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Surge Protection for Rotating Ac Machines

Arresters and Capacitors

The General Problem

Surge protection for the insulation in rotating machines such as motors and generators poses problems somewhat different from those involved in static apparatus such as transformers and switchgear. The windings of power transformers, for example, are usually liquid immersed and have relatively high impulse voltage withstand strengths. The insulation strength of machines is less. This is so for reasons of economy and performance. The insulation in machines is dry, and space is limited. Not only must the voltage stresses from conductor to machine iron be limited to a high degree, but because of the limitations on insulation, the voltage stresses developed between turns of multi-turn coils become important. The magnitude of the surge voltage permitted between turns must be controlled so that it will not cause puncture of turn-to-turn insulation, resulting in short-circuited turns. In transformers, the turn-to-turn insulation can be made sufficient to withstand the turn-to-turn stresses that occur, provided the surge voltage from terminal to iron is properly limited. Also, it is practical in transformers to introduce, when desirable, contrivances such as shielding which produce a favorable voltage distribution in the windings. This is not practical in rotating machines.

Voltage Stresses Between Turns

Consider first the problem of the voltages between turns. If a rapidly rising voltage is applied to the terminal of a winding, the voltage across turns is not necessarily uniformly distributed. The voltage penetrates into the winding as a traveling wave with a velocity determined by the constants of the winding. Thus, at a point in the winding, the voltage to frame may still be zero while at another point the voltage is high. The insulation between turns spanned by this voltage difference is stressed by it.

How this comes about is illustrated in figure 1 and figure 2. In figure 1, A-A is a straight wire with a traveling voltage wave E, moving from left to right, and F is the wave front in microseconds. If $\frac{de}{dc}$ is the rate of rise of voltage in KV per mcirosecond, V is the velocity of propagation of the wave in feet per microsecond, L is the length of wire in feet spanned by F, L' is any length of wire less than L, and e is the voltage in KV across L', these quantities are related in the following manner: L=FV. and e=(de/dt) (L'/V). Thus, there is a difference of potential along the wire. If the wire is wound up into a coil, voltage appears between turns as the wave progresses through the coil. A rotating machine can be thought of as a transmission

Figure 1. Traveling Wave in a Straight Wire.

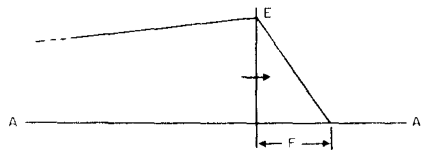


Figure 2. Traveling Wave in a Coil of Wire.

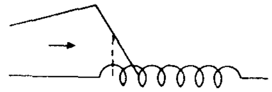


Figure 3. Simple Oscillatory Circuit.

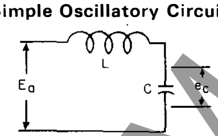
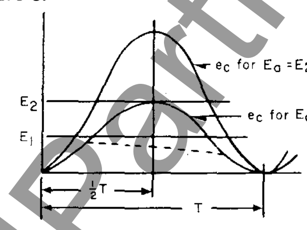


Figure 4. Voltage Across the Capacitor in Figure 3.



line with distributed contants, the essential difference being that the machine winding is wound back on itself, thereby producing voltage between turns. The lower the rate of rise of the voltage, de/dt, the lower the turn-to-turn stress. This immediately suggests a way of protecting the turn-to-turn insulation – limitation of the rate of rise of the voltage that can be impressed on the line terminal of the coil. This is the method used in practice.

The basic principle is to control the rate of rise by a circuit consisting of inductance and capacitance in series, and limiting the voltage that can be impressed on this system. If a constant voltage E_a is suddenly impressed on an inductance L and a capacitance C in series, as in figure 3, it is well known that the voltage across the capacitance, e_c, will be an oscillatory one, oscillating about E_a until the losses in the circuit damp out the oscillations. The period is $T = 2\pi\sqrt{LC}$, in microseconds when L is expressed in microhenries and C in microfarads. It reaches its peak in the time $\frac{1}{2}T = \pi\sqrt{LC}$. By properly choosing the values of L and C, then, a minimum time, ½T, can be fixed. This alone, however, does not set a limit to the rate of rise of e_c. To accomplish this, the voltage E_a impressed on the circuit must be limited also. For it is obvious from figure 4 that if E_a is increased, the rate of rise is also increased because ½T remains the same, being determined by L and C, whereas the maximum value of e_c increases. So three members are required to limit the rate of rise of e_c – a capacitance, an inductance, and a means of limiting E_a. In practice, E_a is fixed by a lightning arrester. The machine is connected in parallel with the capacitance, so that the surge voltage impressed from terminal to iron is e_c.

Voltage Stresses, Condutor to Iron

The three components discussed do not yet protect completely. Figure 4 shows that the

Figure 5. The Fundamental Protective System.

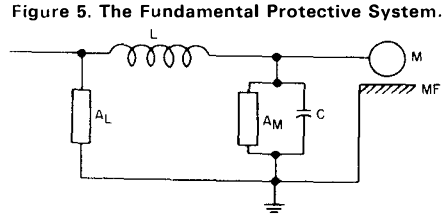
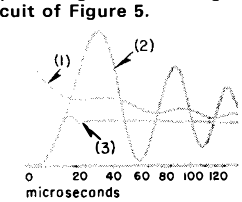


Figure 6. Cathode Ray Oscillograms of Voltages in the Protective Circuit of Figure 5.

(1) Voltage Across Line Arrester A_L.

(2) Voltage e_C with Machine Arrester A_M Disconnected.

