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Substations – Volume IV – Power Transformers

Instructor: Lee Layton, PE

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5272 Meadow Estates Drive
Fairfax, VA 22030-6658
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Substation Design
Volume IV
Power Transformers

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This series of courses are based on the "Design Guide for Rural Substations", published by the Rural Utilities Service of the United States Department of Agriculture, RUS Bulletin 1724E-300, June 2001.

Preface

This course is one of a series of thirteen courses on the design of electrical substations. The courses do not necessarily have to be taken in order and, for the most part, are stand-alone courses. The following is a brief description of each course.

Volume I, Design Parameters. Covers the general design considerations, documents and drawings related to designing a substation.

Volume II, Physical Layout. Covers the layout considerations, bus configurations, and electrical clearances.

Volume III, Conductors and Bus Design. Covers bare conductors, rigid and strain bus design.

Volume IV, Power Transformers. Covers the application and relevant specifications related to power transformers and mobile transformers.

Volume V, Circuit Interrupting Devices. Covers the specifications and application of power circuit breakers, metal-clad switchgear and electronic reclosers.

Volume VI, Voltage Regulators and Capacitors. Covers the general operation and specification of voltage regulators and capacitors.

Volume VII, Other Major Equipment. Covers switch, arrestor, and instrument transformer specification and application.

Volume VIII, Site and Foundation Design. Covers general issues related to site design, foundation design and control house design.

Volume IX, Substation Structures. Covers the design of bus support structures and connectors.

Volume X, Grounding. Covers the design of the ground grid for safety and proper operation.

Volume XI, Protective Relaying. Covers relay types, schemes, and instrumentation.

Volume XII, Auxiliary Systems. Covers AC & DC systems, automation, and communications.

Volume XIII, Insulated Cable and Raceways. Covers the specifications and application of electrical cable.

Chapter 1
Power Transformers

The primary function of a power transformer is to transform system voltage from one nominal level to another. The transformer has to be capable of carrying the power flow for its particular location in the system under various operating conditions and contingencies, such as line or transformer outages. The photo shown below is an example of three single-phase power transformers in a substation.

This course deals primarily with oil-filled power transformers with nominal primary voltage ratings of 230 kV and below and utilizing one of the following methods of cooling:

- Self-cooled (OA)
- Self-cooled and assisted by forced-air (OA/FA for one stage; OA/FA/FA for two stages)
- Self-cooled and assisted by forced-air and forced-oil (OA/FA/FOA or OA/FOA/FOA for two stages)

The type of cooling used is based on the requirements of the specifications, the size of the transformer, and the manufacturer’s standard design. Meeting these specific requirements usually results in the power transformer’s being the largest, heaviest, and most costly piece of equipment used in a substation.

Because of their great importance and complexity, power transformers require special care in their application, specification, and procurement. This is best accomplished by taking full advantage of applicable industry standards and guides of national organizations such as the American National Standards Institute (ANSI), Institute of Electrical and Electronic Engineers (IEEE), and National Electrical Manufacturers Association (NEMA), etc.

The following discussion highlights various aspects of power transformers and provides guidance and recommendations to assist cooperatives in obtaining the proper equipment for their systems.

Types

Power transformers may be either autotransformers or multi-winding conventional transformers. A three-phase installation may consist of a three-phase unit or three single-phase units. The decision as to what type of transformer to purchase depends on such factors as initial installed cost, maintenance costs, operating cost, reliability, etc. Three-phase units have lower construction and maintenance costs and can be built to the same efficiency ratings as single-phase units. The initial cost of a three-phase transformer is usually approximately one-third less than four single-phase units. Additionally, the exposure of three-phase units to long outages can be minimized system-wide when a mobile substation or transformer is available for backup in case of failure.

The kVA ratings for various sizes of transformers are covered by the standards such as IEEE Std. C57.12.00, which defines the preferred continuous ratings for both single - and three-phase units. Transformers 10,000 kVA and below can accommodate one stage of cooling only, while transformers larger than 10,000 kVA can include up to two stages of cooling. Each stage of cooling increases the capacity of the transformer by a fixed percentage of the base (OA) rating. For three-phase transformers rated between 750 and 2,000 kVA, increasing the base level of cooling to forced air cooling will increase the continuous kVA capacity by 15 percent. For transformers rated 2500 kVA to 10,000 kVA, the increase is 25 percent. For transformers above 10,000 kVA, additional stages of cooling may be used to increase the continuous kVA rating of the transformer by 33 percent per stage. Transformers larger than those listed in the tables can be purchased and would normally be triple rated or would have provision for the future addition of two stages of cooling equipment to produce a triple rating.

The choice between conventional two- or three-winding transformers and autotransformers involves their basic differences as they may affect the application and cost factors. In general, autotransformers are considered primarily because of cost advantages where the voltage transformation ratio is favorable, up to possibly 3-to-1. Beyond this ratio, the cost advantage of autotransformers diminishes. Also, autotransformers are wye connected and thus provide only an in-phase angular relationship between primary and secondary voltages.

Other advantages of autotransformers are smaller physical size, lighter weight, lower regulation smaller exciting currents, and lower losses. The main disadvantages of autotransformers are lower reactance, more complex design problems, and adverse affect on ground relaying.

Ratings

The selection of substation transformer kVA capacity should be based on anticipated future loads. The selection should consider the effects of load cycle, load factor, and ambient temperature.

Since cooling efficiency decreases with increase in altitude, the transformer manufacturer should be informed when the transformer will be operated at an elevation above 3,300 feet so that the proper cooling system can be provided. See Tables 1 and 2 for guidance on the effect of altitude on temperature rise. Also, multi-winding transformers with loads on various windings at different power factors have higher load losses and may require additional cooling capacity.

Table 1

Maximum Allowable Average Temperature of Cooling Air For Rated kVA

Cooling Method	Altitude			
	3,300 ft	**6,600 ft**	**9,900 ft**	**13,200 ft**
Liquid-immersed, self-cooled	30C	28C	25C	23C
Liquid-immersed, forced-air-cooled	30C	26C	23C	20C
Liquid-immersed, forced-oil-cooled with Oil-to-air cooler	30C	26C	23C	20C

It is recommended that the average temperature of the cooling air be calculated by averaging 24 consecutive hourly readings. When the outdoor air is the cooling medium, the average of the maximum and minimum daily temperatures may be used. The value obtained in this manner is usually slightly higher, by not more than 0.3C, than the true daily average.

Table 2 Altitude Correction Factors	
Cooling Type	**De-rating Factor**
Liquid-immersed, air-cooled	0.4%
Liquid-immersed, water-cooled	None
Liquid-immersed, Forced air	0.5%
Liquid-immersed, Forced liquid With liquid-to-air cooler	0.5%
Liquid-immersed, Forced liquid With liquied-to-water cooler	None

In addition to selecting a transformer capable of satisfying the basic capacity requirements, it is also desirable to give due consideration to inventory and standardization with the objective of simplifying spare parts, testing, maintenance, and unit sparing problems.

