IEEE Guide for Transformers Directly Connected to Generators

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Foreword

(This Foreword is not a part of IEEE C57.116–1989, IEEE Guide for Transformers Directly Connected to Generators.)

ANSI/IEEE C57.12.00–1987, IEEE Standard General Requirements for Liquid Immersed Distribution, Power, and Regulating Transformers, and other related C57 series standards provide guidance to users regarding transformer application, design, connections, performance characteristics, testing etc. However, transformers, directly connected to generators experience excitation and short-circuit duties beyond those covered in the C57 series. Therefore, in 1979, the IEEE Transformers Committee decided that an application guide for such transformers was needed by the industry. Accordingly, a working group was formed and a guide prepared. This guide describes the selection, application, and specification considerations for the unit and unit auxiliaries transformers, taking into account their connections, voltage and kilovoltampere ratings, and excitation and through-fault capabilities during possible operating conditions, both normal and abnormal. Also included are load-tap changing and isolated phase bus-duct heating considering This guide does not address phasing procedures, basic impulse level selection, or loading practices.

This guide is based on the latest knowledge, design, and application experience of the industry. It is intended to provide guidance to application and specification engineers and therefore its use is strictly voluntary. Its use may become mandatory only when required by a duly constituted legal authority or when specified in a contractual relationship.

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CLAUSE PAGE

IEEE Guide for Transformers Directly Connected to Generators

1. Scope and References

1.1 Scope

This guide describes selection and application considerations for the unit transformer and unit auxiliaries transformer. Consideration is given to connections that include direct connection and connections through generator breakers and load break switches. The considerations referred to in this guide apply to hydroelectric and thermal electric generating stations. Various transformer connections and possible operating problems under normal and abnormal conditions are treated.

Phasing procedures, basic impulse insulation level selection, and loading practices are not covered.

1.2 References

This guide shall be used in conjunction with the following publications:

[1] ANSI C50.13-1977, American National Standard Requirements for Cylindrical Rotor Synchronous Generators.[1]

[2] ANSI C57.12.30-1977, American National Standard Load-Tap-Changing Transformers 230 000 Volts and Below 3750/4687 Through 60 000/80 000/100 000 kVA, Three Phase.

[3] ANSI C57.12.70-1978 (R1987), American National Standard Terminal Markings and Connections for Distribution and Power Transformers.

[4] ANSI C84.1-1982, American National Standard Voltage Ratings for Electric Power Systems and Equipment.

[5] ANSI C92.2-1987, American National Standard Power Systems —Alternating-Current Electrical Systems and Equipment Operating at Voltages above 230 Kilovolts Nominal—Preferred Voltage Ratings.

[6] ANSI/IEEE Std 100-1988 IEEE Standard Dictionary of Electrical and Electronics Terms.[2]

[7] ANSI/IEEE Std 505-1977 IEEE Standard Nomenclature for Generating Station Electric Power Systems.

[8] ANSI/IEEE C57.12.00-1987 IEEE Standard General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers.

[1]ANSI publications are available from the Sales Department, American National Standards Institute, 1430 Broadway, New York, NY 10018.
[2] ANSI/IEEE publications are available from the Institute of Electrical and Electronics Engineers, Service Center, 445 Hoes Lane, Piscataway, NJ 08854-4150 or from the Sales Department, American National Standards Institute, 1430 Broadway, New York, NY 10018.

2. Definitions

The definitions listed below are in accordance with ANSI/IEEE Std 100-1988 [6][3] and ANSI/IEEE Std 505-1977 [7].

generator (rotating machinery): A machine that converts mechanical power into electrical power.

station service transformer (SST): A transformer that supplies power from a station high-voltage bus to the station auxiliaries and also to the unit auxiliaries during unit startup and shutdown or when the unit auxiliaries transformer is not available or both.

unit: The generator or generators, associated prime mover or movers, auxiliaries, and energy supply or supplies that are normally operated together as a single source of electric power.

unit auxiliaries transformer (UAT): A transformer intended primarily to supply all or a portion of the unit auxiliaries.

unit transformer (UT): A power system supply transformer that transforms all or a portion of the unit power from the unit to the power system voltage.

3. Introduction

The unit-connected generating system came into usage as generator size and generator bus fault current levels began to exceed the capability of breakers that were available to isolate the generator from the power system. Generally, the generator auxiliaries load is fed from a transformer that is connected directly to the generator bus. An alternate source of power is normally supplied from the transmission system by a second transformer during unit startup, shutdown, and other contingencies. Such a system is shown in Fig 1. Typically, an isolated phase bus is used for connection between the generator and its UT and UAT; thus, the system is unit connected.

Studies indicate that through faults for the UT are normally not severe in terms of either thermal or mechanical duty. However, the stresses in the UAT can be severe under certain conditions, such as low-side faults, paralleling out of phase with the SST, and generator load rejection.

On units without generator breakers, faults at location (3) in Fig 1 will be fed predominantly by two sources, namely, through the UT from the system and from the generator. Normally the differential relay protection system, which will detect faults at location (3), will initiate a unit trip that will disconnect the unit from the system and remove the generator excitation. The loss of load may result in a higher voltage on the generator that will continue to feed the fault. This higher voltage due to load rejection will increase the generator's current contribution to a level higher than before load rejection. However, the system contribution will be absent. The generator's contribution will continue at a level and for a period that depends on the generator's fault-current decrement characteristics. The fault-current decrement characteristics are a function of the generator short-circuit parameters and its excitation system. As a result of the generator's fault-current decrement characteristics, faults at location (3) in Fig 1 may exceed the thermal and mechanical capabilities of the UAT if it is designed solely in accordance with ANSI/IEEE C57.12.00-1987 [8].

