8

Fuses

8.1 GENERAL COMMENTS

Fuses are used when it is possible to use a simple and economic method of protection against overcurrents and faults. They are fast to act when a major fault occurs and are very reliable.

The characteristics of fuses vary widely depending upon the application for example:-

- Distribution feeders to transformers.
- Induction motors.
- AC and DC services.
- Rectifier and thyristor circuits.
- Static load service, such as heaters.
- High voltage and low voltage services.

The terminology and standards vary considerably between countries. Typical international standard codes are:-

- Europe. IEC60282 and 60644 for high voltage fuses
IEC60269 for low voltage fuses.
- USA. UL 248-1/CSA-C22.2 (15 parts)

Reference 1 gives a description of the standards used in the USA as well as a theoretical treatment of the subject.

Reference 2 gives a comprehensive description of most aspects of fuses including mathematical models together with comments on European and US practice. It also contains a full listing of the most useful IEC standards in its Chapter 8. See also Reference 3 article 110, sub-section 10, for applications where the rated voltages are up to 600 volts.

The melting process of a fuse is a complicated subject. However, for the practising electrical engineer in the design and application side of the industry it is usually only necessary to be familiar with some of the basic characteristics of fuses. Fuse manufacturers are able to vary the shape and steepness of the characteristics by carefully designing the shape of the fuse element, by surrounding the element with different heat removing media and by selecting different fusable metals and alloys. The main parameters concerning an application are,

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- Rated voltage.
- Rated current.
- Rated frequency.
- AC and DC service and type of load current.
- Time versus current characteristic.
- Time versus I^2t characteristic.
- Rated breaking capacity.
- Rated power dissipation of the fuse.
- Cut-off current in AC service.
- Pre-arcing and arcing times.
- Dimensions.

8.2 OPERATION OF A FUSE

The operating sequence of a fuse is:-

1. The fuse element heats up and finally melts.
2. As soon as melting occurs a gap is formed at one or more points along the element.
3. An arc is then established across each gap.
4. The heat of the arc further melts the ends of the elements at each gap and so the gap is increased.
5. Hence the arc length increases and the arc becomes weaker. A point is reached when the arc becomes unstable and cannot be maintained.
6. The arc is extinguished and the circuit is isolated by the fuse.

8.3 INFLUENCE OF THE CIRCUIT X-TO-R RATIO

The following discussion will only relate to AC circuits. Fuses are used mainly to interrupt large fault currents and so the discussions will concentrate on short circuits. Fuses can operate within a quarter of a cycle and so it is often the case that the short-circuit current is asymmetrical, see sub-section 7.2.7.

All circuits which contain inductive reactance and resistance have an X-to-R ratio, in practice between 2.0 and 100.00. In short-circuit analysis it is usually necessary to relate the asymmetrical current to the symmetrical current. This can only be done if the short-circuit power factor of the circuit and hence the X-to-R ratio is known. Table 8.1 shows the relationship between these parameters and currents. Normally the short-circuit power factor is low, between 0.01 and 0.45. It is customary in short-circuit analysis to assume that one of the phases has the worst-case situation of fully asymmetrical current. Figure 8.1 shows an example, together with the various definitions of times and currents.

The fuse will operate during the first half-cycle if it is properly selected. As the current increases the fuse element melts and eventually the melting causes the circuit to become interrupted. During melting the period is called the ‘melting time’ (US terminology) or ‘pre-arcing time’ (UK terminology). After the melting time an arc is maintained for a short period called the ‘arcing time’. If the fuse failed to operate, or was not included in the circuit, the current would continue to rise to

Table 8.1. Characteristic currents that are related to the X-to-R ratio of a circuit