(3) Voltage e_C with Machine Arrester A_M Connected.



voltage e_c can rise theoretically to twice the value of E_a. In practice this is not likely because of damping. However, the crest of e_c may exceed E_a by a considerable amount and endanger the insulation from conductor to iron. It will usually be necessary to restrain e_c to a value even less than E_a in order to insure good protection. This is done by applying a second lightning arrester in parallel with the capacitor. Then, when e_c rises to the sparkover voltage of this second arrester, it limits e_c as indicated by the dashed lines in figure 4.

The Fundamental Protective System

The complete basic protective circuit for rotating machines is shown in figure 5. It consists of four necessary components. The first arrester, A_L, limits the incoming voltage. The inductance L and capacitance C limit the rate of rise of the voltage at the machine terminal. The second arrester, A_M, limits the magnitude of the voltage from the machine terminal to its iron or frame. The symbol MF represents the machine frame.

In practice, the inductance may be a lumped inductance such as a coil or a current-limiting reactor, or it may be a transformer or a length of the incoming line itself. The capacitance is usually a capacitor, but if the circuits are in cable, its capacitance may be sufficient under certain conditions. The line

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arrester, A_L, is a standard arrester as is used for the protection of liquid immersed transformers. The arrester at the machine, A_M, is usually one designed especially for this purpose, with low and closely controlled sparkover and discharge voltages.

The operation of the circuit in figure 5 is shown by the oscillograms of figure 6. They are the results of laboratory tests made by applying an impulse from the surge generator to the terminals of the line arrester, A_L. In the first two oscillograms (1) and (2), the machine arrester, A_M, was not connected. Trace (1) is the voltage across the line arrester, A_L. This is the voltage impressed on the LC circuit. The rate of rise of this voltage is obviously very rapid although the trace of the wave front is not discernible in the reproduction. Trace (2) is the voltage e_c. The more gradual rise in the voltage and the overshoot of the crest beyond the impressed voltage (1), are apparent. Trace (3) is the voltage as limited by the complete protective circuit. The rate of rise is controlled by L, C, and A_L. The crest is controlled by A_M.

Circuit Constants

Consideration should be given to the constants that are desirable. The turn-to-turn insulation of most modern machines over 5000 kva is designed so that each coil will stand full line-to-line rated voltage. However, many smaller motors and older machines were designed for only half this strength. In many cases motors in particular are abused so that the insulation strength may be impaired. Some machines have as high as 40 turns per coil with 20 turns per coil not uncommon. Most turbine generators have coils with from 1 to 3 turns.

The standard practice has been adopted of sloping the voltage wave so that the time to reach maximum recommended voltage is ten microseconds or more. This applies to the time required to reach the voltage equal to the value machine designers recommend as a safe limit. This value corresponds to the crest of the 60 cycle test voltage applied to the machine insulation. In the case of modern large machines with one or two-turn coils, fronts of three or four microseconds would be safe. However, the extent to which successive impulses may age machine insulation is not known with certainty. The conservative ten-microsecond front for all machines is still considered desirable not only for this reason but also to permit a uniform, more or less standardized method of surge protection. There is long experience behind this procedure, and in dealing with the protection of generators or motors that may be vital cogs in a system or a process, conservatism is advisable.

The desired limitation on the rate of rise of voltage can be obtained with various combinations of L and C. The general practice, in the interest of standardization, is to use a lumped capacitance of one-half microfarad in the range from 2400 to 6900 volts, one-quarter microfarad in the range from 11.5 to 13.8 kv, and one-eighth microfarad for ratings 14.4 kv and above where lumped capacitance is required. The series inductance, if lumped as in a choke coil or a reactor should be at least 175 microhenries.

Effect of Machine Neutral Grounding

It is necessary to consider the machine neutral grounding, since the surge entering the machine winding eventually reaches the neutral. Machines may be wound delta, in which case the windings are ungrounded. Large machines are usually wye wound. Their neutral point may be ungrounded, solidly grounded, or grounded through an impedance such as a reactance, a resistance, or a transformer with resistance in its secondary which is equivalent to high-resistance grounding. For a machine whose neutral is solidly grounded, it is obvious that there will be no potential from conductor to ground at the neutral. In the case of a wye-connected machine with the neutral ungrounded, voltage will appear at the neutral when the traveling wave in the winding reaches the neutral. If the surge enters on one phase only, it will travel on beyond the neutral into the other two phases and there will be some reduction in voltage because the surge impedance of two windings in parallel is less than that of the one winding over which the surge arrives. If the surge enters on all three phases at once, which is not unlikely if the machine is conductively connected to overhead lines, it is reflected back into the windings when it reaches the open neutral because it has no other place to go. The resultant voltage at the neutral is the sum of the incident and reflected waves. The degree to which it exceeds the incoming wave depends on the rate of rise of voltage and the electrical length of the winding. For a given winding, the lower the rate of rise of voltage, the less the resultant voltage at the neutral. In delta-wound machines, the excess voltage will appear at the midpoints of the phases, assuming surges to enter on all three simultaneously. If the machine neutral is grounded through an impedance and surges arrive over all three windings, the resultant voltage that appears at the neutral is dependent on the relation of this impedance to the surge impedance, R, of the machine windings. If the two are equal, there is no change in voltage at the neutral when the surge arrives, because there is no reflection; the surge is absorbed in the grounding impedance without change. If the impedance to ground is less than R, there is a negative reflection and the resultant voltage is lower than the incident voltage. If it is greater than R, there is a positive reflection, and with infinite impedance, the reflected voltage is equal to the incident, so that the resultant voltage may be twice the incident. Thus, it is apparent that the protection applied to machines must give consideration to the voltages at the far ends of the windings as well as at the line terminals.

