

CHAPTER 3

PROTECTION OF ROTATING MACHINES

Surge protection for rotating machine insulation presents somewhat different problems from those involved in static apparatus such as transformers and switchgear. The power transformer windings, for example, are usually oil insulated and have high impulse-voltage withstand strengths. For reasons of economy and performance, the insulation in machines is dry and space is limited. Not only must the voltage stresses from the conductor to machine iron be limited but, because of the limitations on insulation, the voltage stress between turns of multi-turn coils becomes an important factor. The magnitude of the surge voltage between turns must be controlled to avoid puncture of turn-to-turn insulation, resulting in short-circuited turns. To obtain reliable operation, the surge exposure must be carefully examined and adequate surge protection provided for large motors and generators.

The turn-to-turn insulation in transformers can be made sufficient to withstand the turn-to-turn stresses if the surge voltage from terminal

to iron is properly limited. It is also practical to introduce shielding devices, for example, which produce favorable voltage distribution in the windings. This is not practical in rotating machines.

Lightning Surges

In the study of rotating machine protection, the need to protect against lightning surges is generally accepted. A lightning stroke can hazard a machine by one of two methods: by lightning striking an overhead line and propagating a wave through the system to the machine terminals; and by lightning striking immediately adjacent to the terminals, subjecting the machine to a severe surge. The surge generated in the first case is limited by the line insulation, and the rate of rise is determined in part by the amount of attenuation that occurs as the surge travels through the system.

Switching Surges

It is also possible to have a severe surge generated by a switching operation in a line connected to the motor. The surge can be generated either during switching operations in circuits

connected to the machine, or during the starting of a motor. Generally, the most severe switching surges are generated when a motor is energized through a cable from a bus which has other cables connected to it. Field measurements⁽¹⁾ made for energizing and de-energizing motors with circuit breakers revealed no surges during de-energization, but steep surges with times to crest of as little as $0.1\mu s$ and magnitudes approaching twice normal line-to-ground voltage were detected at the motor terminals when a motor, cable-connected from a bus, was energized.⁽¹⁾ The more cable circuits connected to the bus, the more nearly the surge voltage on the energized motor terminals approaches twice the crest normal line-to-ground voltage. Thus, to ensure complete surge protection for a machine, it must be protected against both lightning and against switching surges.

Since the means of protection against lightning and switching surges is basically the same, the following discussion will apply to protection against both types of surges.

ROTATING MACHINE INSULATION

To adequately protect any machine against power surges, its insulation strength must be known. Rotating machines have two general types of insulation: turn-to-turn insulation, or the turn insulation;⁽²⁾ and

conductor-to-iron insulation, or ground-wall insulation.

The voltage across the turn insulation when a surge voltage is applied to the terminals of a machine is dependent upon the surge voltage rate of rise, number of turns per coil, turn length, velocity of propagation, and coupling between turns. Of these, the rate of rise can best be used to limit the voltage between turns. The criterion used for protection of machines which have multiple turns per coil is that the time to crest of the surge voltage be equal to or greater than $10\mu s$.⁽³⁾

On modern machines, the ground-wall insulation impulse strength has been determined to be more than 1.25 times the crest of a one-minute 60 Hz ASA* proof test, or twice rated line-to-line voltage plus 1,000 V.⁽⁴⁾

Protecting Turn Insulation

When a steep-fronted surge is applied to a winding terminal, the voltage penetrates the winding as a traveling wave with a velocity determined by the constants of the winding. At a point in the winding, therefore, the voltage to iron may still be zero, while at another point the voltage is high. The voltage difference between the two points stresses the intervening turn insulation. (See Figures 3-1 and 3-2.) A traveling

*American Standards Association.

