1. Transient currents in power systems

1.1 Short circuit current

Typically short circuit currents in power systems are related to circuit breaker performance. Depending on the point on wave timing of the short circuit initiation, the short circuit current has decaying d.c. component with the maximum of the a.c. crest value. Power system short circuit phenomena are represented by Fig. 1.1 in most simplified manner. In actual power systems some parallel circuits with respective L/R (d.c. decaying time constant) values exist, still the circuit as Fig. 1.1 can be mostly applied with practically enough accuracy.

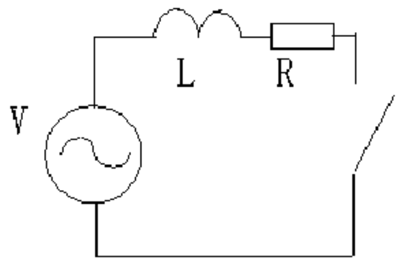


Fig. 1.1 Simplified circuit diagram

The following analytical solution is easily obtained. :

$$i = I\{\sin(\omega t + \alpha - \vartheta) - \exp(-R/L)t \cdot \sin(\alpha - \vartheta)\}$$

$$\vartheta = \tan^{-1}(\omega L/R)$$

$$\sin(\alpha - \vartheta): \textit{DC component at } t = 0$$

$$\omega: \textit{a.c. source angular velocity}$$

Current in inductance is to be continuous, therefore irrespective of the point on wave short circuiting timing, the current starts from zero. So for compensating the instantaneous a.c. value to zero for the short-circuiting time, d.c. component exists. Appling ATP-EMTP, an example is shown in Fig. 1.2, also see the attached data file, where each current starts from zero value and equal a.c. component waves irrespective of the d.c. and short circuiting timings are shown.

In practical system circuits, where the circuits are mostly three phases, both positive/negative and zero sequence parameters are to be considered in three phase circuits. Also for practical systems, discharging currents from parallel capacitances, such as transmission lines, cables, or shunt capacitor banks, are occasionally not insignificant. Such discharging currents have components of several hundred Hz and mostly decay after a few tens ms from the short-circuiting time. But in special cases, they may not be negligible after several tens ms from the short circuit initiation when the currents are to be interrupted by circuit breakers. A typical example, corresponding to an extremely high density network near a megalopolis, is shown in Fig. 1.3, which is a case of EHV substation bus-bar is short circuited, where extremely high capacitances such as EHV cables via certain length of overhead line (20km) and high capacity of shunt capacitors in the tertiary winding side of the transformer are connected. Care should be taken in such calculation regarding the damping of the transient current frequency by capacitance discharging current. The frequency of the transient is in the order of several hundreds Hz, so the losses in transformers, transmission lines, cables, etc. are to be based on that frequency range.

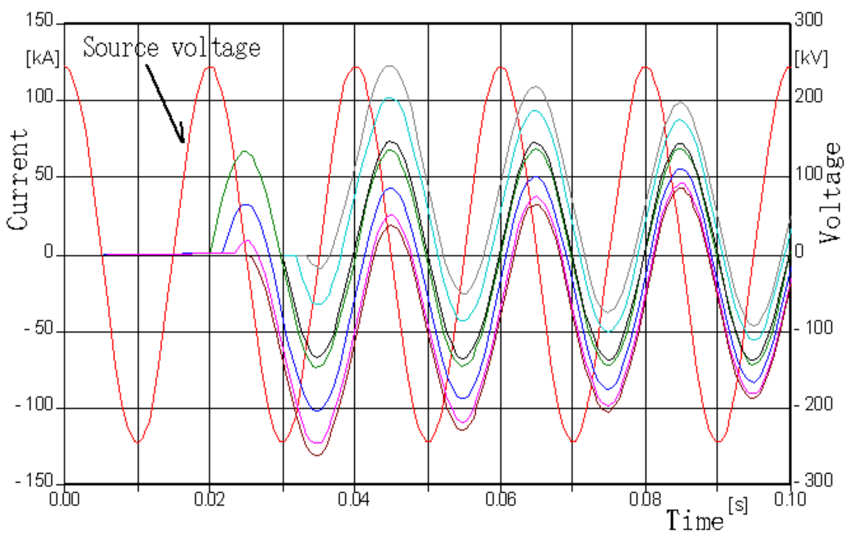


Fig. 1.2 Short-circuit current in Fig. 1.1

The calculation was done for a 550 /300 kV sub-station, the capacity of which transformer is (in