Normal transformer design is based on ambient temperatures of 40°C maximum, 30°C average over 24 hours, and –20°C minimum. Abnormal ambient temperatures should be made known to the manufacturer at the time of purchase since they usually require modifications in the design of the transformer.

Nominal voltage ratings of a transformer are selected to conform to system voltage conditions and Tables 3, 4, 5, and 6 list standard voltages. Transformers should not be subjected to operating voltages or volts per hertz above 105 percent of any rated secondary tap when operating loaded to nameplate kVA rating when the load power factor is 80 percent or higher and the frequency is at least 95 percent of rated value. In addition, transformers should not be operated continuously above 110 percent of rated secondary tap when operating at no-load. Multi-winding transformers and autotransformers may be restricted further depending on the specific design criteria specified when the transformer was purchased.

Table 3 Typical Single-Phase Transformer Ratings 833 – 8,333 kVA						
High Voltage kV	**Low Voltage Rating**					
	15 kV Class		**25 kV Class**		**35 kV Class**	
	Min	**Max**	**Min**	**Max**	**Min**	**Max**

	(KVA)	(KVA)	(KVA)	(KVA)	(KVA)	(KVA)
23,000	833	2500	-	-	-	-
34,500	833	3333	-	-	-	-
46,000	833	8333	-	-	-	-
69,000	833	8333	-	-	-	-
115,000	2,500	8,333	2,500	8,333	2,500	8,333
138,000	2,500	8,333	2,500	8,333	2,500	8,333

Table 4

Typical Three-Phase Transformer Ratings Without Load Tap Changing Under Load

750 – 10,000 kVA

High Voltage kV	Low Voltage Rating					
	15 kV Class		25 kV Class		35 kV Class	
	Min (KVA)	Max (KVA)	Min (KVA)	Max (KVA)	Min (KVA)	Max (KVA)
23,000	1,000	10,000	-	-	-	-
34,500	1,000	10,000	-	-	-	-
46,000	1,500	10,000	-	-	-	-
69,000	1,500	10,000	-	-	-	-
115,000	5,000	10,000	5,000	10,000	5,000	10,000
138,000	5,000	10,000	5,000	10,000	5,000	10,000

Table 5

Typical Three-Phase Transformer Ratings with Load Tap Changing Under Load 3,750 – 10,000 kVA

High Voltage kV	Low Voltage Rating					
	15 kV Class		25 kV Class		35 kV Class	
	Min (KVA)	Max (KVA)	Min (KVA)	Max (KVA)	Min (KVA)	Max (KVA)
23,000	3,750	10,000	-	-	-	-
34,500	3,750	10,000	-	-	-	-
46,000	3,750	10,000	-	-	-	-
69,000	3,750	10,000	-	-	-	-
115,000	5,000	10,000	5,000	10,000	5,000	10,000
138,000	5,000	10,000	5,000	10,000	5,000	10,000

Table 6

Typical Three-Phase Transformer Ratings with or without Load Tap Changing Under Load 12,000 – 60,000 kVA

High Voltage kV	Low Voltage Rating					
	15 kV Class		25 kV Class		35 kV Class	
	Min (KVA)	Max (KVA)	Min (KVA)	Max (KVA)	Min (KVA)	Max (KVA)
23,000	12,000	30,000	-	-	-	-
34,500	12,000	30,000	-	-	-	-
46,000	12,000	30,000	-	-	-	-
69,000	12,000	30,000	-	-	-	-
115,000	12,000	60,000	12,000	60,000	12,000	60,000
138,000	12,000	60,000	12,000	60,000	12,000	60,000

161.0	12,000	60,000	12,000	60,000	12,000	60,000
230.0	12,000	60,000	12,000	60,000	12,000	60,000

Table 7 lists basic insulation levels commonly used for various system voltages. Neutral terminal BIL may be specified at a different level than the line terminals depending on the type of system grounding being used. Table 8 lists the minimum insulation levels for neutral terminals. Continuous improvements over the years in the protective margins provided by surge arresters have enabled users to select reduced insulation levels for transformers, at appreciable cost reductions, without sacrificing reliability.

Table 7

Transformer High Voltage BIL Rating

Single Phase Transformers		Three Phase Transformers		
Voltage Rating (V)	**Basic Impulse Level (BIL) (kV)**	**Voltage Rating (V)**	**Basic Impulse Level (BIL) (kV)**	
			Distribution	**Power Transformer**
2400/4160Y	75	2,400	45	60
4800/8320Y	95	4,160	60	75
13,200	110	12,470	95	110
23,000	150	23,000	125	150
34,500	200	34,500	150	200
46,000	250	46,000	-	250
69,000	350	69,000	-	350
115,000	450	115,000	-	450
138,000	550	138,000	-	550
-	-	161,000	-	650
-	-	230,000	-	750

Table 8

Neutral Insulation Levels

(Minimums)

Application	Nominal System Voltage (kV)	Minimum Low-Frequency Insulation Level (kV, RMS)	
		Grounded solidly or thru CT, or a Regulating Transformer	Grounded thru a Ground Fault Neturalizer or isolated but Impulse Protected
Distribution or Power	1.2	10	10
	2.6	15	15
	5.0	19	19
	8.7	26	26
	15.0	26	26
	25.0	26	34
	34.5	26	50
	46.0	34	70
	69.0	34	95

For higher line terminal system voltages than shown in Table 8, the insulation level at the neutral shall be specified to conform to the service requirements, but in no case shall be less than 34 kV. When specified, Y-Y connected transformers using a common, solidly grounded neutral may use a neutral bushing selected in accordance with the requirements of the low-voltage winding. Any selection of a transformer with reduced BIL is a user responsibility and requires knowledge of certain system characteristics.

On effectively grounded systems, a reduced BIL of one step below full basic insulation level may be appropriate for transformers with nominal ratings of 115 kV and above. An insulation coordination study may be required to ensure that adequate margin is maintained between transformer insulation strength and the protective level of protective equipment.

A transformer can supply a load beyond its nameplate rating for various periods of time, which may or may not affect its normal life, depending on several factors related to temperature conditions in the transformer.

Taps

No-load tap changers (NLTC) and/or *load tap changers* (LTC) can be obtained on power transformers. The addition of no-load taps in the primary of a substation transformer makes it possible to adapt the transformer to a range of supply voltages (usually a 10 percent overall range of which 5 percent is above nominal and 5 percent below nominal, usually in 2.5 percent steps). Since no-load taps are not capable of interrupting any current including transformer charging current, the transformers have to be de-energized when the manual no-load tap position is changed. All taps should have full capacity ratings. Any decision to use load tap changing transformers should be based on a careful analysis of the particular voltage requirements of the loads served and consideration of the advantages and disadvantages, including costs, of alternatives such as separate voltage regulators.