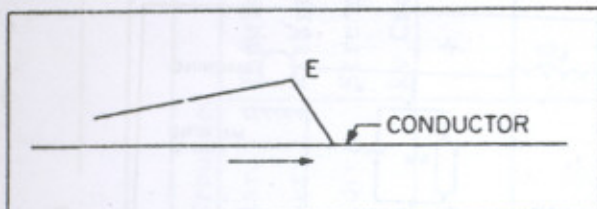


Figure 3-1
Traveling Wave on a Straight Wire..

wave moving along the straight wire in Figure 3-1 produces a potential along the wire. If this wire is coiled, as in Figure 3-2, voltage appears between turns as the wave progresses through the coil.

A rotating machine can be thought of as a transmission line with distributed constants, the essential difference being that the machine winding is wound back on itself. Thus, voltage along the winding produces voltage between turns and the lower the rate of rise of the voltage, the lower the turn-to-turn stress. This immediately suggests that limiting the rate of voltage rise across the terminals of the machine winding is a means of protecting the turn-to-turn insulation.

The basic principle is to control the rate of rise of the voltage with a circuit consisting of inductance and capacitance in series, plus some means of limiting the voltage that can be impressed on the system. If a constant voltage E_a is suddenly impressed on an inductance L and a capacitance C in series (Figure 3-3a),

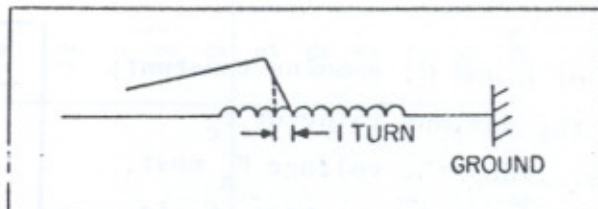


Figure 3-2
Traveling Wave in Rotating-machine Winding.

the voltage will oscillate about E_a (Figure 3-3b) until the circuit losses damp out the oscillations. The oscillation period is $T = 2\pi\sqrt{LC}$, and the voltage peaks at time $= 1/2 T = \pi\sqrt{LC}$. By judiciously selecting L and C , time to peak ($1/2 T$) can be minimized.

Figure 3-3b shows that if E_a is increased, the rate of rise is also increased since $1/2 T$, which is a

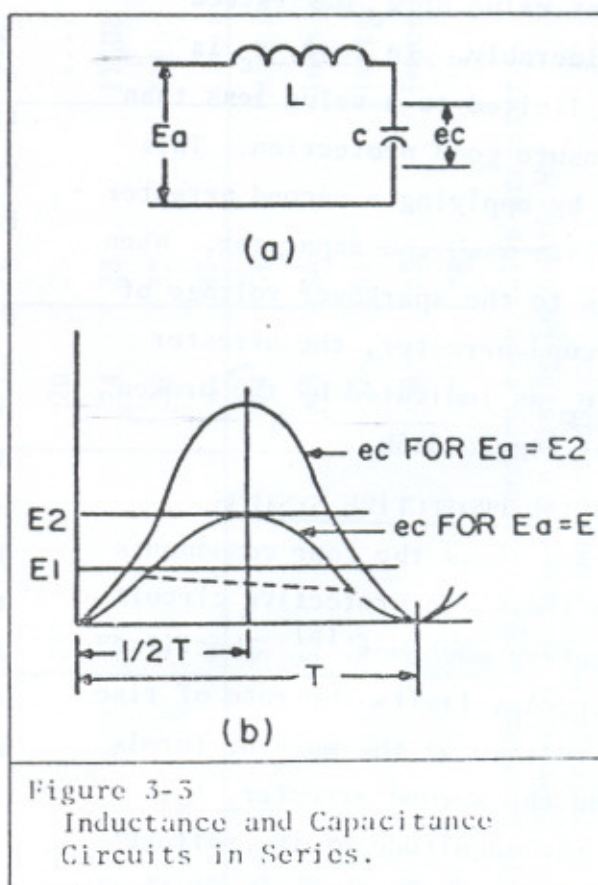


Figure 3-3
Inductance and Capacitance
Circuits in Series.

function of L and C , remains constant; whereas, the maximum value of e_c increases. Thus the voltage E_a must also be limited. In practice, E_a is limited by an arrester.

Since single-turn machines have only one winding, they have no turn insulation and it is unnecessary to protect these machines against steep fronted surges.