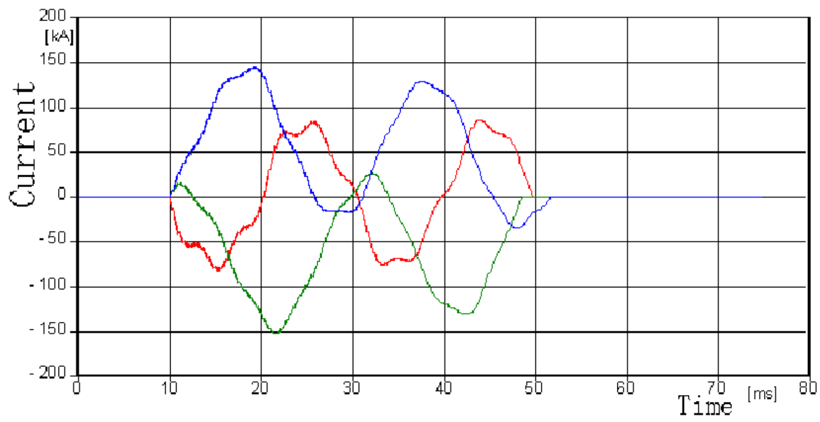


Fig. 1.3 Short-circuit currents in EHV sub-station

total) 3GVA, 600MVA of capacitor bank is connected to the tertiary side of the transformer, total ca. 40 km of EHV cables are connected to the 300kV bus-bar via 20km of overhead transmission line. Damping resistances in the circuits were carefully adjusted for the transient current frequencies. Applying "Fourier On" menu, GTPPLT or Plot XY, the Fourier spectrum is easily obtained and the wave shape in Fig. 1.3 (with maximum transient component) has 10% of 5th harmonics, which can yield 50% of enhancement of di/dt value at the current interruption. The value may significantly affect to certain type of circuit breaker performance. For details of the system parameters applied, see the attached data file.

Note:

Such short circuit current distortion is significant where very high capacitance(s) exists via certain inductance, e.g., transmission line, transformer, series reactor of shunt capacitor bank, etc.

1.2 Transformer inrush magnetizing current

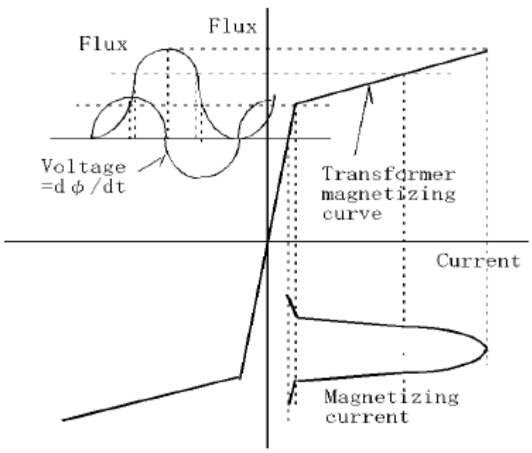


Fig. 1.4 Transformer inrush magnetizing current

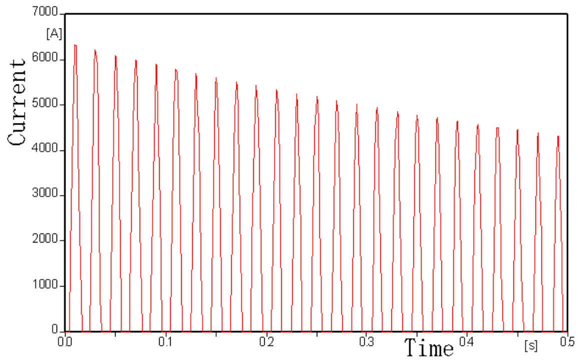


Fig. 1.5 Transformer magnetizing current 550kV, 1GVA transformer

Transformer inrush magnetizing current is often explained applying the diagram as Fig. 1.4. For EHV high capacity transformers, the values often record up to several thousand A, while the steady state magnetizing currents are less than 1 A. Such calculation applying ATP-EMTP is relatively simple, introducing actual transformer magnetizing characteristics. An example is shown in Fig. 1.5, where No. 93 True non-linear inductor simulates an actual 550kV, 1GVA transformer characteristics, which can accept initial residual flux. For the detailed data, see the file attached. In the data file, the magnetizing current region of 10 ---- 10000 A is simplified due to less data was available. For correct calculation, this region may be of great importance.

