.2 Inrush currents when energizing single capacitor bank

The energizing of a single capacitor bank may be represented by the circuit diagram of Figure 2.6. The maximum rms value of inrush current for the single bank may be calculated using the formula given in the literature (N.R.Schultz 1956; IS - 505 1970).

\[ I_{\text{max, rms}} = \frac{E_{b_n}}{X_{CN} - X_{LS}} \left[ 1 + \frac{\sqrt{X_{CN}}}{\sqrt{X_{LS}}} \right] \] (2.4)

The above formula applies to delta-connected capacitor banks if \( X_{CN} \) is determined as the reactance of the equivalent line-to-neutral capacitor kvar. The line-to-neutral reactance of any three phase capacitor bank, whether it is connected in wye or delta can be calculated as

\[ X_{CN} = \frac{(kV_L)^2}{\text{Mvar}} \]
FIGURE 2-6 A CAPACITOR BEING ENERGIZED THROUGH AN INDUCTANCE
Inspection of the formula (2.4) indicates that the peak inrush current to a single capacitor bank is always less than the short circuit current at that point.

For example, assume a 5.4 Mvar capacitor bank to be located on a 13.8 kV system which has a short circuit requirement of 250 MVA at the capacitor location. Solving,

\[
X_{LS} = \frac{(13.8)^2}{250} = 0.76 \, \Omega
\]

and

\[
X_{CN} = \frac{(13.8)^2}{5.4} = 35.4 \Omega
\]

From (2.4),

\[
I_{max,rms} = \frac{7980}{35.4-0.76} \left[ 1 + \frac{\sqrt{35.4}}{\sqrt{0.76}} \right] = 1800 \, A
\]

The symmetrical short circuit current is

\[
I_{SC,rms} = \frac{250000}{\sqrt{3} \times 13.8} = 10450 \, A
\] (2.5)

Thus the momentary rating of a switching device for control of a single bank should be based on short circuit current rather than on the maximum inrush current to the bank.

2.5.3 Inrush current in multistep banks

When one or more steps in a capacitor bank are already energized, the maximum peak current that flows into the next capacitor group to be energized is determined by the momentary discharge from those units already in service.
Since the impedance between the charged and uncharged group is very small, high peak inrush currents can be expected as analyzed below.

The energizing of the last step in a three-step capacitor bank may be represented by the circuit diagram of Figure 2.7. If no charge is on the step being energized, the maximum peak inrush current may be determined approximately by the following formula:

\[
I_{\text{max, peak}} = \frac{\sqrt{2} E_{i-n} \sqrt{Ce}}{\sqrt{Le}}
\]

(2.6)

Where \( Ce \), for example, in Figure 2.7 is given as

\[
Ce = \frac{(C_1 + C_2) C_3}{C_1 + C_2 + C_3}
\]

and \( Le \) becomes

\[
Le = \frac{L_1 L_2}{L_1 + L_2 + L_3}
\]

The frequency of the inrush current may be calculated by the formula:

\[
f = \frac{10^6}{2\pi \sqrt{(LeCe)}}
\]

(2.7)

The values of \( L_1, L_2 \) and \( L_3 \) of Figure 2.7 are difficult to determine accurately. It is a general practice to neglect the inductance of the capacitor leads and the bus structure and to use 0.15 \( \mu \)H/m as the inductance of the open conductor runs, including the length through the circuit breakers. This will give a low value of inductance which gives a current that is on the conservative side. If more exact calculations are required, the values of internal bank inductance may be obtained from the manufacturers as given in paper (Donald F. Miller 1976).
FIGURE 2.7 ENERGIZING OF THE THIRD STEP
OF A MULTISTEP CAPACITOR BANK
To illustrate the use of the above formulae, assume a typical installation on a 13.8 kV system which has a short circuit requirement of 250 MVA. Assume that two 5.4 Mvar banks are already energized, and the third is to be energized. Assume that the distance from the terminals of each capacitor bank through its circuit breaker to a common point on the bus is 6.7 m. Using 0.15 $\mu$H/m of conductor run, each of the inductances $L_1$, $L_2$ and $L_3$ would be 10 $\mu$H. $C_1$, $C_2$ and $C_3$ are each equal to 75 $\mu$F. From equation (2.5)

\[ I_{\text{max, peak}} = \frac{\sqrt{2}}{\sqrt{3}} \frac{13800}{\sqrt{15}} \sqrt{50} = 20600A \]

The frequency of inrush current would be

\[ f = \frac{10^6}{2\pi \sqrt{(50 \times 15)}} = 5082 \text{ Hz.} \]

Because of the interrupting requirement for this particular application, a 250 MVA breaker would be chosen which has a short circuit interrupting capacity of 19500 A and a momentary current rating of 37000 rms. Thus the short circuit current would dictate the momentary rating of the breaker for controlling the third step of the capacitor bank.

The calculated inrush current, although of a high natural frequency, should not exceed the published 60/50 Hz momentary current rating of the switching device unless specified otherwise. Although there may be little correlation between the effects of high frequency currents and 60/50 Hz currents, the fact remains that the 60/50 Hz rating is the only one recognized in the industry standards for circuit breaker performance. The user, therefore, has three alternatives: a) utilizing a larger breaker than would otherwise be necessary, b) inserting additional reactance to limit the inrush current, or c) taking a risk on the basis that breaker performance at the high natural frequency may be acceptable even though the current magnitudes may exceed normal 60/50 Hz momentary rating.
2.6 USE OF FUSES FOR PROTECTION OF CAPACITORS AND CAPACITOR BANKS

2.6.1 Protection by fusing

Complete protection must be provided for a capacitor installation. This will consist of protecting the individual units as well as the bank. Both fuses and relays may be employed depending upon the rating of the bank, its location in the system and other factors. Fusing is the basic protection for the capacitor units, both individually and in groups. Relays and circuit breakers are applied for overall bank protection and for capacitor switching. Normally the decisions about the unit and group fusing will be made by the factory engineer when the bank is being designed (IEEE guide 1980).