Abnormal operating conditions, such as generator load rejection, may result in high-generator bus voltages that may also cause overexcitation of the transformers connected to the generator bus. Should a fault occur at location (3) in Fig 1 during this period of overexcitation, both the thermal and mechanical capability of the UAT may be exceeded.

Out-of-phase paralleling of the UAT with the SST can produce high currents that may exceed the mechanical capability of these transformers. Frequency mismatch between the generator and system voltages also can cause severe mechanical stresses on the transformers.

[3] The numbers in brackets correspond to those of the references in 1.2.

A generator breaker at location (2) in Fig 1 would not completely eliminate all of the system problems described in the preceding paragraphs. Generally, it can be shown that thermal and longtime overexcitation exposures of the UAT can be eliminated by the use of a generator breaker, but the mechanical aspects of paralleling two sources out-of-phase or of frequency mismatch must still be given consideration in the design of the UAT.

The following is a list of other considerations that should. be evaluated in the selection. and application of UTs and UATs.

1) Cooling requirements
2) Single-phase versus three-phase transformers for UT applications
3) UTs with single high-voltage winding and split low-voltage windings
4) Overall economic evaluation of equipment costs, installation costs, and the cost of losses

Due to limited scope, these other considerations are not discussed in this guide. However, they should be considered in the selection of transformer parameters.

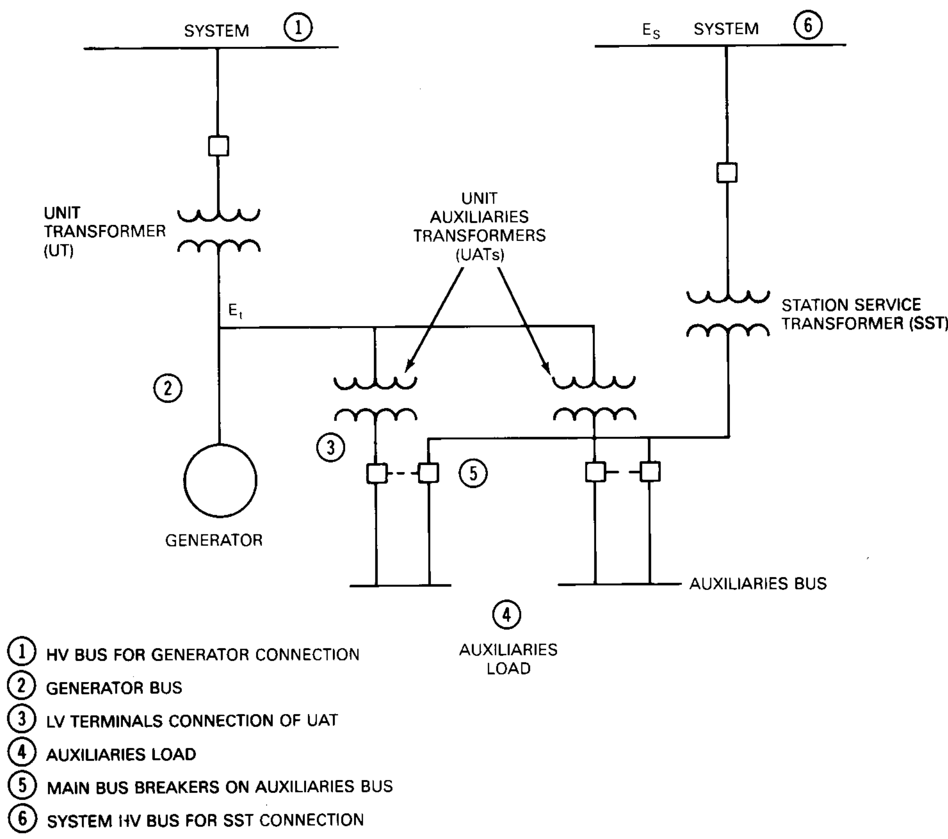


Figure 1— Typical Generating Station Auxiliaries Power System One-Line Diagram

4. Transformer Connections

4.1 Unit Transformer Connections

The most common connections used for large UTs are shown in Fig 2. For voltages above 115 kV where the neutral is normally solidly grounded, the high-voltage wye connection is advantageous due to the economics of reduced neutral dielectric insulation.

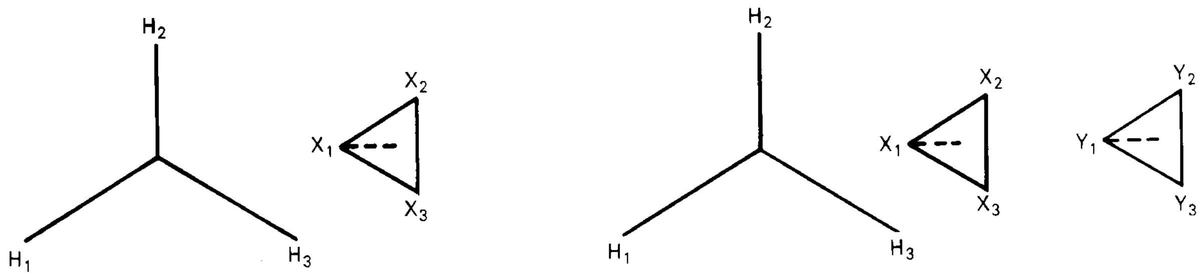


Figure 2— Typical Unit Transformer Connections

4.2 Unit Auxiliaries Transformer Connections

The most common connections used are shown in Fig 3.

The delta connection on the high-voltage side allows the proper phase angle around the system loop.