In Fig. 1.5, the current gradually decays due to, mainly, the resistance(s) in the circuit. The actual applied voltage to the inductance component is reduced by the resistance drop, so, the voltage is more or less asymmetrical due to the asymmetry of the magnetizing current. Therefore the current goes gradually to symmetrical one, down to less than 1 A. For correct calculation as for the damping of the current, care is to be paid for the correct resistance value(s) in the circuit.

Notes:

- In the attached data calculating Fig. 1.5, the magnetizing characteristic is modelled by only 3 segments for one polarity. If correct value(s) for 10 ---- several 1000 A current value(s) is wished, more accurate modelling for the current range may be necessary.
- Three non-linear inductance menus are available:

Type 98 Pseudo non-linear reactor : Most simple and useful for general usage but initial (residual) flux is not applicable. Type 93 True non-linear inductance : Initial flux is applicable. Calculation is only a little bit slower. Care should be paid when applying initial flux, current dose not starts from zero but a certain value relevant to the flux value on the magnetizing curve.

- Type 96 Pseudo-non-linear hysteretic reactor : Care should be paid when up going and down going, the current/flux locus traces the same line for each, i.e., the width between the two lines is constant.

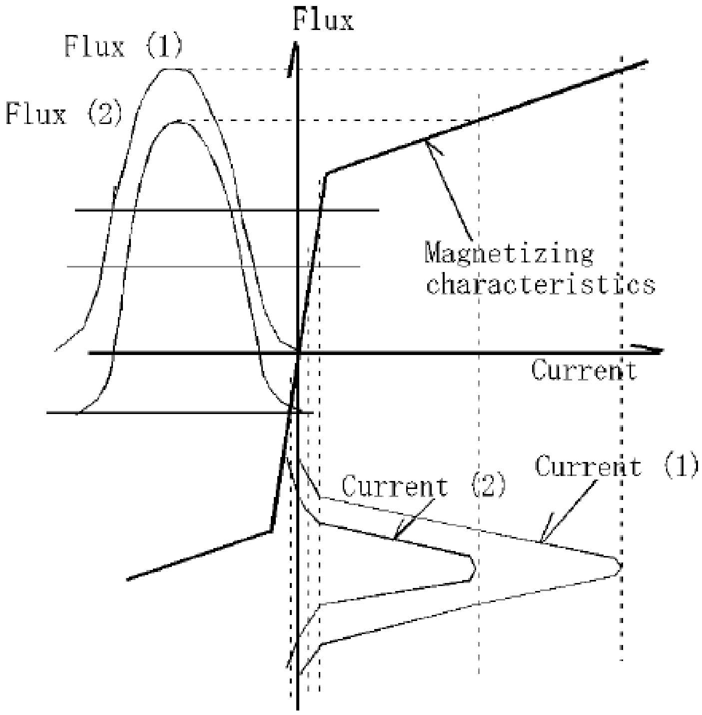


Fig. 1.6 Magnetizing current under d.c. current superimposed

1.3 Transformer magnetizing current under geo-magnetic storm condition

Strong geo-magnetic storms originated by the Sunspot are known to attack the earth approximately every 11 years, when approx. DC current due to the terrestrial magnetism change flows in a very long transmission line in north – south direction which reaches up to ca. 100 A. The transmission line terminates with a transformer at each sub-station. Therefore DC current flows through the transformer in such circumstance up to in the order of 100 A. The DC current mostly flows only one side winding of the transformer, thus the iron core is saturated much. The flux goes out of the iron core and may make heated the transformer iron case due to the higher iron loss rate of the material. In 1989, a large black out in US and Canada electric utilities were reported due to such origin. Transformer magnetizing performance is shown in Fig. 1.6 under such DC current superimposed. By a certain AC voltage applied, the flux linkage can be any of flux (1) or flux (2) depending on the initial condition. In mathematics, the matter corresponds to the integration constant, i.e., the flux is integration of the applied voltage to the inductance. Corresponding magnetizing current is Current (1) or Current (2). Thus any kind of current can exist. Actually the flux bias, i.e. the initial condition of the time period concerned, is fixed as steady state condition. As for the inrush current shown in the previous section, the initial current is the most interest in most cases. But the phenomena in this section lasting several ten minutes, steady state condition is most interested. As for the circuit diagram in Fig. 1.7, the next equations are easily obtained. :

$$E_{ac} + E_{dc} = R\,i + d\phi / dt\ , \qquad E_{dc}(t_2 - t_1) = \int_{t_1}^{t_2} R\,i\ dt, \qquad E_{dc} / R = \frac{1}{t_2 - t_1}\int_{t_1}^{t_2} i\,dt$$

The second equation is the integration of the first one. The third one is just modification of the second one, which shows the average current value is just the DC current value applied.