Short circuit X-to-R ratio	Short circuit power factor	Ratio to rms symmetrical current: Max 1-phase peak current	Max 1-phase rms current at 1/2 cycle	Avg 3-phase rms current at 1/2 cycle
Infinity	0.0	2.828	1.732	1.394
100	0.01	2.785	1.696	1.374
49.993	0.02	2.743	1.665	1.355
33.322	0.03	2.702	1.630	1.336
24.979	0.04	2.663	1.598	1.318
19.974	0.05	2.625	1.568	1.301
9.9501	0.1	2.455	1.436	1.229
6.5912	0.15	2.309	1.330	1.171
4.8990	0.2	2.183	1.247	1.127
3.1798	0.3	1.978	1.130	1.066
2.2913	0.4	1.819	1.062	1.031
1.7321	0.5	1.694	1.026	1.013
1.3333	0.6	1.594	1.009	1.004
1.0202	0.7	1.517	1.002	1.001
0.75	0.8	1.460	1.0002	1.00005
0.6198	0.85	1.439	1.00004	1.00002
Zero	1.0	1.414	1.0	1.0

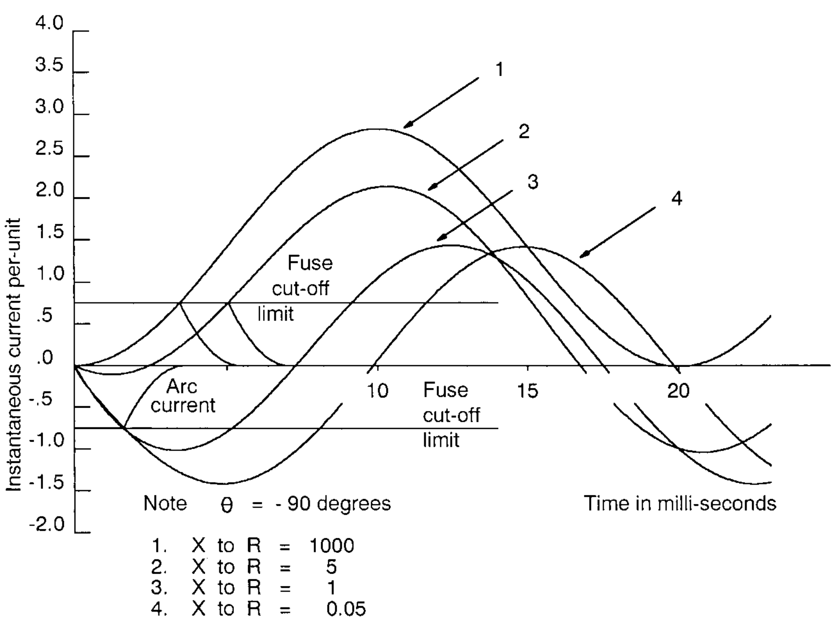

Figure 8.1 Fuse cut-off curves for different X-to-R ratios of the fault circuit. The curves show how the clearance time varies with the ratio..

its maximum possible value, called the 'maximum asymmetrical' (US) or 'asymmetrical prospective' (UK) current. The peak value of the actual fault current that the fuse allows to pass is called the 'peak let-through' current.

Clearly the higher the fault current the faster the fuse will operate, which is the required characteristic of a fuse. However, the application engineer must balance speed of operation with other factors such as the type of load. For example when an induction motor is started direct-on-line, the starting current will be as much as 7 times the running current. This starting current will actually fall within the range of currents that can cause the fuse to operate. Therefore a compromise is required between fast action during a fault and allowing the motor sufficient time to run up. Static loads do not require such a compromise and so fast action can be optimised by choosing a lower fusing factor (see sub-section 7.4). Rectifiers and thyristors require extra-fast fuses since permanent damage can be done very quickly when fault currents occur.

8.4 THE I^2t CHARACTERISTIC

During operation the fuse may be regarded as a constant resistance (R) until interruption occurs. The power dissipated by the fuse is therefore I^2R. The energy release by the fuse is therefore approximately:-

$$\text{Energy } U = I^2Rt$$

Where t is the melting time plus the arcing time and I is the current flowing in the fuse.

Therefore a fuse can be described by its I^2t characteristic as being a measure of the energy released during its operation. Obviously the mechanical design of the fuse must be capable of containing this energy, which is released in an explosive manner.

Historically early designs began to fail until it was realised that the prospective fault currents in typical power systems had gradually increased. This was due to the natural development and expansion of those systems. Reference 1 gives a good description of the I^2t characteristic.