Protecting Ground-Wall Insulation

The three components already discussed do not protect the rotating machine completely. Figure 3-3b shows that the voltage e_c can rise to twice the value of E_a . While this is not likely due to damping, the crest value of e_c may exceed E_a considerably. In fact, e_c is usually limited to a value less than E_a to ensure good protection. This is done by applying a second arrester in parallel with the capacitor. When e_c rises to the sparkover voltage of this second arrester, the arrester limits e_c as indicated by the broken lines of Figure 3-3b.

FUNDAMENTAL PROTECTIVE SYSTEMS

Figure 3-4 shows the four components used in the basic protective circuit for rotating machines.⁽⁵⁾ The first arrester, A_L , limits the rate of rise of the voltage at the machine terminal; and the second arrester, A_M , limits the magnitude of the voltage

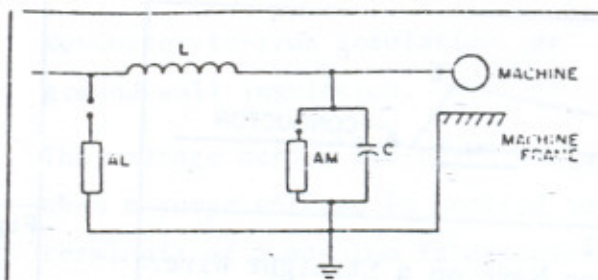


Figure 3-4
Fundamental Protective System.

from the machine terminal to the machine frame. The arrester, A_L , is the standard type of arrester used to protect oil-filled transformers. The inductance may be a transformer or a length of line. The capacitance is usually a capacitor, unless the machine is connected to a cable, in which case the cable may supply the capacitance.

A_M is usually a specially designed arrester with low and closely controlled sparkover and discharge voltages. Table 3-1 lists the protection levels of station-type arresters designed for machine protection.⁽⁶⁾ The oscillograms shown in Figure 3-5 illustrate the operation of the circuit in Figure 3-4. They are the results of laboratory tests made by applying an impulse from a surge generator to the terminals of the line arrester, A_L . In the first two oscillograph traces, Traces (1) and (2), the machine arrester A_M was not connected. In Trace (1), the voltage across the line arrester, A_L , is the voltage

Table 3-1

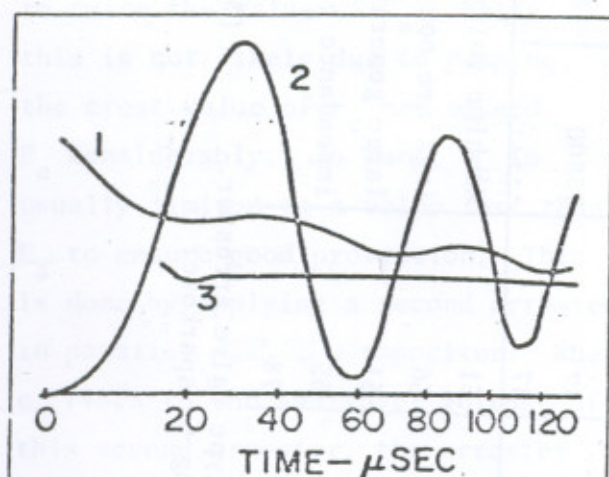
Protection Levels of Station-type Arresters Designed for Machine Protection