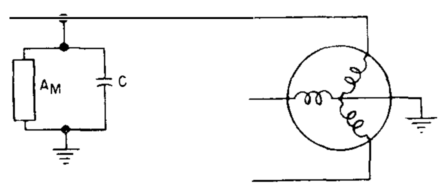
If there is danger of excess voltage appearing at the neutral, the most obvious countermeasure is to apply protection at the neutral point as well as the line terminals. An alternate method is to apply enough capacitance at the line terminals to slope the entering voltage to such a degree that the excess voltage at the neutral or at the midpoints of delta windings is limited by that means. In fact, this is the only solution in the case of delta machines where the midpoints of the windings are not accessible. This is one reason for standardizing on capacitors of one-half microfarad for machines operating at 2400 to 6900 volts, although for solidly-grounded neutral machines one-quarter microfarad would be sufficient. In cases of 11.5 and 13.8 kv machines whose neutral is not adequately grounded, one has a choice of applying one-quarter microfarad capacitors at machine terminals and added protection at neutral or applying two such capacitors in parallel per phase at line terminals to obtain one-half microfarad with no protection at neutral. The choice is determined by economics. One-half microfarad per phase should be used on delta machines. In the case of machines connected to exposed lines only through transformers and not conductively, neutral protection is not required and one-quarter microfarad at each line terminal is sufficient as discussed under "a transformer used as the inductance", page 7. Unit connected generators 14.4 kv and larger with delta-wye transformers and with no directly connected overhead lines are protected with a 0.13 microfarad capacitor at each line terminal.

Surge Protection for Rotating Ac Machines

Arresters and Capacitors

Protective Devices at the Machine

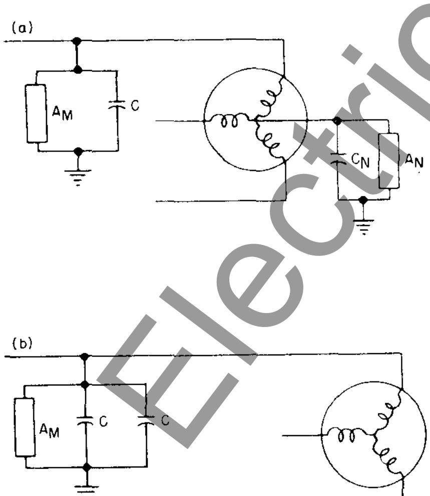
In fig. 7 and fig. 8, two arrangements are shown for the protective capacitors and arresters at machines where the machines are conductively connected to overhead exposed lines. Note that the overall cost of the equipment as shown in fig. 8(a) may be less than that required for fig. 8(b) because fewer capacitors are required and the neutral capacitor and arrester may be of lower voltage ratings than the terminal devices. Machines that are coupled to overhead lines through the medium of transformer only may not require as much protection at the machine because the only way lightning voltage can normally get to the machine is by transfer through the transformer windings. The transformer acts like a high inductance and may modify the conditions assumed for fig. 7 and fig. 8. The transformer installation is discussed under "a transformer used as the inductance".



① The neutral is considered grounded as far as effects on the reflected voltage are concerned if the impedance between neutral and ground does not exceed 50 ohms of resistance or 0.2 ohm of 60-cycle reactance per 100 ohms of winding surge impedance. Minimum surge impedance may be considered 100 ohms unless actual value is known. This grounding is from standpoint of surge reflection only and does not necessarily determine whether the system is or is not effectively grounded for the purpose of selecting a voltage rating for the arrester.

Machine Voltage Class	Capacitor C Rating		Machine Arrester A_M Rating Kv Rms	
			System Neutral Grounded	
	Microfarad	Kv Rms	Effectively	Not Effectively
For Grounded and Ungrounded Machines				
650	1.0	0.65	0.65	0.65
2400	0.5	2.4	3.0	3.0
4160	0.5	4.16	3.0	4.5
4800	0.5	4.8	4.5	6.0
6900	0.5	6.9	6.0	7.5
For Grounded① Machines (for Ungrounded① 11.5 and 13.8 Kv Machines, see Figure 8)				
11500	0.25	11.5	9.0	12.0
13800	0.25	13.8	12.0	15.0

Figure 7. Protection at the Machine for All Grounded ① Neutral Machines and for Ungrounded ② Neutral Machines Up to and Including 6900 Volts Where Machines are Directly Connected to Exposed Overhead Lines (Terminal Protection Must be Applied to Each Phase).



Machine Voltage Class	Terminal Equipment			Neutral Equipment		
	Capacitor C Rating		Arrester A_M Rating	Capacitor C_N Rating		Arrester A_N Rating
	Micro-farad	Kv Rms	Kv Rms	Micro-farad	Kv Rms	Kv Rms
If System is Not Effectively Grounded from Arrester Standpoint – Figure 8(a)						
11500	0.25	11.5	12	0.5①	6.9	7.5
13800	0.25	13.8	15	0.25	11.5	9.0
Or As in Figure 8(b)						
11500	2x0.25	11.5	12	...	...	...
13800	2x0.25	13.8	15	...	...	...
If System is Effectively Grounded from Arrester Standpoint – Figure 8(a)						
11500	0.25	11.5	9	0.5①	6.9	7.5
13800	0.25	13.8	12	0.25	11.5	9.0
Or as in Figure 8(b)						
11500	2x0.25	11.5	9	...	...	...
13800	2x0.25	13.8	12	...	...	...

① 0.25 microfarad would be sufficient, but standard 6.9 kv capacitor is 0.5 microfarad.

Figure 8. Protection at the Machine for High Voltage (11.5 Kv and Higher) Machines Metallically Connected to Overhead Exposed Lines not Adequately Grounded from the Standpoint of Surge Voltage as Explained in Figure 7 (Terminal Protection Must be Applied to Each Phase).