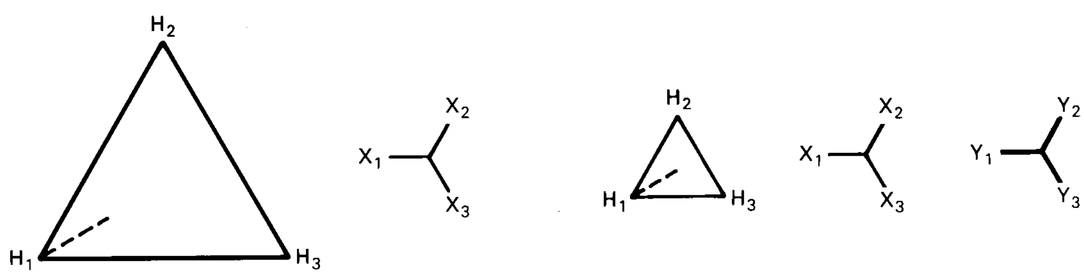


Figure 3— Typical Unit Auxiliaries Transformer Connections

4.3 Unit Transformer and Unit Auxiliaries Transformer External Connections

In Fig 1, usually the unit auxiliaries bus and the system bus are required to be in phase for bus transfer considerations. Proper phasing can be obtained by using the connections shown in Figs 2 and 3 for the UT and the UAT respectively. Assuming a standard delta-wye UT (Fig 2) and a phase-voltage sequence of A, B, C on the low side connecting A to X_1, B to X_2, C to X_3 and A' to H_1, B' to H_2, and C' to H_3 will result in a phase displacement of 30° with the high side leading the low side. With the same phase-voltage sequence and now A connected to X_3, B to X_2, C to X_1 and A' to H_3, B' to H_2, C' to H_1, the resulting phase displacement will still be 30°, but now the low side will lead the high side by 30°. The corresponding would be true for the UAT.

For further information on this subject, see ANSI/IEEE C57.12.70-1978 (R1987) [3].

5. Selection of Parameters of Unit Transformer

The primary function of the UT is to transform the power output of the generator (less auxiliaries power and unit transformer losses) from the generator terminal voltage to the transmission system voltage. Thus, the correct selection of UT parameters should be governed by the electrical characteristics of the generator system and the transmission system to which the UT connects.

5.1 Generator Bus Electrical Characteristics

5.1.1 Generator Capability Curve

The typical generator reactive capability curve shown in Fig 4 is for rated generator voltage.

ANSI C50.13-1977 [1] states that "the generator shall operate successfully at rated kilovoltampere, frequency, and power factor at any voltage not more than 5% above or below rated voltage, but not necessarily in accordance with the standards of performance established for operation at rated voltage." The result of this statement is that the generator capability curve is different for voltages other than rated, except at the rated power factor point. The most noticeable difference is in the underexcited region when operating below rated voltage. Capability curves for other generator voltages can be obtained from the manufacturer. Generally, at lower than rated voltage, the underexcited voltampere reactive (VAR) capability is reduced, whereas the overexcited reactive VAR capability is almost unaffected for ± 5% voltage variation from the rated voltage. Generally, when the generator is operated below 95% voltage, the megavoltampere reactive (MVAR) rating is reduced by the square of the voltage ratio when operating in the underexcited region.

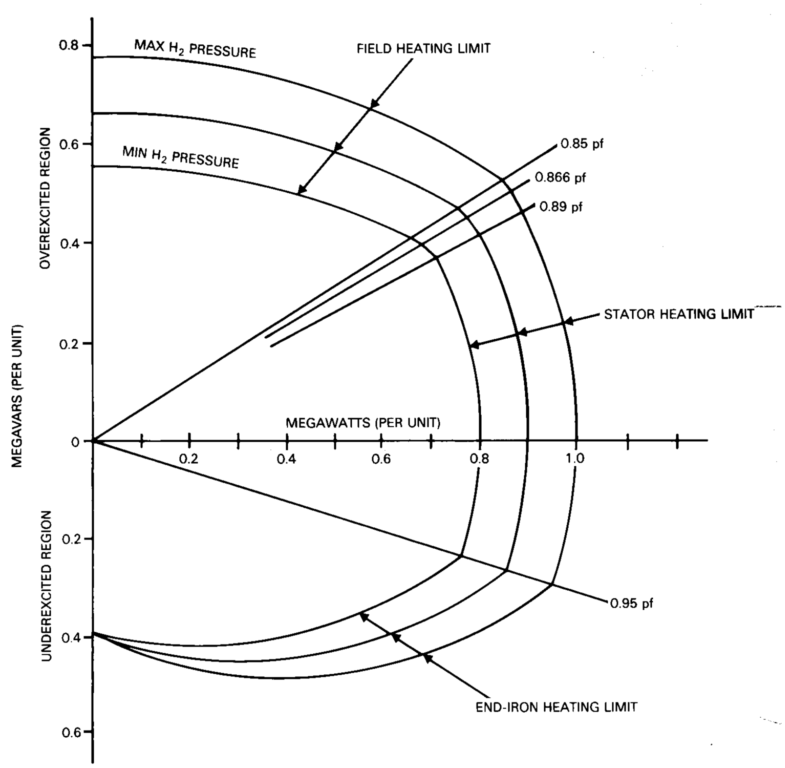


Figure 4— Generator Reactive Capability Curve

5.1.2 Turbine Limit

The generator megawatt (MW) output is limited by the turbine capability. This is shown in Fig. 5. The UT megavoltampere MVA rating should never limit the generator MW output for any expected turbine output.