Lightning Arrester				Rotating Ac Machine					
Rating kv Rms	Maximum Impulse Sparkover kv Crest(2)	Maximum Discharge Voltage kv Crest(3)		Machine Circuit Neutral Grounding					
		1500 Amperes	5000 Amperes	Effectively Grounded			Not Effectively Grounded		
				Voltage Class	Standard 60 Hertz Sparkover	Impulse Withstand Strength kv Crest	Voltage Class	Standard 60 Hertz Sparkover	Impulse Withstand Strength kv Crest
650 Volts(1)	3	3	3.5	650	3.3	4	650	3.5	4
3	9.5	8	9.5	2400	8.2	10	2400	8.2	10
3	9.5	8	9.5	4160	13.2	16	....	...	..
4.5	14.5	12	14	4800	15.0	19	4160	13.2	16
6	19	16	19	6900	20.9	21	4800	15.0	19
7.5	24	20	23	....	....	..	6900	20.9	21
9	28	24	28	11500	33.9	42	....	...	..
12	37	32	37	13800	40.5	50	11500	33.9	42
15	46	40	47	.....	....	..	13800	40.5	50
16.5	51	44	51	Machine voltages in these ratings are not standardized--large generators usually have impedance grounded neutral			14400	42.1	53
18	55	48	56				16500	48.0	60
19.5	60	52	61				18000	52.3	65
21	64	56	65				20000	57.9	72
24	76	67	78				24000	69.2	86

- (1) Standard 3-phase secondary type valve arrester.
 (2) Sparkover on test wave rising to sparkover voltage in 10 microseconds.

- (3) Crest voltage across arrester during discharge of a 1500 ampere or a 5000 ampere 8 x 20-microsecond circuit.

impressed on the LC circuit. The rate of rise of this voltage is rapid, and the trace of the wave-front is not discernible in the reproduction. Trace (2) is the voltage across the capacitor, e_c . Despite the steep rate of rise on the applied voltage, e_c rises slowly. The overshoot of the crest of e_c beyond the applied voltage is apparent. With the second arrester, A_M , applied, the crest of e_c is limited, as shown in Trace (3). In this latter case, the rate of rise is controlled by L , C , and A_L , while the crest is controlled by A_M .



CATHODE-RAY OSCILLOGRAMS OF VOLTAGE IN THE PROTECTIVE SYSTEM:

- 1) VOLTAGE ACROSS A_L ;
- 2) VOLTAGE, e_c , ACROSS C WITH A_M NOT CONNECTED;
- 3) VOLTAGE, e_c , WITH A_M CONNECTED

Figure 3-5

Machine Neutral Protection

In most cases, surge protection is not required at the machine neutral. However, where it is possible that overvoltage could occur at the neutral, the system should be studied in detail. There are two ways of providing neutral protection:

1. If the neutral is accessible, it can be protected by applying a capacitor and an arrester to the neutral as shown in Figure 3-6a. (6,7)
2. Where the neutral is not available or the above neutral protection is too expensive, the normal capacitance at the machine terminals can be doubled, as in Figure 3-6b. (6,7)

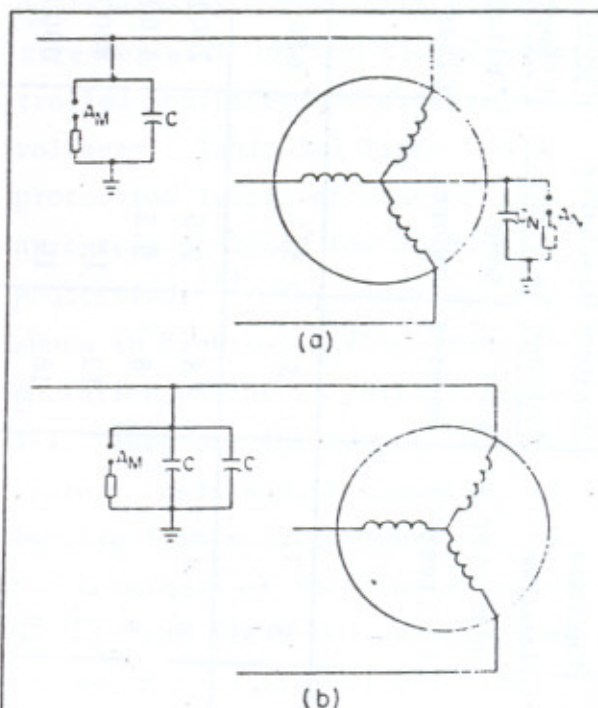


Figure 3-6
Recommended Protection for
Ungrounded Neutral Machines
Rated 11.5 KV and Higher.