Different types of fuse for the same rated voltage and current will release different amounts of energy since their characteristics are deliberated designed to be different. The energy released is due to two separate functions, melting the fuse element and extinguishing the arc.

The actual value of let-through current for a given fuse will depend upon the nature and magnitude of the prospective fault current e.g. asymmetrical or symmetrical. This is because a greater current has to be reached in the symmetrical case than in the asymmetrical case to create the same amount of melting energy. This is due to the shape of the current waveform in the first cycle, which can be seen in Figure 8.1.

The maximum value of the let-through current is called the 'peak let-through current I_p'.

The importance of the peak let-through current is in relation to the thermal and mechanical stresses that occur in the downstream equipment e.g. contactors, cables.

Furthermore the I^2t characteristics of any of the downstream equipment must be greater than the fuse, otherwise the equipment will suffer thermal damage. (For a given fault current the fuse clearance time must always be at least several times lower than the corresponding I^2t time of the downstream device.)

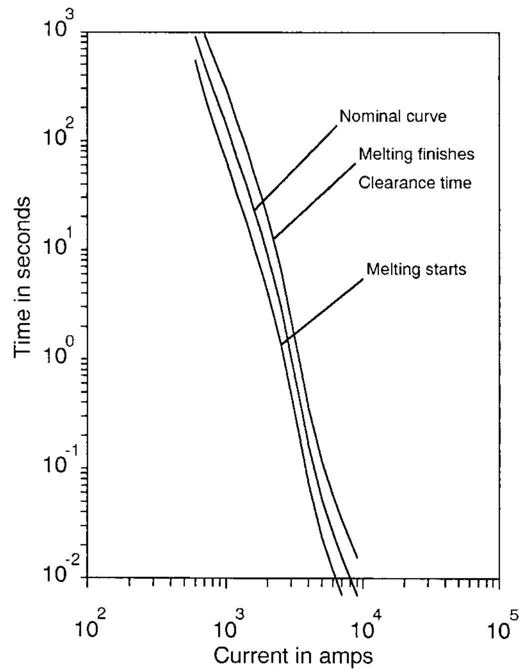

Figure 8.2 Melting, nominal and clearance time curves versus current for a typical 250 A fuse.

The melting time and clearing time are of related significance when two fuses, which are in series, need to be coordinated, e.g. a feeder fuse and a large outgoing fuse. The feeder fuse must not melt during the clearing time of the outgoing fuse when a common fault current passes. Figure 8.2 shows the important times and currents of a typical 250 amp fuse. The shape of the curve is typical.

A fuse may be called upon to operate in one of two ways:-

— Current limiting-short time duty.

— Non-current limiting-long time duty.

In a 60 Hz system the peak of the fault current will occur in 0.0042 sec (symmetrical) or 0.0084 sec (fully asymmetrical). For a 50 Hz system the times are 0.005 sec and 0.01 sec respectively. If the fuse clears the fault in less than about 0.003 sec then the fuse is said to be current limiting.

However if the prospective current is not at its maximum then several cycles of current may occur before sufficient heat is created to melt the fuse. In this situation the fuse is said to be non-current limiting. This applies to times beyond about 0.01 sec on the fuse curve of Figure 8.2. As the prospective current is reduced the non-current limiting time, or operating time, increases considerably. A particular design of fuse may take several hours to operate if the prospective current is only a small amount above the asymptotic value of the fuse. Four hours is used by manufacturers as a reference value. It can be seen therefore that times less than 0.003 sec are important when high currents occurs.

It should be noted that when the melting time exceeds about 0.1 sec the corresponding arcing time is less than 0.01 sec. Therefore for times above 0.1 sec it may be assumed that the melting or pre-arcing time is in fact the clearance time. The fuse manufacturers normally give curves for the time range of 0.01 to 1000 seconds. For times less than 0.01 sec it is better to seek the advice of a particular manufacturer.

During the current limiting phase the operating time is influenced by whether the prospective current is asymmetrical or fully symmetrical. The time is determined by the integrated amount of heat generated and this is a function of the current waveform shape. To help overcome difficulties in relating the terminology used in the non-current limiting phase to that applicable in the current limiting phase, the term 'virtual time' was introduced some years ago.