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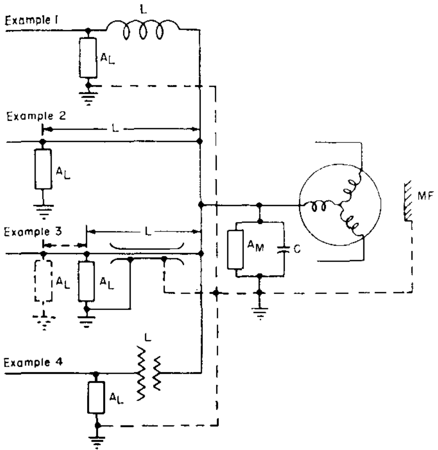
The Inductance and the Arrester on the Line

Fig. 9 shows the practical means of obtaining the series inductance and control of the voltage, E_a, impressed on the L and C circuit. It may be lumped, such as the choke coil or reactor shown in fig. 9, example 1; it may be a length of the overhead line as in example 2; it may be a cable as in example 3; or it may be a transformer as in example 4. The line arrester A_L, is a standard arrester such as used for the protection of transformers.

Figure 9. Practical Means of Obtaining Series Inductance.



The lumped inductance has some advantages where the lines are conductively connected to the machines. The inductance should be at least 175 microhenries if the line arrester is a valve arrester. The ground terminals of all protective devices and the machine frame, MF, should be tied together and grounded. A disadvantage of the choke coil scheme is that it is an added piece of equipment – on systems with heavy short-circuit currents, it must be a sturdy coil. The scheme has been used to some extent. If current limiting reactors are connected in the circuit for their own purposes, they may be used as the protective inductance. Their inductance is usually large compared to the values stated above. Thus, they provide efficient protection.

A length of the line is probably the most widely used inductance because it is simple and already available. The length out to the line arrester, A_L, should be 500 to 1500 feet. 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 should hit between the line arrester and the machine, the probability is that the machine will not be protected adequately because the full required inductance will not be in series with the capacitor. Also, the line arrester cannot limit the voltage impressed on the system as effectively as for strokes ahead of the line arrester. These undesirable conditions can be overcome by shielding as described later.

If the machine is connected to the overhead line through a length of cable with metallic sheath, the cable provides some inductance. The inductance of a cable with grounded metallic sheath, however, is less than that of an open wire of the same length. 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 line arrester located at the cable pothead has the advantage that the ground terminal of the arrester can be connected to the cable sheath and it, in turn, connected to the ground terminals of the machine protection and the machine frame, MF. This avoids the harmful effect of ground resistance at the line arrester. Also, with metallic sheathed cable, the conductors are shielded from direct strokes. However, the cable lengths generally used often are not long enough to serve without additional inductance in the form of a choke coil or an added length of line with an additional arrester as indicated by the dashed lines in fig. 9, example 3.

A transformer interposed between the machine protection and the line provides a high inductance and a high degree of protection. It should be borne in mind 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 machine as well. This system has the further advantage in some cases, that the protection at the machine terminals need not be as elaborate as when the overhead lines are conductively connected. Furthermore, with this scheme all of the grounds are readily tied together.

A Length of Overhead Line Used As the Inductance

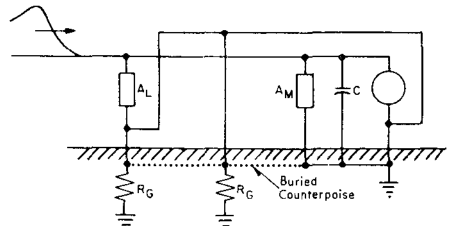
This is example 2 of fig. 9. Five hundred feet of line for 650 volt machines and 1500 feet for all higher voltage classes have been used widely. Detailed studies have been made of the voltage conditions produced at the machine with various circuit and line arrester grounding conditions. The conclusions drawn and the recommendations made in this text are based principally on those studies. The studies were based on certain assumptions regarding the severity of the discharge through the line arrester, A_L. The assumptions are believed to be pessimistic and therefore lead to conservative results. Experience indicates that the conclusions reached and discussed here give good operating results.

Aside from the fact that a stroke may hit the line between the line arrester and the machine thereby impairing the protection and increasing the probability of trouble, the ground resistance at the line arrester becomes of considerable importance because the voltage drop across it with heavy surge currents flowing may be large. It adds to the arrester voltage and the total is impressed on the L and C circuit. Ground resistance is not so important if the ground terminals of the protective devices and the machine can be tied together, as they readily can be in fig. 9, examples 1, 3 and 4. A ground resistance in series with the arrester in excess of two to three ohms may permit voltage high enough to produce a rate of rise at the capacitor which is not safe for the machine turn-to-turn insulation. Three ohms may be difficult to obtain in some regions and practically impossible in others. Thus, with this protection there is some possibility of damage to the machine.

On the other hand, the scheme has been used widely and with good success, except in regions of high soil resistivity and frequent severe lightning. The reasons why it has been satisfactory in many instances are that the occurrence of high, steep discharge currents in the line arrester, A_L, is infrequent and the chances of the line adjacent to the machine being struck are small. Using the average figure of one stroke per mile per year, the average probability of a stroke of 1500 feet of line is one in 3½ years in isokeraunic levels of 30 to 40. Moreover, many strokes will not be so severe as to endanger the machine if it has the protection suggested in fig. 9, example 2. However, if it is essential that the machine remain in service, and if the lightning exposure is high and the grounding conditions unfavorable, the system of fig. 9. example 2 should be elaborated.