Since there is normally no need for neutral protection, it will not be discussed any further here. More detailed information can be found in References 7 and 8.

Protective Devices at the Machine

Tables 3-II and 3-III give the requirements for the protective capacitors and arresters at the machine terminals and at the machine neutrals. Machines that are coupled to overhead lines through a transformer may not require as much protection at the machine because in many cases, the only way a surge can get to the machine is by transfer through the transformer windings. The transformer behaves as an inductance and may modify the conditions assumed to obtain the values in Tables 3-II and 3-III. (The transformer-connected unit is detailed later.)

INDUCTANCE AND ARRESTER ON THE LINE

There are three methods of obtaining the inductance required in the basic system shown in Figure 3-4: the inductance can be a length of overhead line (Figure 3-7, Example 1); a cable (Example 2); or a transformer (Example 3).

Overhead Line

A length of overhead line (Figure 3-7, Example 1) is probably the most widely used inductance because of its simplicity and ready availability. The length out to the line arrester, A_L ,

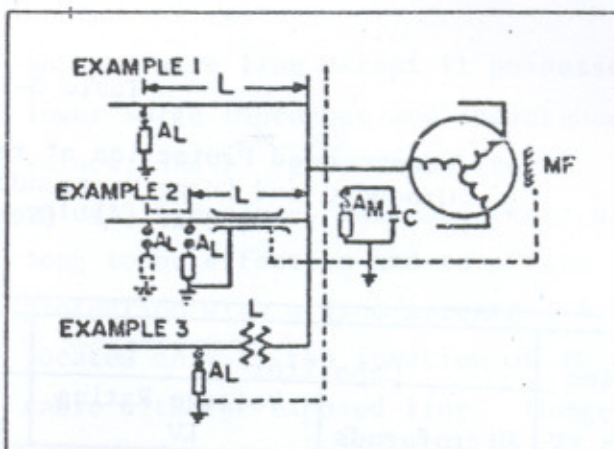


Figure 3-7
Practical Means of Obtaining Series Inductance.

should be 500 to 1,500 ft. A disadvantage of this scheme is that the resistance of the ground connection of the line arrester, A_L , enters into the voltage impressed on the protective circuit. Furthermore, if a stroke hits between the line arrester and the machine, the machine will probably not be adequately protected because: the required inductance will not be in series with the capacitor; and the line arrester cannot limit the voltage impressed on the system as effectively as for strokes ahead of the line arrester.

The ground resistance at the line arrester is also of considerable importance. With high surge currents, the voltage across the ground resistance is high. This voltage adds to the arrester voltage, and the total is impressed on the L and C circuit. If the ground terminals of the protective devices and the machine can be tied together (Figure 3-7, Examples

Table 3-II

Recommended Protection at the Machine Terminals for all
Grounded and Surge Ungrounded Neutral Machines up to
6.9 KV. (4) (See Figure 3-6.)

Machine Voltage Class KV	Capacitor		Arrester Rating KV	
	Microfarads	Voltage Rating KV	Effectively Grounded System	Not Effectively Grounded System

For surge grounded neutral and surge ungrounded neutral machines

0.65	1.0	0.65	0.65	0.65
2.4	0.5	2.4	3	3
4.16	0.5	4.16	3	4.5
4.8	0.5	4.8	4.5	6
6.9	0.5	6.9	6	7.5

For surge grounded neutral machines

11.5	0.25	11.5	9	12
13.8	0.25	13.8	12	15

Table 3-III

Recommended Protection at Machine Terminals and/or at the
Neutral for Ungrounded Neutral Machines Rated 11.5 KV
and Higher. (4) (See Figure 3-6.)

Machine Voltage Class KV	Terminal Equipment				Neutral Equipment		
	Capacitor		Arrester Rating KV		Capacitors		Arrester
	Micro- farads	KV	Effectively Grounded System	Not Effectively Grounded System	Micro- farads	KV	Rating KV

For protection scheme shown in Figure 3-6a.