Impedance

Transformer impedance affects transformer voltage regulation, efficiency, and magnitude of through short-circuit currents. Both regulation and efficiency are generally improved with lower impedance. However, these desirable results should be viewed along with higher through-fault currents permissible with lower impedance. Higher load-side fault currents can be potentially damaging to the transformer and may also require higher fault current ratings of load-side equipment at increased cost. Prudent compromises are thus often required in specifying transformer impedance.

Where through-fault currents are not a significant factor, it is generally desirable to specify as low impedance as possible that will not result in increased transformer cost. Standard impedance ranges for various transformer BIL ratings are listed by manufacturers, and cost penalties may apply when the impedance falls above or below these ranges. The standards permit manufacturing tolerances of ±7.5 percent of the specified impedance for two-winding transformers and ±10.0 percent for multi-winding transformers and autotransformers. These are important to remember if transformer paralleling is being considered and if the margin between transformer through-fault current and equipment ratings is very close. Standard impedances for various voltage ratings are given in Table 9. Distribution substation transformers (500 kVA or smaller) should be specified with standard impedance where possible. These impedances are sufficient to make the transformer self protecting under any secondary faults.

Table 9

Transformer Impedances (Self-Cooled Rating)

BIL (kV)	No Load Tap Changing		With Load Tap Changing
	480V	2,400V and greater	2,400V and greater
<150	5.75[1]	5.5[1]	-
150	6.75	6.5	7.0
250	7.25	7.0	7.5
250	7.75	7.5	8.0
350	-	8.0	8.5
450	-	8.5	9.0
550	-	9.0	9.5
650	-	9.5	10.0
750	-	10.0	10.5

Notes

1. Above 5,000 kVA, use 150kV BIL ratings.

2. Impedance Voltage:
   - Percentage Impedance Voltage at the self-cooled rating as measured on the rated voltage connection shall be as listed in IEEE C57.12.
   - Tolerance on Impedance Voltage shall be as specified in IEEE C57.12.
   - Percentage Departure of Impedance Voltage on Taps for De-energized Operation: the percentage departure of tested impedance voltage on any tap from the tested impedance voltage at rated voltage shall not be greater than the total tap voltage range expressed as a percentage of the rated voltage.

3. This does not apply to load-tap-changing taps.

Phase Relation

Proper phase relationships between the various winding voltages are extremely important in transformer application. These have to be selected to fit existing or planned conditions in the particular system.

Standard single-phase substation transformers are built with subtractive polarity. The polarity of a three-phase transformer is fixed by its connections between phases and by relative location of leads. A standard delta-wye or wye-delta, three-phase, step-down transformer will result in the high-side voltages leading their respective low-side voltages by 30 degrees. An installation of three single-phase transformers can be connected to accomplish this same relationship.

Autotransformers are connected wye-wye, and no phase angle exists between the high- and low-side voltages. This may preclude the use of autotransformers, in some cases, even when they are otherwise preferred.

Also give attention to the proper physical orientation of transformers within the substation and to their connections to ensure that the proper phasing is obtained on all buses. Standard bushing arrangement on a three-phase transformer, when viewed from the low-voltage side, is from left to right H0 (when required), Hl, H2, and H3 on the high-voltage side and X0 (when required), X1, X2, and X3 on the low-voltage side. If a tertiary or third winding is provided, the bushing arrangement is Y1, Y2, and Y3 left to right when viewed from the side nearest these bushings.

Parallel Operation of Transformers

In most cases, the purchase of two smaller size transformers, to be operated in parallel in one circuit, in lieu of one full-size transformer, is not recommended. Two transformers will cost more than a single transformer of equivalent capacity, their combined losses are higher, and they require a more elaborate and expensive substation structure to accommodate them. However, where a situation exists for possible parallel operation, such as where continuity of at least partial service in event of failure of one unit is of great importance, the transformers should be individually protected and the following guidelines considered.

Any two or more transformers can be operated in parallel, provided their impedances are in the same order of magnitude when considered on their own kVA base, their voltage taps and voltage ratios are essentially the same, and their polarity and phase voltage displacement are or can be made alike.

Equal impedances will permit proportionate sharing of the load between transformers. If not equal, the load will be divided in inverse proportion to the magnitude of the impedance. This condition is satisfactory within reasonable limits, as determined by requirements, and may be of little consequence where the larger of two transformers has the lower impedance and will carry more than its proportionate share of the load. However, if the smaller unit has the lower impedance, it will carry more than its share of the load and may even become severely overloaded, while the larger unit still has available capacity. This is demonstrated in the following example. Protecting transformers operating in parallel as a single unit is not recommended. The sensitivity of the high-side protection is significantly reduced, and the occurrence of nuisance tripping during energization is increased due to incorrect differential relay harmonic restraint unit operation.

Example 1 - Larger Transformer Has the Smaller Impedance

Two transformers, Tl and T2, are operating in parallel. Tl is rated 10 MVA with an impedance of 10 percent. T2 is rated 25 MVA with an impedance of 7 percent. On a common 100 MVA base, impedance of Tl is 100 percent and impedance of T2 is 28 percent.

Power flow divides inversely with the relative impedances on a common base. Assuming a total power flow of 30 MVA, Tl would carry 6.6 MVA and T2 would carry 23.4 MVA, both within their ratings.

The power flow distribution is obtained by solving two simultaneous equations, where Pl and P2 represent the power flows through Tl and T2, respectively, and Z_{100} is the impedance on a 100 MVA base. Since we know the total load is 30 MVA and it is divided between the two transformers, we can write the expression,

P1 + P2 = 30

And the load will be split according to the impedance,

$$\frac{\mathbf{P1}}{\mathbf{P2}} = \frac{\mathbf{Z_{100}\ (of\ T2)}}{\mathbf{Z_{100}\ (of\ T1)}}$$

So,

$$\frac{\text{P1}}{\text{P2}} = \frac{28}{100} = 0.28$$

Re-arranging we have,

P1 = 0.28 * P2

We can then substitute 0.28*P2 into the first equation,

(0.28 *P2) + P2 = 30

P2 = 30 / 1.28 = 23.4 MVA

Therefore,

P1 = 30.0 – 23.4 = 6.6 MVA.

Example 2 - Smaller Transformer Has the Smaller Impedance
The same as Condition I, except Tl has an impedance of 7 percent, and T2 an impedance of 10 percent. On a 100 MVA base, the impedance of Tl is 70 percent and the impedance of T2 is 40 percent. Tl would carry 10.9 MVA and T2 would carry 10.1 MVA. Tl is clearly overloaded, whereas T2 has capacity to spare.