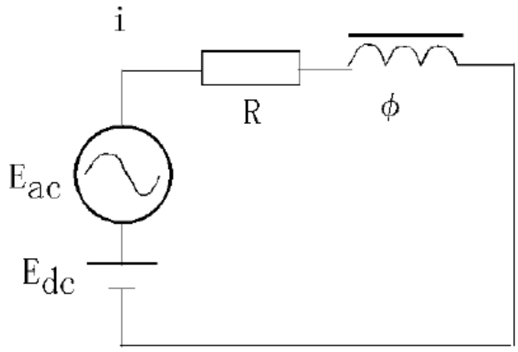


Fig. 1.7 Circuit diagram for geomagnetic storm condition

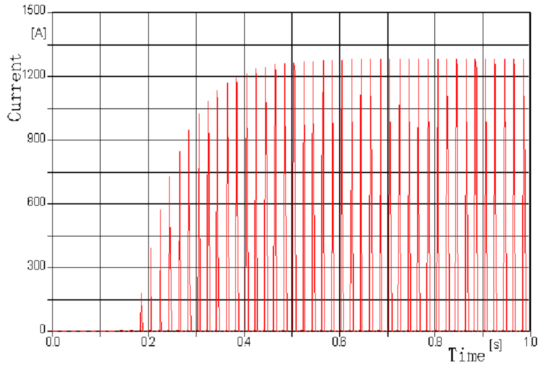


Fig. 1.8 ATP-EMTP calculation of transformer magnetizing current under geomagnetic storm

ATP-EMTP calculation result is shown in Fig. 1.8, also see attached data file for the circuit parameter details. In the calculation to attain shorter time interval to the steady state, the series resistor values are intentionally enhanced. Otherwise, the time to steady state is to be several ten seconds for the actual circuit parameters. The calculation was done applying both AC and DC voltages to the transformer without initial residual flux.

Note :

- Geomagnetic storm condition lasts several ten minutes, while the thermal time constant of a transformer is in the order of one --- several hours. Higher current lasting less than one minute such as inrush current is of no importance as for the thermal phenomena. Electrical time constant around a transformer is far less than one minute. Therefore, electrically steady state phenomena are of importance regarding geomagnetic storm.
- In the attached data file calculating the phenomena, introducing initially residual flux and/or an other timing of source voltage, different current wave shape is obtained only for the initial time iterval. After some time interval, current reaches to the same steady state value.

1.4 Inrush current in capacitive circuit

Capacitive circuits such as high capacity shunt capacitor banks or EHV under ground cable systems, when closing by relevant switching facilities, i.e. circuit breakers, may create very high inrush current up to the order of the short circuit one. The frequency of the transient is in the order of a few hundred Hz ---- several kHz. The transient last generally short time interval, so the contact consumption of the relevant switching facility (circuit breaker) is the most concern. Also facilities are influenced electro magnetic forces. Some examples of circuit diagrams are shown in Fig. 1.9 in single phase ones. Most actual circuits are in three phases, so in calculating three phases modelling is necessary for most cases.