11.5	0.25	11.5	9	12	0.5*	6.9	7.5
13.8	0.25	13.8	12	15	0.25	11.5	9

For protection scheme shown in Figure 3-6b.

11.5	2 x 0.25	11.5	9	12			
13.8	2 x 0.25	13.8	12	15			

*0.25 μ F is sufficient, but standard 6.9 KV capacitor is 0.5 μ F.

2 and 3), ground resistance is not so important. A ground resistance in excess of two or three ohms and in series with the arrester may permit voltage high enough to produce a rate of rise at the capacitor which is not safe for the machine turn insulation.

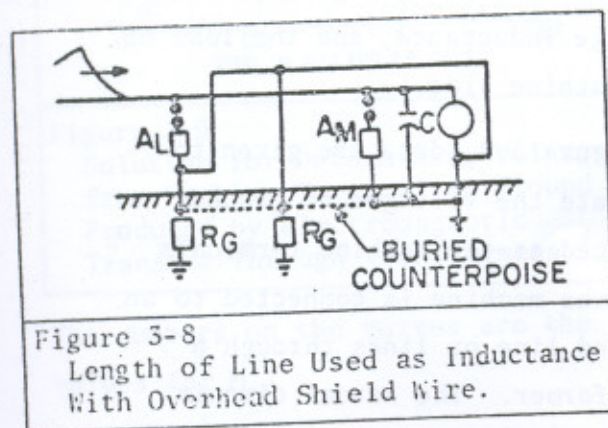


Figure 3-8
Length of Line Used as Inductance
With Overhead Shield Wire.

Figure 3-8 shows a system that provides a high degree of protection under high-exposure conditions. Effective shielding is provided through the addition of a shield wire to which all grounds are connected. The length of line between the line arrester and the machine is still a minimum of 500 ft. With this system the maximum permissible pole and arrester ground resistance, R_G , is higher, in the order of 5 to 10 ohms. If the ground resistance exceeds the recommended value, it can be reduced with counterpoise (Figure 3-8).

Underground Cable

An underground cable with grounded metallic sheath behaves similarly to

an open wire line except it possesses lower surge impedance and inductance values, and a higher capacitance value. Therefore, the cable must be long to be effective and to afford protection with a line arrester, A_L , located only at the junction of the cable with the exposed line. The length of cable required depends on the surge impedance, Z , of the cable. For example, cables with surge impedances of 5, 10, 25, and 50 ohms require minimum lengths of 2,000, 1,000, 500, and 300 ft, respectively. If the installed cable is not long enough, the inductance can be increased by using an additional length of overhead wire, shown by the broken lines of Figure 3-7, Example 2. A shield wire over the additional line is recommended in regions of high lightning exposure. If the cable length is less than 200 ft, the line should be treated as if there were no cable present.

Transformer

The case of a transformer between the machine and overhead line (Figure 3-7, Example 3) provides a high inductance and a high degree of protection. Note that arresters on the line terminals of the transformer are necessary not only for the protection of the transformer but for the protection of the machines as well. In some cases a rigorous analysis of the system indi

cates that no protection at the machine terminals is needed. Despite this, capacitors and arresters are generally installed on large machines as added insurance. A complete analysis should be undertaken whenever the omission of surge protection is contemplated.

Voltage is transferred through the transformer from the line side to the machine side both electrostatically and electromagnetically.

The Electrostatic Component is transferred through the capacitive coupling. With the secondary open or connected to an impedance of several hundred ohms or more, a surge impressed on the primary can produce surges of severe magnitude and steepness on the secondary. These surges can be reduced sufficiently if a resistance of 50 ohms or less, or a capacitance of $0.005\mu\text{F}$ or more, is placed in parallel with the transformer secondary. Although the total capacitance of machine windings usually ranges between 0.02 and $0.6\mu\text{F}$, tests have shown that this capacitance is not effective and that the machine itself exerts very little influence on the electrostatic component.⁽⁹⁾ The machine winding acts as a surge impedance rather than a lumped capacitance. Unless the surge impedance is low enough to suppress the electrostatic component, capacitance external to the machine is required. Except

for capacitors, the only circuit element that could eliminate the electrostatic hazard is cable. A 50-foot cable is usually enough to supply the required capacitance.