5.1.3 Excitation Limiters

Modern units are protected for operation in the underexcited region by limiters in the excitation system. Operation in the underexcited region causes concern for generator end-iron heating and steady-state stability. The end-iron heating limit establishes the underexcited capability curve. The steady-state stability, limit is usually established by classical methods using machine reactances and system short-circuit impedances. Fig 5 shows this classical steady-state stability limit.

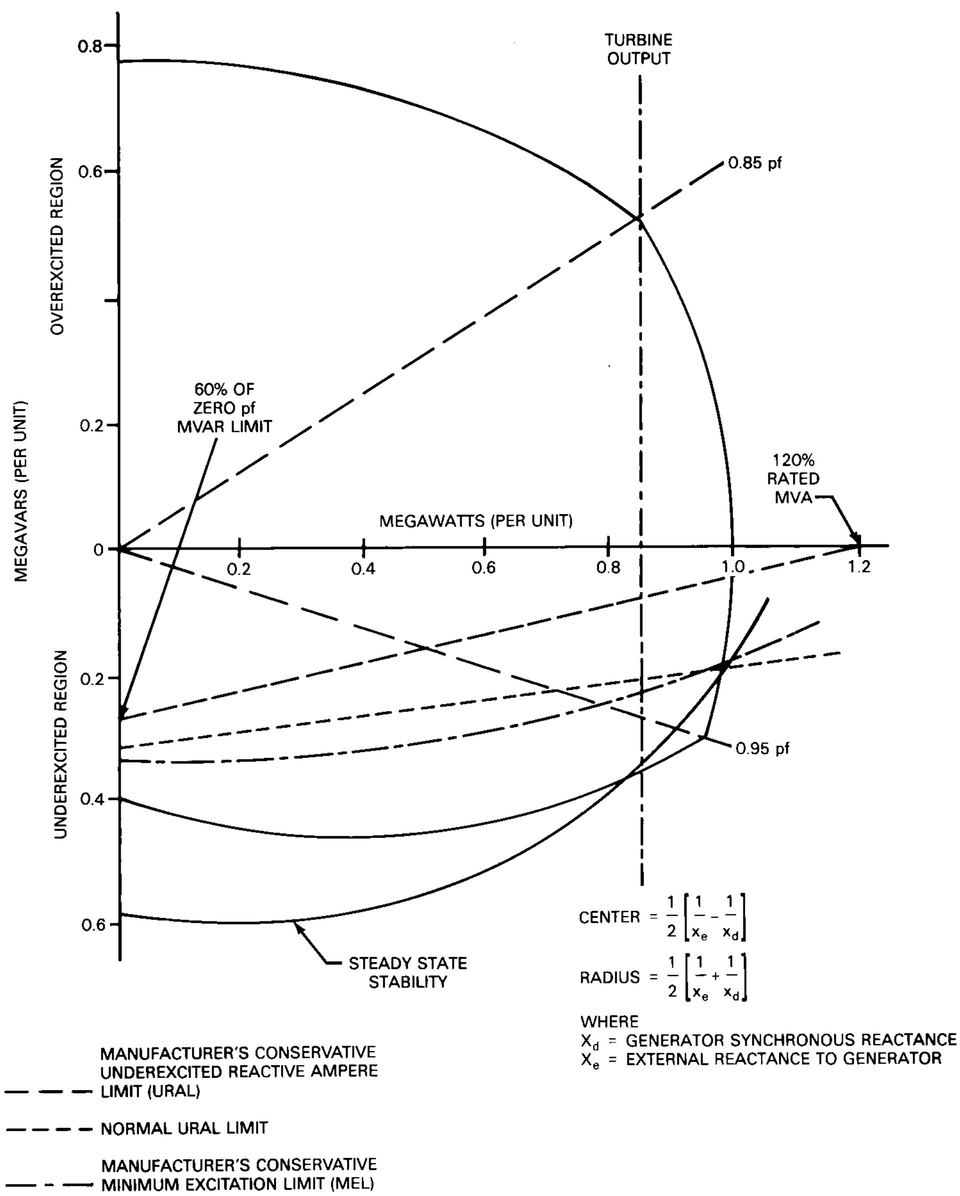


Figure 5— Generator Capability Curve With Typical Underexcitation Limits

5.1.4 Unit Auxiliaries Transformer Loading

The UAT load may affect the allowable voltage swing at the generator bus and the net MVA to the UT low-voltage terminals. Although the generator itself can operate satisfactorily anywhere from 95% to 105% of its rated voltage, the unit auxiliaries load (pump motors, fan motors, etc.), because of other variables, may not, be able to tolerate the resultant swing in. auxiliaries bus voltage. To overcome this problem, UAT with load-tap changers or buses with voltage regulating devices may be required. Load-tap changing may be used to compensate for the effects of voltage variations. However, evaluation of this application should consider its delayed response, effect on frequency of maintenance and possible effects on availability of the turbine generator unit. In industrial applications, capacitors are sometimes used to provide needed voltage boosts during low source voltage conditions or power-factor corrections. Utilities seldom use capacitors, voltage regulators, or load-tap changing transformers for voltage regulation of auxiliaries. Without such voltage regulation help, the operating voltage range of the generator may be restricted so as to provide adequate voltage levels for the auxiliaries system. The restricted generator operating voltage may prevent use of the full range of the generator's VAR capability.

The real power requirement of the UAT load is usually subtracted directly from the gross generator MWs to obtain UT input MWs. Likewise, the reactive power requirement of the UAT load is usually subtracted from lagging (overexcited) gross generator reactive power output or added to leading (underexcited) gross generator reactive power output to obtain UT input MVAR.

5.1.5 Unit Stability

One of the parameters in maintaining unit stability with the transmission grid is the impedance. Planning studies will usually provide upper limits for the UT impedance.