Example 3 - Both Transformers Have Equal Impedances - Preferred Condition
The same as Condition I, except both TI and T2 have equal impedances on their own base of 8 percent. On a 100 MVA base, Tl has an impedance of 80 percent, and T2 has an impedance of 32 percent. TI would carry 8.6 MVA and T2 would carry 21.4 MVA. Each transformer is carrying its correct share in proportion to its MVA rating.

From an impedance standpoint, it has generally been accepted that transformers can be paralleled successfully if the actual or nameplate impedance of one does not differ by more than 7 ½ percent from the actual or nameplate impedance of the other. For example, a transformer having an impedance of 6 percent can be paired with a transformer having an impedance anywhere between 5.55 percent and 6.45 percent.

Equal tap voltages, or voltage ratios, will permit each of the paralleled transformers to operate as if it were isolated. But unequal tap voltages will create a circulating current flowing forward through the unit having the higher voltage and in a reverse or leading direction through the unit with the lower voltage. This condition is limited only by the series impedance of the two transformers in the current circulation circuit and by the difference in voltage causing the current flow. This condition can be very severe and has to be closely analyzed whenever such operation is contemplated. The condition is most severe when the transformers are not carrying load. It usually is modified sufficiently when load is being carried, and voltage regulation due to load so modifies the voltage difference as to reduce the circulating current to an insignificant level.

Where paralleled transformers are equipped with load tap changers and line drop compensators, incorporate paralleling control schemes into the LTC controls. Schemes that may be evaluated include:

- Negative Reactance Method
- Step-by-Step Method
- Out-of-Step Switch Method
- Cross-Current Compensation Method

Dielectric Requirements

A transformer in service may be exposed to a variety of dielectric stresses. Lightning impulses may reach the terminals of the transformer because of direct hits or, more likely, in the form of traveling waves coming in over connecting lines. Such traveling waves are produced when the connecting lines are exposed to lightning strokes.

Direct hits are practically impossible where adequate direct stroke protection is provided over the substation in the form of ground wires and/or masts. The magnitude of traveling wave impulses reaching the transformer depends on:

- The initial magnitude of the strokes
- The distance the wave has to travel
- Transmission line characteristics,
- Transformer characteristics and protective characteristics of surge protective devices

How well the transformer can withstand any impulse voltages reaching it depends on the condition of the insulation at the time of the impulse. Basic insulation levels can be verified by impulse tests. Most large transformers receive impulse tests prior to shipment from the factory. This may not be a routine test performed by the manufacturer for certain size transformers. If an impulse test is desired, include this requirement in the testing section of the transformer specifications.

Normal line energization and de-energization or power circuit breaker operations during system faults produce switching surges that travel down the conductors to the connected transformers. Switching surges generally present no particular problem to transformers rated 230 kV and below. Transformers rated 115 kV and above are designed for the switching impulse insulation levels (BSL) associated with their assigned BIL. *Switching impulse insulation* levels are defined in Tables 10 and 11. In general, switching surge withstand capability of a transformer is approximately 83 percent of its BIL. Where justified, factory switching surge tests may be applied to verify switching surge withstand capability.

Table 10

Dielectric Insulation Levels

Distribution & Class I Power Transformers

Application	BIL (kV Crest)	Chopped-Wave Impulse Levels		Front-of-Wave Impulse Levels		Low Frequency Test Level (kV RMS)
		Minimum Voltage (kV Crest)	Minimum Time to Flashover (us)	Minimum Voltage (kV Crest)	Specific Time to Sparkover (us)	
Distriubtion	30	36	1.0	-	-	10
	45	54	1.5	-	-	15
	60	69	1.5	-	-	19
	75	88	1.6	-	-	26
	95	110	1.8	-	-	34
	125	145	2.25	-	-	40
	150	175	3.0	-	-	50
	200	230	3.0	-	-	70
	250	290	3.0	-	-	95
	350	400	3.0	-	-	140
Class I Power	45	50	1.5	-	-	10
	60	66	1.5	-	-	15
	75	83	1.5	-	-	19
	95	105	1.8	165	0.5	26
	110	120	2.0	195	0.5	34
	150	165	3.0	260	0.5	50
	200	220	3.0	345	0.5	70
	250	275	3.0	435	0.5	95
	350	385	3.0	580	0.58	140

Table 11
Dielectric Insulation Levels
Class II Power Transformers

Nominal System Voltage (kV)	BIL (kV Crest)	Chopped-Wave Level (kV Crest)	Switching Impulse Level (BSL) (kV Crest)	Induced-Voltage Test		Applied Voltage Test Level (kV RMS)
				One-Hour Level (kV RMS)	Enhancement Level (kV RMS)	
<15kV	110	120	-	-	-	34
25	150	165	-	-	-	50
34.5	200	220	-	-	-	70
46	250	275	-	-		95
69	250	275	-	-	-	95
115	350	385	280	105	120	140
	450	495	375	105	120	185
	550	605	460	105	120	230
138	450	495	375	125	145	185
	550	605	460	125	145	230
	650	715	540	125	145	275
161	550	605	460	145	170	230
	650	715	540	145	170	275
	750	825	620	145	170	325
230	650	715	540	210	240	275
	750	825	620	210	240	325
	825	905	685	210	240	275
	900	990	745	210	240	395
345	900	990	745	315	360	395
	1050	1155	870	315	360	460
	1175	1290	975	315	360	520
500	1300	1430	1080	475	550	-
	1425	1570	1180	475	550	-
	1550	1705	1290	475	550	-
	1675	1845	1390	475	550	-
765	1800	1980	1500	690	800	-
	1925	2120	1600	690	800	-
	2050	2255	1700	690	800	-

Properly applied surge arresters are very effective in limiting the magnitude of both impulse and switching surge voltages reaching the transformer to levels below their withstand capabilities. Reduced transformer BIL levels are often possible, at appreciable cost reduction, while still maintaining adequate protective margins.

Transformers may be exposed to abnormal power frequency voltages during system fault conditions. Single-phase-to-ground faults produce abnormal voltages to ground on the un-faulted phases. The amount that these voltages increase above normal depends on how solidly the system is grounded. With adequate BILs and surge arrester ratings, these temporary abnormal voltages should present no difficulty for the transformer.

External porcelain insulation on a transformer is designed to withstand voltages to which it may be subjected under varied atmospheric conditions. Severe atmospheric contamination may require increased bushing BILs, increased porcelain creep distances, special porcelain treatment, or washing procedures. Local experience under similar conditions is usually the best guide as to the most practical solution.

Standard transformer external insulation is based on applications below 3,300 feet. Above 3,300 feet, the lower air density offers less voltage withstand capability, and the external insulation level has to be de-rated. Normal ratings are decreased approximately 10 percent for each 3,300-foot increase in elevation above 3,300 feet.