The Electromagnetic Component

is a function of the ratio of turns, the voltage impressed on the transformer line terminals, the winding connections, neutral ground, the leakage inductance, and the load on the machine side.

In Figure 3-9, data are given to estimate the voltages to ground produced at the machine terminals when the machine is connected to an exposed line or lines through a transformer. The actual circuit is Diagram 1; while Diagram 2 is the equivalent circuit.

E_a = discharge voltage of the line arrester.

V_m = voltage at the machine terminal.

L = leakage inductance of the transformer in μH on a line-to-neutral base on the machine side.

C = positive-sequence line-to-neutral capacitance in μF on the machine side.

R = effective surge impedance of the machine. If several machines are in parallel, it is the resultant of the paralleled impedances.

N = ratio of the machine to line voltages, phase to phase.

T = period, $2\pi\sqrt{LC}\mu\text{s}$

M = $\sqrt{LC/2RC}$

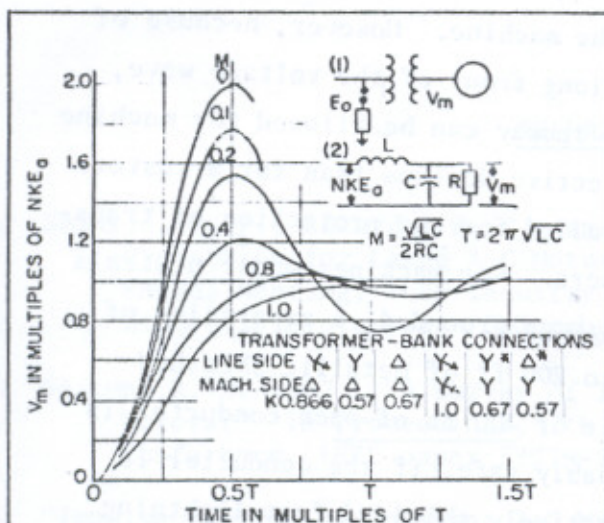


Figure 3-9
Solution for Determining Voltages from Machine Terminal to Ground Produced by Electromagnetic Transfer Through Transformers.*

The numbers on the curves are the values for M.

First the value of E is determined. A figure should be obtained for R, the machine surge impedance. If R cannot be determined, use 500 to 1,000 ohms per machine for slow-speed machines from 2.4 KV to 13.8 KV, and 500 ohms for machines with speeds above 1,800 rpm. (This will usually be conservative.) Calculate L from the impedance of the transformer. Transformer leakage reactances are given in Reference 10. Three-winding transformers can be treated accurately in terms of their equivalent leakage-reactance circuit.⁽¹⁰⁾ A safe

*K is the same whether neutral of one Y winding is grounded or isolated.

approximation, however, results from considering the tertiary windings open, and treating the transformer as a two-winding one. Determine C from the amount of cable on the capacitor installed. Find T, M, NKE_a , and use the curves in Figure 3-9 to obtain the solution.

Unit-connected Generators

A typical unit-connected generator is connected to the system as shown in Figure 3-10.⁽¹¹⁾ Arresters on the high-voltage terminals protect the transformer insulation. When the arrester sparks over, its discharge voltage is transferred through the transformer and modified in magnitude and wave-shape by the surge characteristics of the transformer, generator, and cable or isolated phase bus. If, when this surge voltage impinges on the generator terminals, it overstresses the generator insulation, arresters, or arresters and capacitors should be installed.

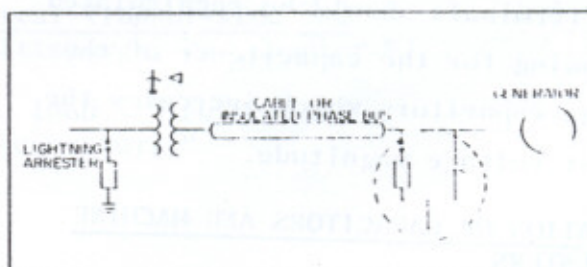


Figure 3-10
Typical Unit-connected Generator Has Lightning Arresters on Line Terminals at Main Transformers.