5.2 Transmission System Electrical Characteristics

5.2.1 Voltage

The high-voltage winding of the UT is connected to a transmission system that has, one of the nominal ratings as shown in ANSI C84.1-1982 [4]. However, it is equally important to know the range of required operating voltage over the life of the plant. For example, a 230 kV switchyard voltage may be expected to operate under normal conditions, from 218 kV (95%) to 242 kV (105%), for the life of the plant.

5.2.2 Reactive Power

To maintain desired voltage profiles on the transmission system, the generator must be able to provide a desired level of reactive power to the UT high-voltage terminals for a specific transmission voltage. Transmission planning studies, generally provide this information.

5.3 Evaluation of Parameters

Having determined the generator bus and the transmission bus electrical characteristics and requirements, the various UT parameters can be evaluated so as to optimize total system performance. The parameters are as follows:

1) Highest high-voltage winding tap voltage rating
2) Impedance
3) Transformation ratio
4) Megavoltampere rating
5) Lower high-voltage winding tap voltage ratings
6) Winding current rating
7) Overexcitation

All of these parameters should be evaluated against generator bus voltage and power flow, unit stability, UAT power requirements, transmission bus voltage, and transmission bus reactive power requirements.

The above parameters may be selected by any of several methods. Regardless of the method used, it is recommended that the effect of the selected parameters be portrayed graphically under various generator output and system voltage combinations. The purpose of the graph is to demonstrate visually that correct parameters have been selected.

A typical graph is shown in Fig 6. The graph shows the change in generator voltage with a change in reactive power output While the generator is producing its maximum real power output. The graph is drawn from calculated values using a specific tap on a specific transformer and various constant transmission system voltages. The example used. here represents a UT rated at 23 kV–345 kV. The low-voltage winding voltage rating of 23 kV equals approximately 96% of the generator 24 kV rating Low-voltage winding voltage ratings from 95% to 100% of generator voltage rating are typical in the industry.

It can be seen from the solid line on this graph that the generator voltage will remain within its allowable 95% to 105% range while producing its full MW and MVAR capability (both lead and lag) when the system voltage is 362 kV and the unit transformer is set on the 345 kV tap. The dotted lines on the graph show similar characteristics for the system voltages 354 kV and 345 kV.

Figure 7 and Eq 1 may be used to develop graphs similar to Fig 6. A computer program can easily be written using this equation to help generate necessary data to develop graphs. In Fig 6, the impedance determines the slope of each line, and the turns ratio determines its position in the vertical direction. Ideally, it is desirable for a generator to be able to absorb VARs to its limit. when the system voltage is at its highest expected level and to produce VARs to its limit, when the system voltage is at its lowest expected level. This is seldom possible for a fixed tap setting in the UT, and thus a compromise is usually required. At the time the UT is specified, the generator voltage rating is usually fixed. The transmission system voltage levels for the present and future are obtained from transmission planning studies.

$$\overline{V_s} = \overline{V_g \cdot V_{gbase}} \left[\frac{V_{THV}}{V_{TLV}}\right] - \left[\frac{\frac{MW \pm jMVAR^*}{MVA_T}}{V_g \cdot \frac{V_{gbase}}{V_{TLV}}}\right] \cdot (R_T + jX_T) \cdot V_{THV} \tag{1}$$

where

V_s	= system voltage, kV
V_g	=generator voltage (assumed to be at zero angle for reference), per unit on V_{gbase}
V_{gbase}	= generator nameplate voltage rating, kV
V_{THV}	= high-voltage winding tap voltage rating of UT, kV
V_{TLV}	= low-voltage winding rating of UT, kV
($MW \pm jMVAR$)	= generator output (less unit auxiliaries load), MW and MVAR
MVA_T	= megavoltampere rating of UT for V_{THV} tap
$R_T + jX_T$	=resistance and reactance of UT, per unit on MVA_T and V_{THV} base

* = complex conjugate

The relationship between the generator voltage and MVAR output is not linear. However, the graph approaches a straight line in the range of values under discussion.

Increasing the generator's output of positive MVARs will tend to cause the system voltage to be raised Also, decreasing the output of positive MVARs will tend to cause the system voltage to be lowered. The extent of this voltage change is determined by the total system makeup. A computer load-flow program is used to forecast these voltage changes.

The usefulness of a certain transformer tap with different system voltages can be calculated with Eq 1 and plotted as dotted lines in Fig 6. It is evident that the 23 kV–345 kV or 24 kV–360 kV tap will allow full generator utilization at higher system voltages (354 kV to 362 kV). However, at lower system voltages (354 kV and lower), when the generator is required to absorb maximum VARs, the 345 kV tap limits the absorption of any VARs. The 23 kV–345 kV tap is limited to system voltages approximately 354 kV and above if full generator VAR utilization is required.

Similar graphs may be drawn for each transformer tap. These graphs will aid in the selection of taps for different system voltages.

The effect of different transformer impedances is illustrated in Fig 8. It can be seen that the lower the impedance, the more nearly horizontal the generator voltage/ MVAR output line becomes and, therefore, provides higher flexibility. Conversely, the higher the impedance, the greater the slope of the line, thereby becoming more restrictive in VAR absorption or VAR production.