Note that during current limiting operation the melting time and the arcing time are of the same order, see Figure 8.2. The term virtual time (t_v) can be used in conjunction with the melting, arcing and clearing times by using the following mathematical expressions:-

$$\text{Melting } t_v = \frac{\text{Melting energy (amp}^2\text{ secs)}}{\text{Prospective current (rms sym amps)}^2}$$
$$= \frac{1}{I^2}\int_o^{t_m} i^2 \mathrm{d}t \text{ seconds}$$

Similarly,

$$\text{Arching } t_v = \frac{\text{Arcing energy}}{\text{Prospective current}^2}$$
$$= \frac{1}{I^2}\int_{t_m}^{t_c} i^2 \mathrm{d}t \text{ seconds}$$

And,

$$\text{Clearing } t_v = \frac{1}{I^2}\int_o^{t_c} i^2 \mathrm{d}t \text{ seconds}$$

Where, t_m is the melting time period.

t_c is the clearing time period.

$t_c - t_m$ is the arcing time period.

The manufacturers use this procedure to extrapolate their curves below 0.01 sec and t_v is therefore a theoretical time. Virtual time is related to the prospective current by definition and so the manufacturer will quote the maximum prospective current that can be used in conjunction with his curves. At this point the engineer is encouraged to consult the manufacturers for advice on the selection of fuses for current-limiting duty.

The above discussion on current limiting and virtual time have been included for completeness so that the reader is made aware of their significance.

8.4.1 Worked Example

An example of fuse selection:-

A 6600 volt induction motor is fed from a fuse-contactor starter. Find the most appropriate fuse rating and the appropriate size of a PVC cable for the motor. The following data are known:-

Motors:

- Rated kW = 760 kW.
- Rated cos Ø = 0.9.
- Rated efficiency = 0.96.
- Starting current = 4 times rated current.
- Starting cos Ø = 0.3.
- Starting time = 5 seconds.

Cable:

- Route length is short and volt-drops are negligible for starting and running.
- Derating factor to account for grouping, burying, racking, ambient temperature is 0.65.
- 3-core cable sizes available are 25, 35, 50, 70, 95 mm sq, their nominal current ratings are, 100, 125, 155, 190, 235 amps respectively.
- I^2t characteristics can be found by using a 'k' value of 110 for PVC cables with copper conductors.

Power system:

- Fault level 150 MVA.
- Assume a three-phase fault at the motor.
- Assume an X-to-R ratio of 25.
- Fuse characteristics as shown in Figure 8.4.

The calculations can be carried out in various sequences; the following is just one sequence.

Step 1. Calculate the motor running and starting current.

$$\text{Running current} = \frac{P}{\sqrt{3}V\cos Ø}$$

$$= \frac{7{,}60{,}000}{\sqrt{3} \times 6600 \times 0.96 \times 0.9} = 76.95 \text{ amps}$$

$$\text{Starting current} = 4 \times 76.95 = 307.8 \text{ amps}$$

Step 2. Scale-down the cable ratings to suit the derating factors, prepare a revised table:-

Core size mm sq	25	35	50	70	95
Scaled-down ratings A	65	81	101	124	153

Hence the 'minimum' cable core size to suit the motor running current is 35 mm sq.

Step 3. Calculate the prospective symmetrical and asymmetrical fault currents.

$$I_{\text{sym}} = \frac{\text{Fault MVA of system } (S_f)}{\sqrt{3}\text{ rated voltage } (V)} = \frac{S_f}{\sqrt{3}V}$$

$$= \frac{1{,}50{,}000{,}000}{\sqrt{3} \times 6600} = 13{,}122 \text{ amps rms}$$