Short Circuit Requirements

Failures of substation transformers because of through-fault currents have been a matter of great concern to the industry for many years. The use of larger transformers and the increases in system fault current contributed to the cause of failures. Transformer manufacturers and industry standards began to address the issue of transformer through-fault capabilities in more detail. The standards were expanded along with extensive testing to determine an accurate model of both the thermal and mechanical withstand capabilities of transformers of various sizes. Cooperatives and their engineers should be aware of this problem and should take appropriate measures to safeguard their interests in purchases of power transformers.

The current edition of ANSI/IEEE Std. C57.12 defines the requirements for transformers of various sizes with respect to short-circuit withstand capabilities during any type of external fault. In addition, ANSI/IEEE Std. C57.109 further defines the transformer capabilities in terms of current versus time characteristics to allow proper coordination with transformer overcurrent protection. ANSI/IEEE Std. C57.12.90 now includes an entire section on short-circuit testing of transformers.

In brief, the standard requires the application of six short circuits at maximum current, two of which would result in maximum asymmetry of the fault current based on the reactance to resistance (x/r) ratio to the point of the fault. The transformer should show no damage after this test as indicated by measurements and visual inspections.

The user has to still decide whether to require this test in the purchase specifications. Manufacturers' facilities or test laboratories may be limited in terms of the size of transformer that can be short-circuit tested. Larger sizes conceivably could be tested in the field by the purchaser, but the feasibility of doing so on an operating system is questionable. The laboratory test is fairly costly, and shipping costs to and from the laboratory test facility should be added. The extra shipping and handling would also subject the transformer to a greater risk of transportation shock damage and human error.

It should be recognized that short-circuit testing will not be feasible on the larger sizes of transformers because of the limitations of existing laboratory facilities. Hence, successful experience will be the principal means for measuring the adequacy of short-circuit strength of these transformers. In this respect, it is recommended that experience be accepted as a demonstration that the transformer design has adequate short-circuit strength. This applies only when transformers with core and coils identical in all respects to the transformer covered by the specifications have amassed a total of at least 20 transformer years of experience without major failure attributable to design defects. Where the manufacturer has not built units identical to the transformer covered by the specification, or the experience record is less than 20 transformer years, it is recommended that short-circuit testing be required by the specifications or a different manufacturer be selected.

Autotransformers or conventional multi-winding transformers often have special application and design requirements. In such cases, it will be important to provide system short-circuit information indicating the most severe short-circuit condition that can exist at the terminals of each transformer winding, and any specific impedance requirements.

Cooling Equipment

Most of the smaller substation power transformers on rural systems are the oil-immersed, self-cooled (OA) type. In these types of transformers, the oil transfers the heat from the core and coils to the tank wall or cooling tubes, where it passes to the surrounding air. Temperature differences in the oil cause the oil to circulate by convection through the tubes. Adequate airflow is essential to satisfactory operation.

On larger transformers, this cooling process can be accelerated by various methods: using forced air (FA) from fans over the cooling tubes, by using oil pumps to circulate the oil, or by a combination of forced air and forced oil. Both methods can be automatically controlled in one or two steps from either top oil temperatures or winding temperature or both. Forced cooling methods are usually effective in reducing costs of the larger transformer sizes.

Where any type of forced cooling is relied on, it is essential that attention be given to adequate operational reliability of the pumps and fans. This involves consideration of redundancy in the power supply to the pumps and fans and to individual or group overload protection and disconnecting means. Also, hot spot and top oil temperature devices can be used to alarm for abnormal cooling indications. The temperature limits should be specified to adequately protect the unit but not to limit its overload capability. Suggested alarm limits are listed in Table 12.

Table 12
Transformer Cooling Alarm Limits

Temperature	Insulation Temperature Rise	
	55C	**65C**
Hot Spot	95C	105C
Top Oil	70C	80C

The cooling tubes or heat exchangers on large transformers should be specified for easy removal or isolation from the transformer for repairs. In this case, shutoff valves and bolted flanges are provided at the inlet and outlet of each heat exchanger. Transformers below a range of 10,000 kVA, three-phase, and 5,000 kVA, single-phase, usually have non-removable cooling tubes. These kVA sizes will vary between manufacturers.

Oil and Oil Preservation Equipment

Transformer oil has to be kept free from contact with outside contaminants always present in the atmosphere. On smaller substation transformers, the tank is completely sealed, with a layer of dry air or nitrogen left above the oil to accommodate expansion and contraction of the oil.

Several methods of oil preservation are commonly used on larger size transformers:

- A sealed tank with a positive pressure inert gas layer maintained above the oil by means of a permanently connected tank of nitrogen gas
- A tank completely filled with oil but connected to a raised tank or oil conservator, which maintains a positive oil pressure in the main tank and provides a place for expansion and contraction of the oil

- A conservator tank with a divided expansion tank with two sections and the flexible diaphragm conservator tank
- A conservator tank with a bladder within the conservator tank as a variation of the flexible diaphragm

Figure 1 shows the various oil preservation methods.

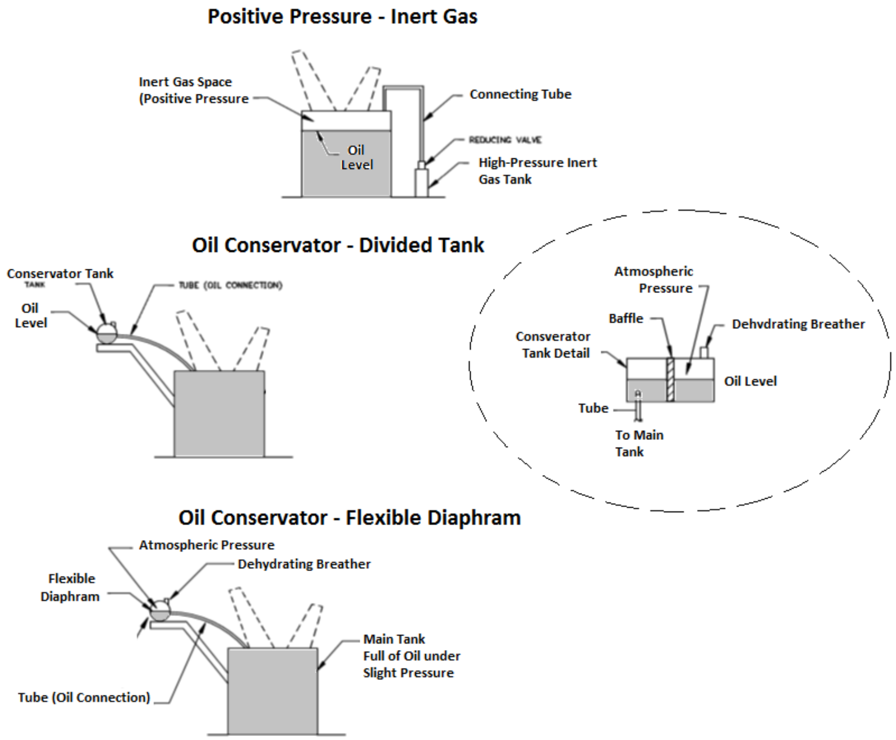

Figure 1

The choice of oil preservation system is mostly a matter of personal preference and experience. All have been successfully used for many years. Regardless of the method used, periodic tests have to be made of the oil and oil preservation system to ensure that oil quality is being maintained. The adjacent photo shows a transformer with a conservator tank.