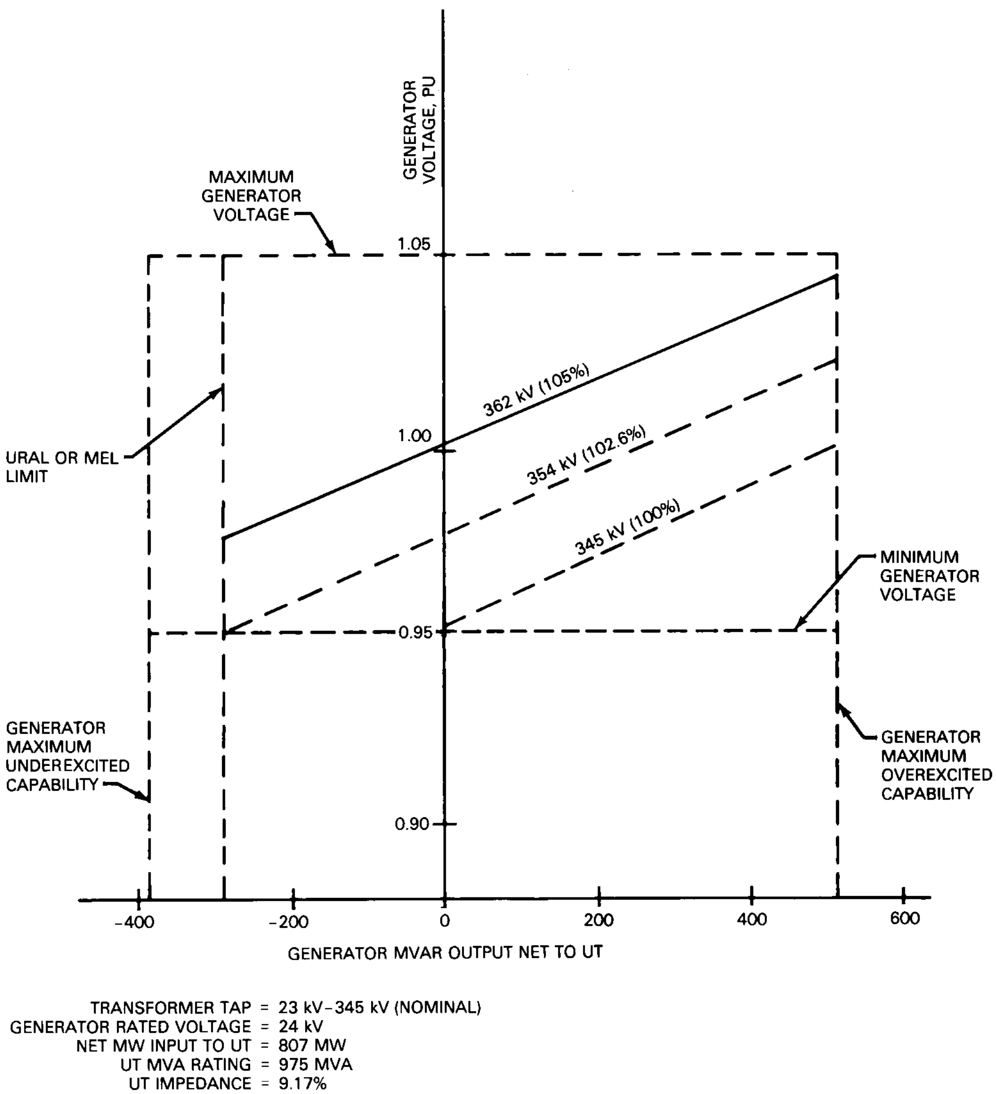


Figure 6— Generator Reactive Capability Limits for Various System Voltages

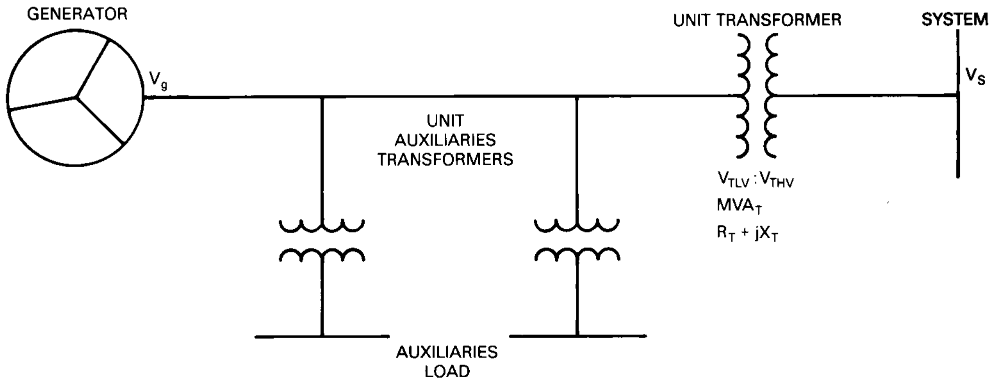


Figure 7— Typical System Connection

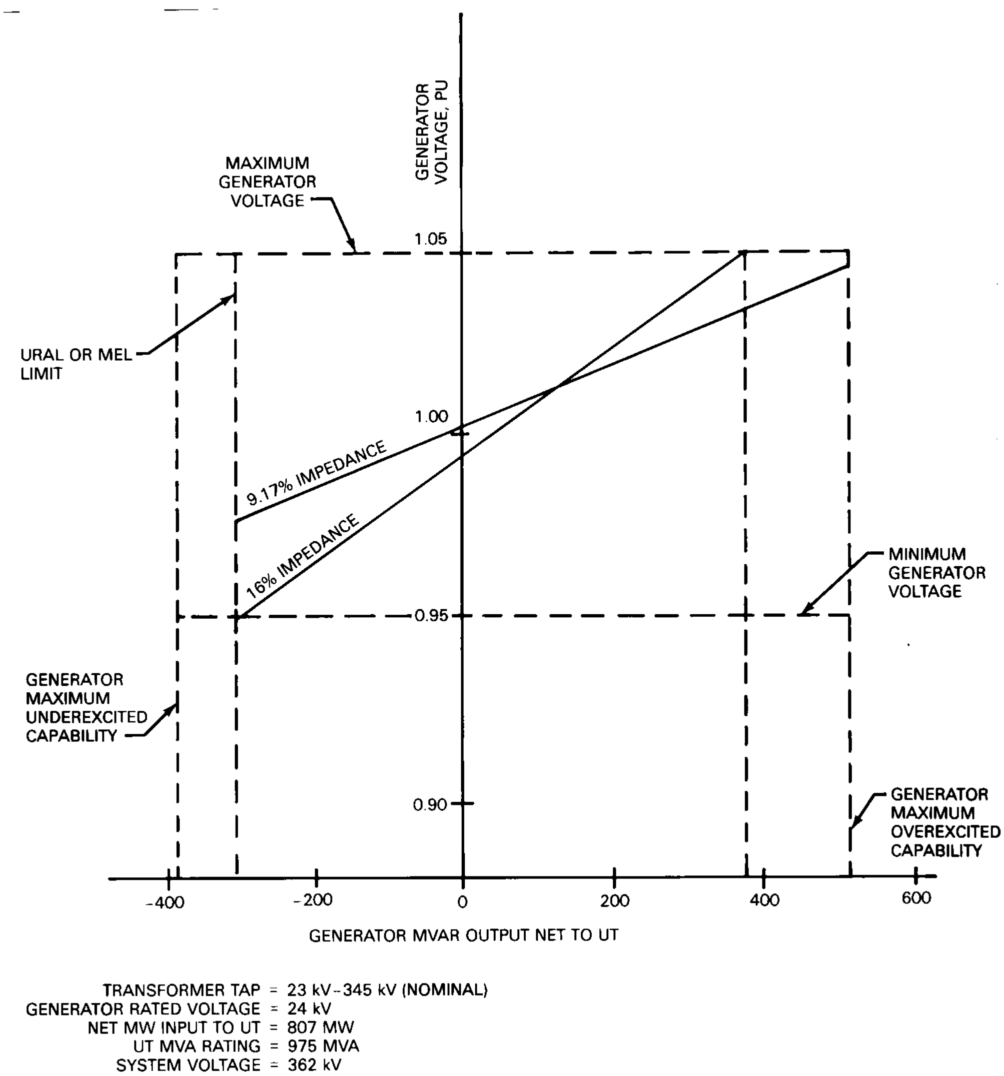


Figure 8— Generator Reactive Capability Limits for Various Unit Transformer Impedances

5.3.1 Highest High-Voltage Winding Tap Voltage Rating

The transformer should be able to operate at the maximum system voltage at which the transmission system is expected to operate. ANSI C84.1-1982 [4] and ANSI C92.2-1987 [5] provide guidance for the recommended voltage levels. The application engineer should be familiar with these voltage levels.

Since ANSI/IEEE C57.12.00-1987 [8] requires a transformer to deliver rated output at 5% above rated secondary voltage, the highest UT tap should not be selected more than 5% below the maximum system voltage.

Selecting the highest high-voltage tap rating greater than 95% of the maximum system voltage may increase the cost of the UT.

5.3.2 Impedance

The UT impedance should meet transient, dynamic, and steady-state stability requirements; limit short-circuit duties to within design values; and provide acceptable voltage regulation. If a generator breaker is used, regulation to the UAT with the generator off should also be considered.

From stability and short-circuit studies an acceptable range of impedances may be established. This range can then be examined using graphs similar to Fig 8. The range of available manufacturers' standard impedances should be considered when making this selection. Values outside the standard range may result in significant cost increases.

The examination should consider the effect of the UT impedance on the generator bus voltage operating range and, in turn, the plant VAR production and absorption. Generally, the generator will be restricted in operating over its full range of reactive power capability (both lead and lag) for the expected system voltage range. Some compromise may have to be made by selecting the appropriate tap rating and impedance to meet the most likely operating condition. It is important to request impedance measurements on all tap positions with the final test report. Depending on the manufacturer’s design, it is possible for impedance to increase, decrease, or remain the same when the tap position is changed.