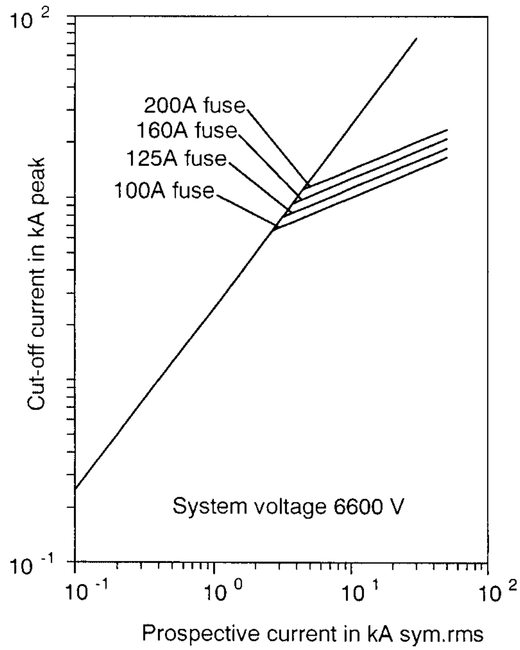

Figure 8.3 Peak cut-off current versus prospective symmetrical rms current for typical fuses in the range of 100 A to 200 A.

See Table H.1b for X-to-R ratio of 25, the doubling factor is 2.661.

Therefore the peak asymmetrical current is I_{pkasym},

$$I_{\text{pkasym}} = 13{,}122 \times 2.661 = 34{,}944 \text{ amps pk}$$

Step 4. Decide upon suitable cut-off current.

Choose the maximum cut-off current to be 45% of the peak asymmetrical fault current

$$I_{\text{pkcutoff}} = 0.45 \times 34{,}944 = 15{,}724 \text{ amps pk}$$

Round this up to 16,000 amps pk

Step 5. Select the largest fuse to suit the cut-off limit.

Use Figure 8.3 even through the prospective current is shown as rms symmetrical. This example is a special case since the X-to-R ratio is known.

$$\text{Prospective current} = \frac{34{,}944}{\sqrt{2}} = 24{,}713 \text{ amps rms}$$

Hence the 'largest' fuse for cut-off limit is 160 amp rating.

Step 6. Compare the I-squared-t characteristic of the fuses with the I-squared-t characteristic of the cables, in Figure 8.4. A 160 amp fuse will protect the 35 mm sq cable for fault currents beyond

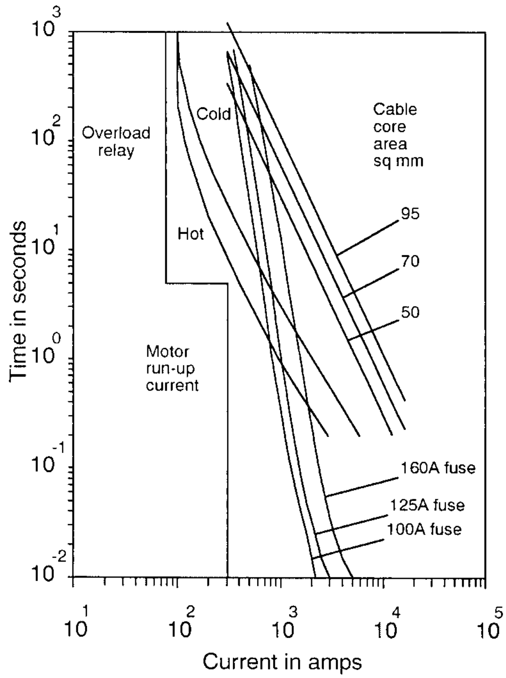

Figure 8.4. Protection of an induction motor and its feeder cable.

about 1200 amps. A 125 amp fuse would reduce this to 1000 amps. Below these fault currents it is necessary to use other additional protection devices e.g. inverse-time thermal image relay, which is the standard practice. The relay curve will need to intersect the fuse curve before the cable is damaged for fault currents within a certain range. To allow the relay to have good coverage it is advisable to choose a smaller fuse and a larger cable. The recommended choice is a 125 amp fuse and a 70 mm sq cable. The fuse gives good protection in this choice for all fault currents above about 650 amps, which is twice the motor starting current. The 125 amp fuse also gives improved cut-off or current limiting performance than the 160 amp fuse.

Step 7. Check the motor starting current versus time characteristic. Assume the starting current to be constant throughout the starting period. Insert the starting current versus time curve on the Figure 8.4. The curve is well clear of the fuse and the cable and gives plenty of scope for the overload relay. In fact the starting time could be as high as 8 or 9 seconds before coordination problems occur.

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