The modern power capacitor unit is extremely reliable as the failure rate being less than 0.1 percent per year (Donald F. Miller 1976). This figure represents the overall average failure rate for all applications for both industrial and utility applications. In particular locations involving frequent switching, the capacitor may not enjoy such high reliability rates and the protection of the units becomes increasingly important. If a failure occurs then proper protection will limit the extent of the damage. Fuses are the most desirable and economical method for protecting against possible consequences of failure. The major purposes of capacitor fusing are: 1) to maintain service continuity, 2) to prevent damage to adjacent capacitors and equipment or injury to personnel, and 3) to provide visual indication of a failed unit.

2.6.2 Fuse protection for individual capacitor units

The requirements for proper fuse selection are as follows as per report (N.R. Clark 1949).
1. The rated voltage of the fuse should not be less than the rated voltage of the capacitor. Since capacitors are designed to operate continuously at 110 percent rated voltage, the fuse should also have a voltage rating which has at least 110 percent of the capacitor unit rating.

2. The maximum interrupting rating of the fuse should be greater than the available short circuit current which can flow if a capacitor unit is shorted.

3. The fuse should have a time-current clearing characteristic that lies below the time-current case rupture probability characteristic of the capacitor units.

4. The selected fuse should have sufficient rating to carry at least 165 percent of rated capacitor current as per NEMA Standard CP-1-1968. This margin allows for temporary overvoltages, switching surges, and manufacturing tolerance in the capacitor itself.

2.6.3 Group fusing

The practice of utilizing one fuse to protect more than one capacitor unit is called group fusing. Small capacitor banks on distribution lines are often group fused where cutouts are used for both protection and switching. On industrial systems with large banks, groups of two or more capacitors may be connected in parallel or series/parallel combinations and protected by a single fuse. Group fusing is considered as a special case of individual fusing and the same criterion is generally applied for the fuse selection. In the case of the 165 percent of rated current criterion, the rating refers to the current of all of the grouped capacitor units protected by the fuse.
2.6.4 Time-current case rupture characteristics

These characteristic curves have been referred to earlier as part of the capacitor unit protection discussion. As the name implies, these curves display graphically the relationship between fault current and time for different case rupture modes. Figure 2.8 illustrates a typical characteristic. For different values of current and time, there are four zones identified as given in literature (Donald F. Miller 1976, John E. Harder 1978).

The probability of case rupture may be defined as the probability of any opening of the case as a result of failure from a mere cracked seam to a violent bursting of the case. Within the safe zone, usually no greater damage than slight swelling of the case will occur. It is possible, however, for a case rupture to occur as a result of very low short circuit currents flowing for extended periods of time. To avoid such case ruptures, the fuse link should be coordinated so that it will clear the fault within 300 s. (IEEE standard No.18, 1968). This is a significant consideration, generally adopted only for ungrounded wye connected banks for which fault current is limited to approximately three times normal current.

The hazardous zone is unsafe for most applications because a failed unit will often rupture with sufficient violence to damage adjacent units. Besides signifying a 50 percent probability of a case rupture, the 50 percent curve also represents an approximate boundary below which violent case ruptures are improbable. Therefore, zone 1, bounded by the 10 and 50 percent curves, is suitable for locations where case opening or fluid leakage would present no hazard. Zone 2, bounded by the 50 and 90 percent curves, is suitable for locations which have been chosen after carefully considering the possible consequences associated with violent rupture of the case. The 90 percent probability curve for Figure 2.8 is vertical at 400 A, signifying that the area beyond this maximum current is in the hazardous zone. Tests have
Available short circuit current in amperes RMS

SAFE ZONE: SAFE FOR MOST APPLICATIONS (USUALLY NO GREATER DAMAGE THAN SLIGHT SWELLING OF CASE)

ZONE 1: SUITABLE FOR LOCATIONS WHERE TANK RUPTURE AND/OR FLUID LEAKAGE WOULD PRESENT NO HAZARD

ZONE 2: SUITABLE FOR LOCATIONS WHICH HAVE BEEN CHOSEN AFTER CAREFUL CONSIDERATIONS OF POSSIBLE CONSEQUENCES ASSOCIATED WITH VIOLENT RUPTURE OF CASE

HAZARDOUS ZONE: UNSAFE FOR MOST APPLICATIONS (CASE WILL OFTEN RUPTURE WITH SUFFICIENT VIOLENCE TO DAMAGE ADJACENT CAPACITORS.)

FIGURE 2.8 PROBABILITY OF CASE RUPTURE CURVES OF POWER CAPACITORS DUE TO INTERNAL ARCING
demonstrated that beyond this value of current, fuse links will not satisfactorily protect against violent ruptures.

2.7 CONCLUSION

Theory of self-excitation has been discussed. It is shown graphically that magnetizing reactance has to be more than capacitance reactance in order to have self-excitation. Protection methods like zinc oxide limiters, use of Pre-U-frame and T-frame motors and use of series resistance against overvoltage due to self-excitation have been presented. In order to obtain the value of series resistance to be connected in series with stator, an experimental method has been proposed.

Capacitor switching and its associated inrush current problem during energizing period are discussed. Use of series inductance to limit the inrush current is presented.

Use of fuses to provide protection of capacitors and capacitor banks is reviewed.