Large generators normally have low surge impedances, usually less than 100 ohms. In Figure 3-9, as the surge impedance of the machine decreases, M increases, and both the rate of rise and crest magnitude of the surge voltage decrease. When $R = \frac{1}{2} \sqrt{L/C}$, and the critical resistance, $M = 1$, the circuit is aperiodic. With machines of low surge impedances, therefore, this factor, combined with the inductance of the transformer, may provide protection.

It is best to evaluate each situation thoroughly before deciding not to use any protective devices at the terminals of unit-connected generators. If the crest magnitude of voltage at the generator terminals is greater than the machine's impulse withstand strength, arresters should be applied at the terminals. Capacitors should be applied if the rate of rise is greater than the maximum permissible. If capacitors rather than arresters are required, the crest magnitude at the terminals should be recalculated allowing for the capacitance of the surge capacitors which increases the crest voltage magnitude.

LOCATION OF CAPACITORS AND MACHINE ARRESTERS

The machine arresters and capacitors should be located as close as possible

to the machine. However, because of the long front of the voltage wave, more leeway can be allowed for machine protective devices than for arresters installed for the protection of transformers. For machines whose neutrals are surge grounded, a separation of up to 200 ft of metallic-sheathed cable or 400 ft of open conductor is probably safe, if the conductor is effectively shielded from lightning. These distances should be halved for machines with inadequately grounded neutrals. If the arrester and the capacitor are not located in the same place, the capacitor should be installed between the machine and the arrester. The capacitor leads place an inductance in series with the capacitor; consequently, the rise in voltage on the phase conductor may be higher than advisable if the capacitor leads are too long. Capacitor leads should be as short as possible. The length of the arrester leads is less important.

If several machines are connected to the same bus through circuits that are not too long, and if all incoming circuits terminate on the bus, all machines can be adequately protected by one set of machine arresters and capacitors on the bus.

REFERENCES

1. Shankle, D. F.; Edwards, R. F.; and Moses, G. L. 1968. "Surge Protection for Large A-C Motors." Paper read at 3rd Annual Meeting, IEEE Industry and General Applications Group, 29 September - 3 October, 1968.
2. Sexton, R. M. 1967. "A Survey of Turn Insulation on Large A-C Motors." In Proceedings, 7th Electrical Insulation Conference, IEEE paper 52C79-23. New York: IEEE.
3. "Impulse Testing of Rotating A-C Machines." A report of ASA-C-50 Subcommittee. AIEE Transactions III, 79 (1960): 182-88.
4. Moses, G. L., and Alke, R. J. 1953. "Studies of Impulse Strength and Impulse Testing on High-Voltage Generators." AIEE Transactions III, 72: 123-31.
5. McCann, G. D.; Beck, E.; and Finzi, L. A. 1944. Lightning Protection for Rotating Machines." AIEE Transactions 63: 319-33.
6. Westinghouse Electric Corp., Bloomington, Indiana. May, 1970. Westinghouse Application Data 38-423.
7. Westinghouse Electric Corp. 1950. Electrical Transmission and Distribution Reference Book. East Pittsburgh, Pa., Chapter 18.
8. Powell, R. W.; Hileman, A. R.; and Maxwell, M. February, 1963. "Lightning Protection of Rotating Machines Directly Connected to Overhead Lines." AIEE Transactions 82: 721-30.
9. Beck, E. 1954. Lightning Protection for Electric Systems. New York: McGraw-Hill Book Co.
10. Westinghouse Electric Corp. 1950. Electrical Transmission and Distribution Reference Book. East Pittsburgh, Pa., Chapter 5.
11. Dillard, J. K., and Hileman, A. R. June 6, 1960. "New Method Guides Protection of Unit-Connected Generators." Electrical World.