Audible Sound

Noise levels produced by transformers, as well as other substation equipment, are becoming a matter of increasing concern to the public. The fact that rural substations are more often located away from congested areas reduces the possibility of complaints. However, this is partially offset by the lower ambient sound levels common in rural areas.

In some areas, noise ordinances may dictate what is required. The designer should accordingly be familiar with the problems and their solutions. A thorough treatment of the subject is beyond the scope of this course, but some practical guidelines follow. Any values given should be treated as approximations.

Sound is usually transmitted radially from the source. Avoid sites that have a direct line of sight to possible areas of complaints. A particularly poor selection would be a low-level site with residential areas on the surrounding higher ground.

Natural or artificial barriers such as mounds or shrubbery positioned between the sound source and the public are desirable. Although these have little effect on sound levels, they can reduce the psychological impact of a new substation and prevent complaints.

Sound levels are attenuated with distance. Approximately a 6-dBA reduction can be obtained with each doubling of the distance between source and point of measurement.

Standard sound levels for transformers are listed in Table 13. Reduced sound level transformers may increase the transformer cost approximately 1 ½ percent for each dBA reduction from these NEMA standard levels. Actual price variations for different sound levels can only be determined in a bid process when all other design factors are considered. Transformer sound levels tend to increase with BIL, kVA, and the number of stages of cooling. A practical limit in designing special low-sound-level transformers is approximately a 12-dBA reduction where forced cooling is required. Greater reductions require expensive measures, such as double-wall tanks.

Table 13
Sound Levels for Liquid Cooled Transformers

Capacity (kVA)	Sound Level (dB)
<51	48
51-100	51
101-300	55
301-500	56
750	57
1000	58
1500	60
2000	61
2500	62

Required sound levels in dBs will vary from one situation to another. Levels sometimes prescribed in ordinances may be approximately 45 dB at night and 55 dB in daytime. These levels may apply only to a potential source of complaint or at the substation boundaries. For comparison, a standard design 20,000 kVA two-winding substation transformer with 350 kV BIL and first stage of auxiliary cooling would have an average sound level of 72 dB.

Sound barriers located near the transformer can be considered as a means of reducing noise levels in the vicinity. Barriers can produce a maximum reduction of approximately 20 dB. A total enclosure can produce a 40-dB reduction. For partial barriers, a reduction of 15 dB is a practical maximum. The effect of the barriers on transformer cooling and transformer removal should also be considered.

Tank

In most cases, the manufacturer’s standard provisions related to the transformer tank will meet requirements for filling and draining, oil sampling, handling, internal inspection, etc. Any special requirements or preferences should be considered at the time specifications are written and their possible extra cost evaluated. Some items to consider are:

- Preferred location of heat exchangers

- Preferred location and height of cabinets and other accessories above transformer base
- Construction of terminal boards
- Paint color
- Provisions for future additions

Accessories

Various accessories are available for use with power transformers. Many of these are standard items normally supplied with the basic transformer while others are special items available at extra cost. Some accessories not furnished as standard items but that may be desired are special bushings, current transformers, bushing capacitance potential taps, bushing potential device, auxiliary power provisions, special relays, special terminals, spare parts, etc.

Electrical Tests and Measurements

Dielectric tests consist of a variety of tests, each performed to prove a certain characteristic of the transformer insulation structure. Dielectric tests are generally specified only on the larger sizes of transformers or on smaller transformers used in especially important applications. Most manufacturers charge for these tests. Table 14 provides guidelines for specifying dielectric tests.

Table 14
Guidelines for Specification of Dielectric Tests on Power Transformers Rated 345 kV and Below

Test	10,000 kVA (OA) or less (Mfr's quality assurance only)	Above 10,000 kVA (OA) Purchaser's Specifications
Reduced Full Wave	Yes	Yes
Chopped Wave	Yes	Yes
Full Wave	Yes	Yes
Low-Frequency Test	Yes	Yes
Partial Discharge	Usually None	Yes

The *full wave impulse test* (1.2 x 50-microsecond wave) is designed to simulate a lightning stroke. Because of its relatively long duration, the full wave impulse test causes major oscillations to develop in the winding. Consequently, not only turn-to-turn and section-to-section insulation are stressed throughout the winding but relatively high voltages can result, compared to power frequency stresses, across large portions of the winding and between the winding and ground.

The *chopped wave impulse test* (similar to the full wave test but 15 percent higher and chopped on the tail in about 3 ms or less), because of its shorter duration, does not allow the major oscillations to develop as fully. It is designed to simulate a lightning stroke truncated by a flashover on an adjacent portion of the insulation system. This test generally does not produce as high voltages across large portions of the winding or between the winding and ground. However, because of its greater amplitude, it produces high voltages at the line end of the winding and, because of the rapid change of voltage following flashover of the test gap, it produces higher turn-to-turn and section-to-section stresses.

The *front-of-wave impulse test* (similar to the chopped wave test but chopped on the front and with a much steeper front) is still shorter in duration and produces still lower winding-to-ground voltages deep within the winding. Near the line end, however, its greater amplitude produces higher voltages from winding to ground, and this, combined with the rapid change of voltage on the front and following flashover, produces high turn-to-turn and section-to-section voltages near the line end of the winding.

The *switching surge test* is related to the other impulse tests, but has a much longer wave front and tail. This slow wave fully penetrates the windings and stresses all parts of the insulation structure.

An *applied voltage test* measures the ability of the transformer to survive at normal frequency overvoltage. It also determines the increase in exciting current.

An *induced voltage test* measures the insulation strength between turns in the winding and the insulation strength of barriers and other major insulation between phases. During this test, a partial discharge (corona) test can be conducted to determine presence, inception, and extinction levels of partial discharges that may be damaging to the insulation structure and eventually lead to failure.

The *partial discharge test* (corona test) consists of measuring the 1 megahertz portion of any pulses produced within the transformer during low-frequency tests and that show up at the transformer terminals. The low-frequency tests are usually performed using 120 to 240 hertz voltages. The magnitude of the partial discharge is expressed in micro-volts.

Most manufacturers take the measurements from each bushing capacitance tap, when these taps are available. A calibration procedure is used to convert the tap readings to an equivalent value at the bushing terminal.

Measurements that produce data required for operation of the transformer include resistance, core and conductor losses, excitation current, impedance, ratio and regulation temperature rise, insulation power factor, polarity and phase relation, etc.