5.3.3 Transformation Ratio

The transformation ratio is probably the most difficult ratio to select intuitively. The consequences of incorrect selection are restrictions on VAR generation or absorption and generator operation outside its +5% voltage range, or both. Typical low-voltage ratings are 95% to 100% of the generator voltage rating while typical high-voltage ratings are 100% to 105% of the system rated voltage. This selection may be made using a load-flow program. An initial estimate should be made using past history and future system expected requirements. Using the initial estimate, a graph similar to Fig 6 should be drawn. Ideally, the solid line should indicate the full flexibility of producing VARs and absorbing VARs for the generator with its voltage varying between 95% to 105% of rated value and with the system voltage at its highest expected level. If not, it shows that the generator output will be restricted under the indicated conditions.

Figure 9 shows the effect of various transformation ratios for the expected highest-system voltage of 362 kV. Note that a change in the turns ratio moves the line in a vertical direction.

Additional estimates of the transformation ratio should be made until an acceptable rating is determined.

While a low-voltage winding voltage rating lower than the generator rating helps to offset voltage drop through the UT, the 95% to 105% allowable generator voltage sometimes runs as high as 100% to 110% in terms of the rated voltage of the low-voltage winding of the UT. Higher than rated input voltage increases core losses in the transformer substantially. Core losses, regulation through the transformer, and selection of high-voltage taps should be factored in the selection of the low-voltage winding voltage rating.

The selection of a high-voltage winding voltage rating that is 105% of the system rated voltage provides the same advantage as selecting the low-voltage winding voltage rating lower than the generator rating and, at the same time, eliminates the increased core losses at 105% generator voltage and possible overexcitation of the high-voltage winding. Methods for achieving suitable over excitation characteristics for the transformer and the system should be evaluated economically.