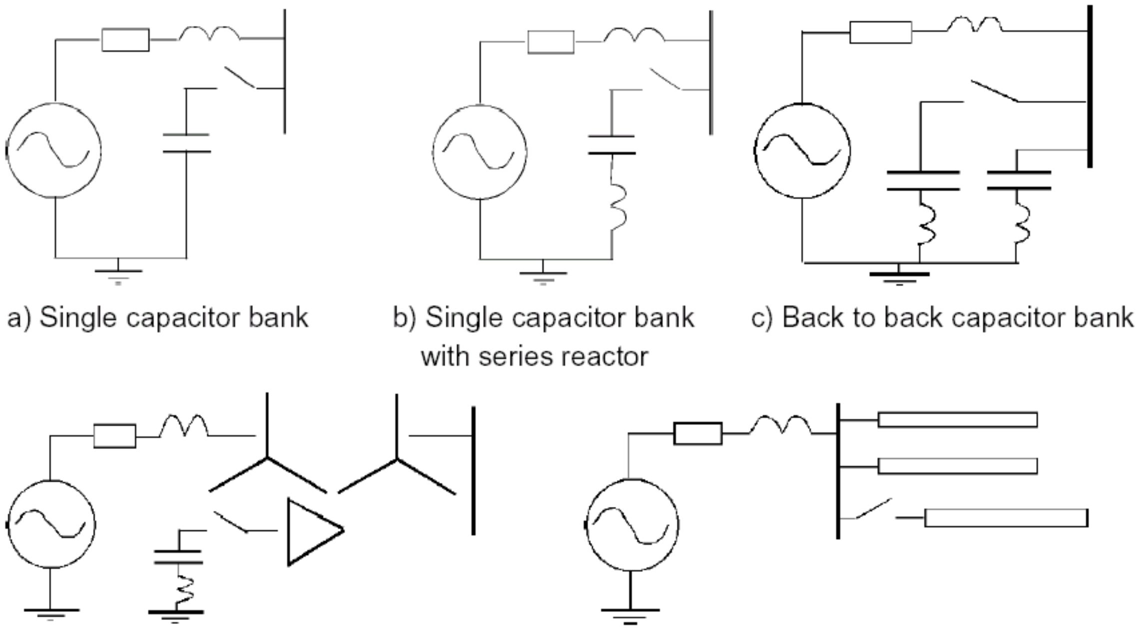
a): Single capacitor bank circuit in most simplified representation. The highest current is easily calculated by V (voltage), C (capacitance) and L (total series inductance). R (series resistance) only influences on the damping of the transient current.

b): Ditto, but with series reactor intentionally added. The practice is very common in Japan to suppress the current and also harmonic current component.: So called back to back capacitor bank circuit, where, if the series reactance values are low, very high inrush current flow. Special care should be paid for circuit breaker application.

c): So called back to back shunt capacitor bank arrangement. When a capacitor bank is switched on while another one is previously energized, true inrush current may flow. The series reactances are to be carefully calculated.

d): In high capacity of sub-stations, capacitor banks are installed in the transformer's tertiary winding circuits. Thus some amount of series reactances are automatically introduced.

e): In EHV under ground cable systems where, especially, plural circuits are connected to the bus bar, fairly high inrush current may be created.



a) Single capacitor bank b) Single capacitor bank with series reactor c) Back to back capacitor bank

d) Capacitor bank in transformer tertiary winding circuit e) EHV cable system

Fig. 1.9 Circuit diagrams creating capacitive inrush currents

EMTP calculations themselves are thought to be not so, so complicated, so no example is shown here. Care should be taken for also the damping elements (resistances) in the circuits. The values depend on the relevant (the inrush current) frequencies, such as transmission lines, cables, transformers, etc. It may be necessary to preliminarily calculate the inrush current frequency, and to re-calculate each damping element. The followings are general ideas for the damping, which might be of your help unless otherwise obtained. Also see as for details in the following relevant sections.

* **Overhead transmission line and underground cable**: Parameters are to be calculated based on the relevant transient frequency. For underground cable, dielectric loss (tan™), which can be neglected in power frequency, might be necessary to be counted in. See section 3.
* **Capacitor bank**:: Appropriate dielectric loss in the relevant frequency range is to be considered. The loss of the series reactor, if any, is in the order of 0.05% of the capacitor bank capacity in power frequency. About 60% of which is copper loss which can be represented by a constant value of series resistor irrespective the frequency. Iron loss (ca. 25% in power frequency) is represented by a constant value of resistor connected in parallel due the fact that the loss depends on the 2nd power of the voltage irrespective of the frequency. Stray loss (ca 15% in power frequency) is proportional to 2nd power of current and 1.5th power of frequency.
* **Power transformer**: Typical losses of a high capacity of transformer is, ------ Iron loss is ca. 0.03% of the capacity, which can be represented by a constant resistor connected in parallel. Load dependent loss is 0.15 --- 0.2%, 85% of which is copper loss and 15% is stray loss. Like capacitor bank's series reactor, the relevant losses are applied.

Attached data files for this chapter:
Data1-01.dat: Calculating a.c. short circuiting currents in a most simplified circuit in Fig. 1.2
Data1-02.dat EHV sub-station with high capacity of shunt capacity bank and cable network to calculate short circuit current in Fig. 1.3
Data1-03.dat EHV transformer inrush magnetizing current calculation for Fig. 1.5
Data1-04.dat EHV transformer magnetizing current calculation under geomagnetic storm condition in Fig. 1.8