Fig. 10 shows a system that provides a high degree of protection under adverse conditions. A shield wire is added, grounded at

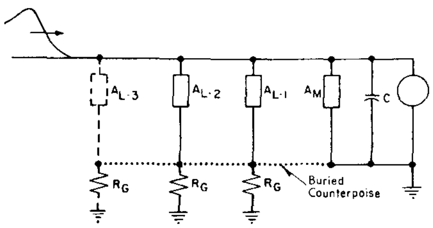
Figure 10. Length of Line Used as Inductance, with Overhead Shield Wire.



Surge Protection for Rotating Ac Machines

Arresters and Capacitors

Figure 11. Additional Arresters When Line Having No Shield Wire is Used as Inductance.



every pole as well as at the line arrester and the machine. All grounds are connected to it. The length of wire between the machine and the line arrester should not be less but need not be more than 500 feet. The shield wire reduces to a minimum the probability of the conductors being struck. It also provides a metallic connection between the line arrester ground terminal and the protection at the machine. With this system the maximum permissible pole and arrester ground resistance R_G, is higher as is shown in the following tabulation:

Maximum Permissible Pole and Arrester Ground Resistance

Spacing of pole grounds. .	250 feet	125 feet
Valve type line arrester. . .	2-5 ohms	4-10 ohms

Note: If these resistances cannot be obtained, a buried counterpoise connecting the grounds together should be added.

The overhead shield wire should be installed in accordance with recommended practice. Generally speaking, the shielding angle should not be more than thirty degrees and the insulation between the shield wire and its down leads, on the one hand, and the line conductors, on the other, should be able to withstand at least 250,000 volts, 1½ x 40 microsecond wave shape, without flashover. This calls for three to five feet of wood and for air clearance of approximately 24 inches.

If a shield wire is not used, the protection of fig. 9, example 2 can be improved by using additional line arresters as in fig. 11. However, this method is not as reliable as that of fig. 10. Severe strokes within 1000 feet of the machine may endanger it. The maximum permissible line arrester ground resistance for the system of fig. 11 is shown in the following tabulation:

Maximum permissible line arrester ground resistance with A_M, A_{L-1}, A_{L-2} etc. spaced 500 feet apart.

	Two sets of Arresters, A_{L-1} and A_{L-2}	Three Sets of Arresters, A_{L-1}, A_{L-2} and A_{L-3}
Valve type line arrester. . . .	5-10 ohms	10-20 ohms

Note: If these resistances cannot be obtained, a buried counterpoise connecting the grounds together should be added.

Summarizing the matter, if a length of line is used as the inductance, the most reliable system is that of fig. 10; that of fig. 11 next; and that of fig. 9, example 2, last. If a number of machines are connected to an overhead system at frequent intervals such as in a tank farm or a pumping system, for example, the shield wire system of fig. 10 is definitely recommended, with the choke coil system as an alternate. The reason for this is that with many machines, although the probability of a particular machine being damaged is not increased, the chances of one or more of the total being injured is increased, because a stroke is likely to occur near one of the machines. For example, consider a system with machines connected to an overhead line at 1000 foot intervals. A stroke to the line could not be more than 500 feet from any machine. The chances are it would be closer. The scheme of fig. 9, example 2 would not be effective for the machine nearest the stroke, and possibly not for both of the machines between which the lightning struck.

Machine Connected to Exposed Line Through Metallic Sheathed Cable

This is example 3 of fig. 9. The length of cable required to provide sufficient wave sloping depends on its surge impedance $Z=\sqrt{L/C}$. Typical values that may be used for the Z of cables are given in the table on this page. If the installed cable is not long enough, the inductance can be increased by adding small choke coils or by utilizing an additional 500 feet of overhead line.

The recommended practices for the given conditions are shown in fig. 12 and fig. 13. The ground resistance R_G is not critical. If additional line is required as in fig. 13, a shield wire over the 500 feet of line between the cable and the first line arrester is recommended in regions of high lightning exposure. Two sets of line arresters are recommended in all cases, one at the cable pothead and one 500 feet ahead of it. If the cable length is less than 200 feet, the line should be treated as if there were no cable present, i.e., as in fig. 10 and fig. 11, except that an additional set of arresters should be installed at the pothead. If the cable is a single conductor cable, grounding of the sheath at both ends may be objectionable because of sheath currents. In such a case, the sheath may be solidly grounded at one end and a small spark gap inserted between the sheath and ground at the other end. In general, it is preferable to ground the sheath at the machine and end insert the gap in the ground lead at the junction with the overhead line. The ground terminal of the arrester A_L should be tied solidly to the sheath.

Effective Surge Impedance (In Ohms) of Paper Insulated Cables

Conductor Size (AWG or MCM)	Belted Cables① Voltage Classes 0-1 Kv	2-3 Kv	4-5 Kv	7-8 Kv	14-15 Kv	Type H Cables 14-15 Kv
Three-Conductor Cables						
4	29	31	34	36	42	22
1	22	25	30	30	36	17
00	14	17	22	23	29	15
250	11	13	15	19	23	11
500	8	9	12	13	17	9
750	5	7	9	10	13	8
Single-Conductor Cables						
4	14	16	19	24	33	..
1	11	12	14	20	24	..
00	8	10	12	16	22	..
250	6	8	9	13	17	..
500	4	6	7	10	13	..
750	5	6	6	8	11	..
1000	4	5	5	7	10	..
1500	4	4.5	4.5	6	8	..

① Effective surge impedance for surge propagation on only one phase. This is the most severe condition. For single-conductor and type H cables it is the positive sequence surge impedance. For belted three-conductor cables it is 4/3 the positive sequence surge impedance.