Shipment

Several shipping considerations are important. During shipping, the transformer may be subjected to its most severe test due to rough handling. Acceleration measuring devices (impact recorder) mounted on the transformer during shipment will help to determine whether the transformer may have been subjected to excessive forces. In any case, make a thorough inspection of the interior of the transformer to determine whether movement of the core and coils has taken place or whether evidence of any other damage exists.

Larger size transformers are shipped without oil but sealed with either a blanket of nitrogen gas or dry air. The method used often varies with the transformer manufacturer. Either method is considered satisfactory, provided proper safety precautions are taken and warning signs are exhibited to deter a person from entering an unsafe tank before it has been purged with proper amounts of air or oxygen.

It is good practice to provide the manufacturer with all necessary information regarding the situation at the final destination. This will enable shipment to be made in the most convenient way. Sometimes it is important for the transformer to be positioned a particular way by the final carrier to facilitate unloading at the site.

Warranty

In general, transformer manufacturers warrant their product to be free of defects in workmanship and material for a specified period. In the event of a defect, the manufacturer may elect to correct the problem at his option either by repairing the defective part or parts or by supplying a repaired or replacement part or parts. Under terms of a normal warranty, the manufacturer assumes no responsibility for disassembly or reassembly of the equipment or return transportation from the field to the factory and back to the field.

Since warranties are subject to many variables, the purchaser is cautioned to exercise care in review and evaluation of each one. Warranty periods vary from one to five years or more. Special warranties are available, at some increase in purchase price, which extends the warranty period and/or include the cost of removing a failed transformer from the field, returning it to the factory, repair, return to the field, reinstallation in the field, etc.

Core and Coils

Transformers can be classified by two different forms of construction: *core form* or *shell form*. Most common is the core-form type manufactured either with cylindrical coils wrapped horizontally around a cylindrical core or with rectangular coils and a rectangular core. Core-form transformers have excellent short-circuit capability for most applications. The shell-form transformer is manufactured with the coils wrapped through the core vertically. Shell-form transformers were developed for very large, high-magnitude short-circuit application such as generator step-up transformers.

Specifications

Purchase specifications should be based on standards of national organizations such as ANSI, IEEE, NEMA, etc.

It is recommended that the purchase specifications be modeled on or checked against the requirements of ANSI Std. C57.97, “Guide for Preparation of Specifications for Large Power Transformers, with or Without Load Tap Changing.” In addition, it is recommended that a special requirement for short-circuit current strength be included. The manufacturer’s standard design should be accepted, and standard sizes, ratings, taps, and accessories should be specified, unless there is a good reason for doing otherwise.

To assist in the evaluation of transformers being offered in a particular case, it is desirable to include in the request for bids the method for evaluation of transformer losses.

Chapter 2
Mobile Substations

Mobile transformers or mobile substations can be used to provide temporary service during equipment maintenance, construction, emergencies, or high load periods. Sufficient mobile units strategically placed can reduce or eliminate the requirements for on-site spare transformers. The photograph below shows a typical mobile substation.

A mobile unit substation or mobile transformer is one in which all the components are mounted on a highway trailer or railcar. These units may be readily moved from one location to another by a tractor or locomotive. Mobile units are used to provide supplementary service during seasonal and temporary load conditions and as spares for existing installations during periods of outage due to equipment breakdowns or planned maintenance and construction. Their use can permit a higher quality of maintenance, more safely and at less cost, and reduce system investment in overall transformer capacity.

The actual makeup of a mobile unit will depend on factors such as the intended scope of application, degree of flexibility and reliability desired, physical size and weight restrictions, safety, and economics. Each user will have to determine the correct blend of these factors for his system.

Mobile Substation Characteristics

A *mobile transformer* is a transformer, usually three-phase, mounted on a trailer or semi-trailer together with cooling equipment such as an oil pump, heat exchanger, fans, etc. It is intended for application in a substation as a spare transformer in place of permanently installed transformers that may have failed or that may be undergoing maintenance. Other uses include provision of extra kVA capacity during temporary heavy load situations. Switchgear, circuit breakers, or reclosers may or may not be included. It is recommended, however, that both high- and low-voltage surge arresters be mounted either on the transformer or on the trailer since the transformer, when in use, may be too far from the substation arresters to be protected adequately.

The availability of a mobile three-phase transformer as a spare permits a saving in the purchase of substation transformers. Instead of buying four single-phase transformers in order to have a spare in each substation, a power system can save a substantial part of this cost by buying one three-phase transformer and depending on the mobile unit for a spare. Because of the much higher cost of the mobile unit, this saving can be realized only if the system operates several substations having approximately the same kVA size and compatible voltage requirements.

A *mobile substation* may include, in addition to the transformer, air switches, surge arresters, high-voltage fuses, reclosers or breakers, voltage regulating equipment, control power and instrument transformers, meters and relays, and a control cabinet and various accessories to permit it to operate as a complete substation independent of any permanent ground-mounted equipment. Thus, it can be used not only as a spare transformer but can replace an entire substation that has been damaged or can serve as a temporary substation in a new location until a permanent substation can be built.

One limitation of a mobile substation is the number of outgoing distribution circuits that can be provided conveniently. Mobile substations can generally provide only one or two distribution circuits without an auxiliary switching structure or other supplementary equipment mounted on a separate trailer.

Three-phase units should be equipped with suitable phase rotation indicators or relays to ensure that power supplied to distribution circuits has the same phase rotation as that supplied from the permanent substation. Relays should also be provided to prevent reverse rotation of the fan and pump motors. Reversing switches should be added to these motors so that they can adapt to the phase rotation of the power supply.

To reduce size and weight, the transformers in mobile units are usually designed for forced-cooled operation with higher impedances based on the forced-cooled kVA rating than are normal for most self-cooled power transformers. These impedances sometimes are as high as 12 to 15 percent. This usually makes it impractical to continuously operate a mobile unit in parallel with a ground-mounted unit unless a sacrifice in total kVA available from the paralleled units is acceptable. Temporarily paralleling the mobile unit with the ground-mounted unit should be acceptable.

Consideration should be given to the risk involved due to increased short-circuit levels. Equipment ratings should be checked to ensure safe operation.

Mobile units customarily use a forced oil–forced air cooling system that is more complex than the self-cooled system common in permanent substations. Before this additional fan and pump load is placed on the substation station power system, its capacity should be carefully checked. Several features are desirable in the cooling system to reduce operating difficulties and to facilitate maintenance and repair:

Valves should be installed in the oil piping between the heat exchanger and the transformer tank. These allow maintenance of the forced oil cooling equipment without drawing down oil in the transformer tank. A flow-type relay should be installed in the forced oil system to sound an alarm or trip the breaker if oil circulation is blocked. If oil circulation or cooling is lost, a mobile unit has no load-carrying capability and it can remain energized only for a few hours without load before excessive overheating would occur. Fan and pump motors should have individual disconnecting switches to expedite fault location. The oil piping should preferably have welded joints and flange connections. Threaded connections are not recommended for mobile units because of possible loosening during transport.