Note: Specific inductive capacity, K=3.7; velocity of propagation, V=512 feet per microsecond.

Figure 12. Protection Recommended if Cable is of the Lengths Stated Below:

Cable surge impedance, ohms.	5	10	25	50
Minimum length of cable, feet.	2000	1000	500	300

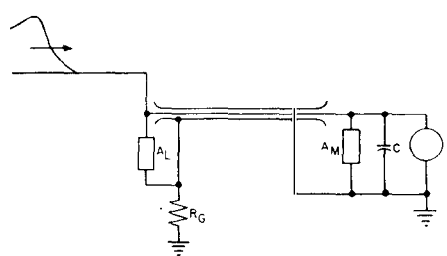
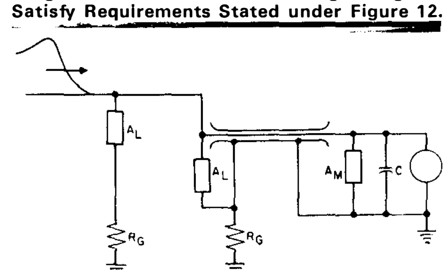


Figure 13. Protection Recommended if Cable is Longer than 200 Feet but not Long Enough to Satisfy Requirements Stated under Figure 12.



Westinghouse

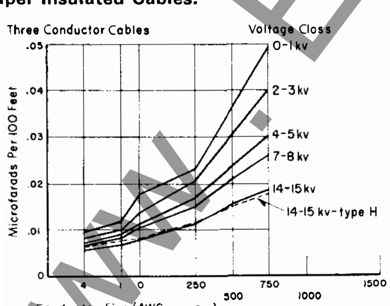
A Transformer Used As The Inductance

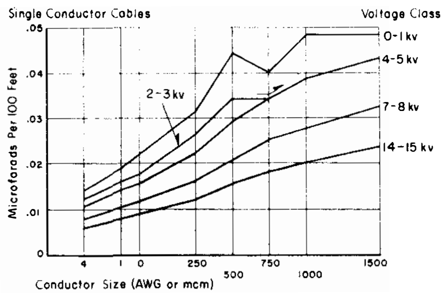
This is example 4 of fig. 9. The transformer acts like a high inductance and in some cases the protection at the machine terminals can be more simple than recommended in fig. 7 and fig. 8. The transformer should always have a set of lightning arresters on or adjacent to its line terminals, preferably of the station type. This arrester not only protects the transformer, but it is essential to the machine protection because it performs the functions of the line arresters, A_L, in fig. 9. The requirements for the protection at the machine can be calculated approximately. In general, it has been the practice to install capacitors and arresters in any event as added insurance on large machines, because compared to the investment in a large machine and the consequences and expense of damage to the machine, the cost of the protective devices is trivial. However, in some instances the machine protection installed has been modified from that shown in fig. 7 and fig. 8.

Where 11.5 kv and higher voltage machines are connected to lines only through transformers and require protection, one 0.25 microfarad capacitor per phase is sufficient at the machine terminals and no protection is needed at the machine neutral, for any condition of machine neutral grounding. If additional lines are conductively connected to the machine, then the recommendations of fig. 7 and fig. 8 should be followed with the proper protection on each of the lines conductively connected to the machine.

Voltage is transferred through the transformer from the line side to the machine side in two ways – electrostatically and electromagnetically. The electrostatic component is transferred through the capacitive couplings. With the secondary open or connected to a high impedance, several hundred ohms or more, a surge impressed on the primary can produce surges of severe magnitude and steepness on the secondary.

Figure 14. ①Positive Sequence Capacitance of Paper Insulated Cables.



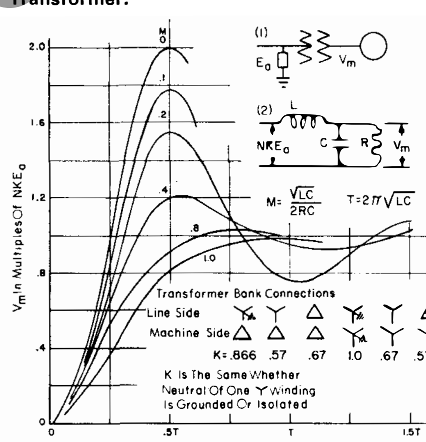


Top curves show values for three-conductor belted and type H (shielded) cables. Bottom curves show values for single-conductor concentric strand cables.

① These values are approximate and will generally serve the purpose; however, if specific values are required, they should be calculated.

However, the electrostatic component is reduced sufficiently if a capacitance of 0.005 microfarad or more is in parallel with the machine side winding of the transformer, or if the surge impedance of the machine or machines in parallel is 50 ohms or less. Surge impedances of this low order are usually found only on large high speed single turn machines. Although the total capacitance of machine windings usually ranges between 0.02 and 0.6 microfarad, tests have indicated that this capacitance is not effective and that the machine capacitance itself exerts very little influence on the electrostatic component. 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 commonly may be present to eliminate the electrostatic component as a hazard, is cable. The capacitances of typical cables are given in fig. 14. A total length of 50 feet of cable is usually enough to supply the necessary 0.005 microfarad. Consequently, if that much cable or more is connected either between the machine and the transformer or in parallel with the machine, surge protective capacitors are not required for the electrostatic component.

Figure 15. Solutions for Determining the Voltages from Machine Terminals to Ground Produced by Electromagnetic Transfer Through Transformer.



(1) Actual Circuit.
(2) Equivalent Circuit.