The mobile unit's alarm circuits should be temporarily connected to the substation alarm bus. Alarm indications should be considered for such items as hot oil temperature, low oil level, high combustible gas content, breaker lockout, security gate open or unlocked, and any other important indications of abnormal conditions.

In designing the protection for a mobile unit, consideration should be given to two factors that distinguish it from the normal substation situation:

1. A mobile unit is much more expensive.
2. The temporary nature and perhaps hurried installation may increase the probability of a fault.

Both factors may dictate a better than normal protection scheme.

Mobile Substation Application Considerations

Several aspects should be considered in applying mobile transformers or substations:

1. Size and maneuverability of the equipment
2. Installation location and provisions
3. Electrical clearances

4. Primary and secondary connections
5. Grounding
6. Auxiliary system requirements
7. Safety

1. Size and Maneuverability of the Equipment

One of the primary advantages of mobile equipment is its ability to be used at more than one location. To accommodate installation, adequate space has to be available to position and connect the equipment at all intended locations. It may be impossible to use larger units in some locations without substantial modifications because of the lack of sufficient space.

Substation entrances and access roads should be evaluated before committing particular equipment to the location in question. Prior planning can save much time and facilitate installation.

2. Installation Location and Provisions

The mobile transformer or substation location should permit primary and secondary connections as short as possible to the permanent substation equipment. It is desirable to utilize bare conductors for the connections. Sometimes, insulated cables can be used where electrical clearances cannot be maintained or where connections are long. The location should permit any required connections to be made quickly and safely without disturbing adjacent equipment. The ease and speed of installation can be influenced by the proximity of energized equipment.

Substations for which mobile equipment has been designated should have provisions for installation of the equipment. The provisions can simply be terminals on permanent substation equipment or buses for connecting the mobile equipment. It may be desirable to include bus extensions and/or disconnect switches in some substations to facilitate the connections, particularly if they may be made while the substation is energized.

If low-voltage AC or DC supplies are required, permanent facilities can be provided in the vicinity of where the mobile equipment will be positioned. A weatherproof cabinet containing any necessary terminal blocks, switches, or protective devices can be provided for terminating the low-voltage circuits. Temporary connections can be made from this cabinet to the control cabinet on the mobile equipment. Connections into the substation alarm system can also be provided in this or another cabinet. Terminal blocks, test switches, indicating lamps, or any other necessary equipment can be located in the cabinet.

Provisions for grounding the equipment can consist of terminals or ground rods connected to the main grounding grid.

3. Electrical Clearances

Maintaining adequate electrical clearances between the mobile equipment, its connections, and other equipment is of prime importance. Installation using bare conductors should not be considered for a location unless minimum required clearances can be maintained. Insulated conductors can be used in some locations if the minimum clearances cannot be maintained.

4. Primary and Secondary Connections

All primary and secondary connections should be as short as possible and should be made with bolted connections. If possible, use bare conductors. However, for situations where minimum electrical clearances cannot be maintained or where connections are long, insulated conductors can be employed. Insulated cables of the shielded type may be used where connections are quite long or exposed enough so that bare conductors may be a hazard. Cables should be equipped with suitable terminations (stress cones, potheads) at each end. Because of the expense of higher voltage (69 kV and above) cable and terminations, it is especially desirable that the primary connections be short so that bare vertical jumpers can be used safely. The ease with which connections can be made is a major factor in determining the speed with which a mobile unit may be put into service. It may be desirable to store at the substation any large pieces of equipment required to complete the installation, such as temporary wood poles, insulators, etc.

Conductors used should be sized to carry the maximum loads expected without overheating and to sustain anticipated fault currents without damage. They should be checked for sufficient length before connecting either end.

Temporary poles or structures may be required in some locations to facilitate the connections and maintain clearances. It is desirable to store any necessary equipment not part of the mobile unit at the substations, where required.

5. Grounding

Adequate grounding of mobile transformers and substations is extremely important for safe operation. At least two independent connections should be made between the trailer and the ground system. The mobile equipment should be connected to the substation ground grid whenever it is close to the substation. In situations where the mobile is located a long distance from the substation and connection to the substation ground grid is impractical, a separate ground system has to be provided.

6. Auxiliary System Requirements

Mobile unit transformers are usually designed for forced-cooled operation. Some units can provide the low voltage necessary for auxiliary equipment operation through the use of on-board supply transformers and equipment. For units without these provisions, low-voltage supplies can be obtained from the substation station service system.

Before the substation station service system is used to supply mobile unit auxiliary systems, the voltage(s) required by the auxiliary systems has to be checked against those available at the substation for compatibility. The system should also be checked for adequate capacity.

If an external DC supply is necessary for power or control applications, the substation control battery can be used. The system should be checked for proper voltage and adequate capacity prior to utilization.

7. Safety

Unless the mobile equipment is completely contained within another fenced area, a separate fence should be provided to surround the equipment. The fence has to provide the same security and protection as would a permanent substation fence. Gates should be provided with adequate locking facilities.

Mobile equipment usually requires some assembly during installation. Barriers and supports may require installation. Some supporting members or braces used to protect the equipment during transit may have to be removed. Assembly and installation should be in strict accordance with the manufacturer’s instructions.

The equipment should be positioned on a level site and blocked to prevent movement. Ground slope at the installation location should not exceed the manufacturer’s recommendations.

A mobile unit has to always be considered as live and dangerous when in an operating position. Great care should be exercised in grounding the trailer and neutrals. Effective barriers around and under live parts should be provided wherever necessary. Interlocks should be considered to prevent energizing the unit if any required barriers are not properly in place. Additionally, a fence should be constructed around the entire mobile unit unless its operating position lies inside the substation’s security fence.

Because of the different application of mobile units as compared to regular substation components, it is often acceptable to consider the mobile unit as a tool that is to some extent expendable. This approach will permit reasonable deviation from strict application of many major, basic electrical properties. Reduced insulation levels, higher temperature ratings, higher impedance, more extreme overloading (into the loss-of-life range), and reduced clearances can all be considered as possible tradeoffs to obtain more transformer kVA capacity and voltage selection flexibility. Other optimal application considerations may be found through discussions with suppliers of mobile units. As mentioned earlier, minimum safety requirements should not be sacrificed to obtain other advantages.

Summary

This course has reviewed power transformers used in electrical substations including mobile transformers. The different types of power transformers were discussed as well as characteristics such as ratings, taps, impedance, polarity, phasing, cooling, and test procedures.

The next course in the series will discuss substation circuit breakers.

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