- E_a is the discharge voltage chosen for the line arrester.
- V_m is the voltage at the machine terminal.
- L is the leakage inductance of the transformer in microhenries on a line-to-neutral base, referred to the machine side.
- C is the positive sequence, line-to-neutral capacitance in microfarads on the machine side. This may be cable or a capacitor.
- R is the effective surge impedance of the machine. If several machines are in parallel, it is the resultant of the paralleled impedance.
- N is the ratio of the machine-to-line voltages, phase-to-phase.
- K is a factor depending on the transformer bank connections
- T is the period, $2\pi\sqrt{LC}$ microseconds.
- M $=(\sqrt{LC})/(2RC)$

The numbers on the curves are the values found for M.

The electromagnetic component depends on such factors as the ratio of turns, the voltage impressed on the line terminals of the transformer, the winding connections and neutral grounding, the leakage inductance and the load on the secondary. The secondary is considered the side that is not surged, i.e., the machine side.

Fig. 15 gives data to estimate the voltages to ground produced on the machine side of the transformer by electromagnetic induction. The procedure is to determine first the value of E_a. A figure should be obtained for R, the machine surge impedance. If it is not available, use 500 to 1000 ohms per machine for slow speed machines from 2400 to 13800 volts; and 500 ohms for machines with speeds above 1800 rpm. This will usually be conservative. Calculate L from the impedance of the transformer. Transformer leakage reactances may be found in the Transmission and Distribution Reference Book. Three-winding transformers can be treated accurately in terms of their equivalent leakage reactance circuit. However, a safe approximation results from considering the tertiary windings open, thus treating the transformer as a two-winding one. Determine C from the amount of cable and fig. 14 or from the capacitor installed. Find T, M, and NKE_a. Then find the solution from the curves of fig. 15.

Unit Connected Generators

The unit connected generator is here considered a single generating unit, simple or compound, connected directly and only to

Surge Protection for Rotating Ac Machines

Arresters and Capacitors

its step-up transformer or transformer bank. The set-up transformer is the only link between the generator and the transmission system. The generator may be tied to the transformer through cable or bus such as isolated phase bus or various lengths. If the generator is a large high-speed machine with single turn coils, its surge impedance may be low – less than 100 ohms.

It will be observed in fig. 15 that, as the surge impedance R of the machine decreases, the quantity M increases. The curves then show that with such an increase in M, both the rate of rise and the crest amplitude of the surge voltage decreases. When $M=1$, $R=\frac{1}{2}\sqrt{L/C}$, the critical resistance. Then the circuit becomes aperiodic. Thus, with machines of such low surge impedance, this factor alone, in combination with the inductance of the transformer may provide protection. Two other factors must be kept in mind, however. One is the capacitance to ground of the circuit between the machine and the transformer. The other is the surge voltage E_a permitted at the transmission line terminals of the transformer. Preferably E_a should be limited by arresters at the transformer. It should be noted that the calculations have been based on the surge impinging on a normal circuit. If it arrives during an accidental ground fault on one phase of the machine circuit, the voltage impressed on the other phases to ground will be higher than calculated according to fig. 15. For the Y-delta transformer connection usually employed in the unit system, it will be twice that for the unfaulted condition. If the omission of surge protection for the machine is contemplated, it is recommended that an analysis be made. Individual cases like any engineering problem should receive individual study. On the basis of the results, the engineer making the application can decide whether the protection should or should not be installed. Many engineers have felt that regardless of the outcome of calculations, machine protection should be installed as an added safeguard to the large investment in equipment and continuity of service.

Location of Capacitors and Machine Arresters

In the application of machine protective devices, more leeway can be allowed in the circuit feet between them and the machine than for arresters installed for the protection of transformers. This is so because of the wave sloping. The slowly rising voltage permits less overvoltage in a given distance. Nevertheless, it is advisable to install the protection as near the machine as practical. It should be remembered that the midpoints of delta wound machines and the neutrals of wye connected machines not adequately grounded, are points of reflection. In the case of machines whose neutrals are grounded through the low impedances mentioned in fig. 7, a separation of up to 200 feet of metallic sheathed cable or 400 feet of open conductor is probably safe, if the conductor is not exposed to lightning. For inadequately grounded machines, these distances should be halved. If the arrester and the capacitor are not located in the same place, it is recommended that the capacitor be installed between the machine and the arrester. The leads from the phase conductor to the capacitor and from the capacitor to ground should be as short as possible. The leads put 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 long. The length of the arrester leads is less important in this particular application.

If several machines are connected to the same bus through circuits that are not too long, and all incoming circuits terminate on the bus, good protection for all the machines is provided by one set of machine protection capacitors and arresters on the bus. If the neutrals of all the machines are not adequately grounded, the protection should be based on inadequate neutral grounding.

Isolated phase bus is commonly used in large stations to connect generators to transformers or to circuit breakers. In some installations, usually in hydroelectric plants, the bus runs may be long.

Standard insulation classes for this bus are 15, 23 and 34.5 kv with 50, 60 and 80 kv, 60 cycle tests and 110, 150 and 200 kv BILs, respectively. Both AIEE and NEMA recognize a reduced BIL of 150 kv in the 34.5 kv class; under certain conditions NEMA recommends the 15 kv insulation class impulse level of 110 kv for busses used with generators rated up to 20 kv, provided adequate surge protection is installed. Such busses are usually in the zone of the generator surge protection, and the reduced bus insulation is believed at least equal to that of the generators. Consequently, the generator protection also protects the bus. In many installations the protection is incorporated in the bus structures. Preferably it should be located at the machine. If this is not practical, then it should be located at least within 100 feet of the machine, generally speaking. In some cases, calculation may indicate that greater separations are permissible.

Isolated phase bus has lower surge impedance than open conductor. Its capacitance to ground is usually greater, and may be enough to eliminate the danger of high voltage from an electrostatic transfer to the transformer. However, in many cases machine protection will be indicated to take care of the electromagnetic transfer. It is again preferable that the protection be located near the machine. As it is separated from the machine, the voltages at the machine increase by a small percentage. In most cases where 13.8 kv or higher machines and isolated phase bus are used, a separation of up to 100 feet increases the voltage at the machine only a few percent and is permissible.

It is recommended that the machine protective devices, when used on circuits of high fault current (for instance, generator leads) be enclosed within barriers so that if an arrester or capacitor is damaged, the damage or arcing will not be communicated to other parts of the circuit. As mentioned later, damage to these devices is comparatively rare, but it is possible.

It is considered that surge protection is not necessary for the generator, the 110 kv BIL should be adequate for the associated bus, for machines whose terminal voltage is 20 kv or less.

When isolated phase bus is arranged so that portions of it can be disconnected from the generator by switching, reduction in the impulse level is not recommended; that is, for voltages between 15 and 20 kv, the level should be 150 kv.

Fusing the Capacitors and Arresters

The motive in connecting the protective devices to the system through fuses would be to disconnect them from the system if one or the other is damaged and short circuited. The fuse will not prevent damage to either device, but it can prevent interference with the service if one is damaged. The hazard involved in fusing resides in the possibility that the fuse may be damaged or otherwise accidently open. Since the fuse normally carries no load current, there is no obvious indication whether it is in good or bad condition. Consequently, it is possible that the circuit to the protective devices may be open and that this remains undetected. The machine then has no protection and is likely to be damaged. For this reason, fusing is not recommended. It seems illogical to insert another protective device to protect against a protective device. The probability of the arrester or capacitor being damaged is remote, provided they are of the proper ratings. Of the few cases of damage to machine arresters that have been noted, most have occurred on delta systems. They are notoriously subject to sustained dangerous overvoltages if one phase is grounded by an

Surge Protection for Rotating Ac Machines

Arresters and Capacitors

arcing fault through solid insulation such as in a machine or a cable. Even then, it is probably better to have the arrester limit the voltage although it may be damaged, than to have this voltage impressed on a machine. Grounding the system is to be recommended. This can be accomplished easily on existing delta systems for the purpose of avoiding high overvoltage during arcing faults. If the neutrals are not accessible, high resistance grounding by means of distribution transformers is a simple means of stabilizing the system voltages. However, such grounding does not make the system effectively grounded from the standpoint of applying reduced rating arresters.

The question of fusing should be weighed by the user and his decision based on his appraisal of the situation. If fuses are used, they should have a minimum rating of 25 amperes and be capable of interrupting the fault current available.

If there are circuit breakers suitably located in the system, the protective devices may often be located on that side of the breaker where a damaged capacitor or arrester will open the breaker and interrupt only a part of the system. On the other hand, if there is concern about the possibility of switching surges, the protective devices should be located on the machine side of circuit breakers; in other words, connected directly to the machine.

The Lightning Arresters

The arresters applied with the capacitor at the machine should definitely be of the valve type for two reasons. First, valve arresters can be made to have low sparkover voltages. Second, the fact that the voltage does not collapse to a low value after sparkover is an advantage in this case, because it does not introduce an abrupt change in voltage at the machine terminals. A quick and large drop in voltage is just as bad as a quick rise because it produces high voltage stresses between turns. The arrester at the machine should not be of the expulsion type.

The machine arresters are usually of special construction, designed to have low impulse sparkover on the slowly rising voltage obtained by the wave sloping devices, and low discharge voltage while passing surge current. They are designated as station type SV arresters for rotating machine protection, or distribution arresters type RM for rotating machine protection. In general, the station type arresters are recommended, especially for large important machines. For smaller motors where the user does not consider the cost of station type arresters warranted, the distribution type may be used. However, it should be specified that they are to be applied to rotating machines.

The preferred ratings for these arresters are 3, 4.5, 6, 7.5, 9, 12 and 15 kv. Higher ratings can be supplied as indicated in the table below. For 650 volt machines, the standard 650 volt, 3 phase, secondary arresters provide adequate protection. The impulse characteristics of the station type arresters for rotating machines are given in the table below. The 60 cycle test voltages, in kv crest, with which machines are tested, are also stated. The discharge voltages of the arresters are given for surge currents of 1500 and 5000 amperes, 8 x 20 microsecond wave shape. These are less than the test currents for standard arresters, used with static, liquid immersed apparatus. The machine arresters are not subjected to high discharge currents in service because the line arrester takes the brunt of the surge. It is recommended that arresters designed for machine protection not be applied to general use. They are intended as components in the protective circuits for machines and dry type, air insulated transformers.

In planning surge protection for rotating machines, it is essential not to lose sight of the fact that several components are required.

Protection Levels of Station Type Arresters Designed for Machine Protection

Lightning Arrester				Rotating Ac Machine					
				Machine Circuit Neutral Grounding					
				Effectively Grounded			Not Effectively Grounded		
Rating kv Rms	Maximum Impulse Sparkover kv Crest②	Maximum Discharge Voltage kv Crest③ 1500 Amperes	5000 Amperes	Voltage Class	Standard 60 Hertz Sparkover	Impulse Withstand Strength kv Crest	Voltage Class	Standard 60 Hertz Sparkover	Impulse Withstand Strength kv Crest
650 Volts①	3	3	3.5	650	3.3	4	650	3.3	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 voltage in 10 microseconds.
③ Crest voltage across arrester during discharge of a 1500 ampere or a 5000 ampere 8 x 20 microsecond current.

Further Information

Prices: Price List 38-420, DS 38-422 and PL 38-430.

Westinghouse Electric Corporation
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