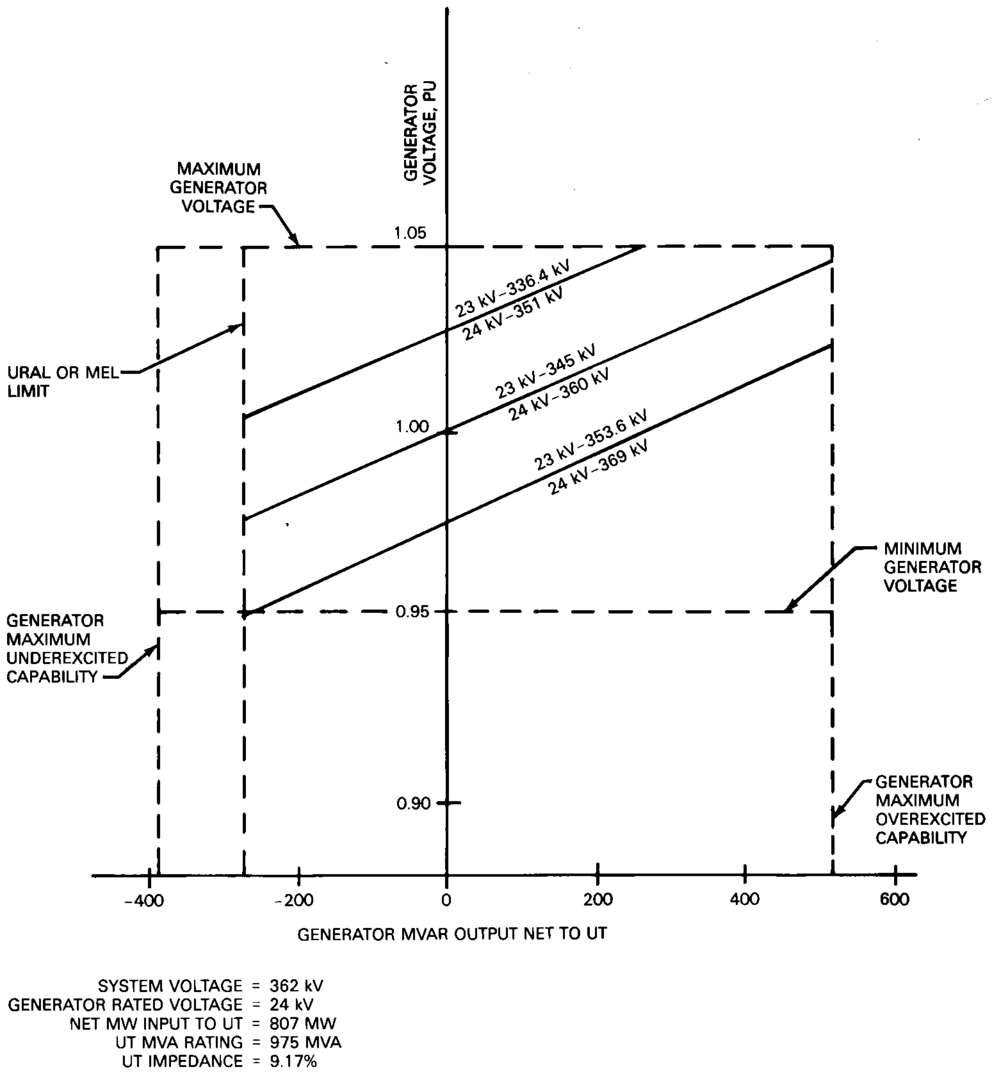


Figure 9— Generator Reactive Capability Limits for Various Transformation Ratios

5.3.4 Megavoltampere Rating

The MVA rating should allow for the full generator utilization (both lead and lag), less the minimum sustained unit auxiliaries load. Note that when the generator is operating at leading power factor (underexcited), the MVAR requirements of the unit auxiliaries load, the reactive losses within the UT, and the MVARs consumed by the generator are all being supplied by the system.

The MVA rating of the UT will also be established on a *trial and error* basis. The MW capability may be initially estimated as the rated MW output of the generator, less minimum sustained auxiliaries MW load (neglect UT MW losses). The MVAR capability may be initially estimated as either maximum overexcited MVAR generator capability, less auxiliaries minimum sustained MVAR load, less estimated UT MVAR losses or maximum underexcited MVAR generator capability, plus auxiliaries maximum sustained MVAR load, plus estimated UT MVAR losses. The latter calculation is most likely to yield the larger UT MVA. Again, a computer program can be easily developed to assist in determining the output MVA rating of the UT.

A conservative UT MVA rating is determined by using the maximum expected generator MW output and corresponding generator MVAR output, neglecting UAT loading and assuming the maximum allowable negative impedance tolerance.

$$\begin{aligned} \mathrm{MVA_T} &= \sqrt{\mathrm{MW_G^2} + \mathrm{MVAR_G^2}} \\ &\cong \sqrt{\mathrm{MW_G^2} + [\mathrm{MVAR_G} - 0.925X_\mathrm{T}(\mathrm{MVA_T})]^2} \end{aligned} \qquad (2)$$

Thus, the required MVA rating may be calculated using a load-flow program, thereby avoiding the number of iterations involved in hand calculations.

The MVA rating, particularly when the generator is underexcited, should have margin for growth in the reactive requirements of the unit auxiliaries load.

5.3.5 Lower High-Voltage Winding Tap Voltage Ratings

If the highest high-voltage tap rating will allow the transformer to fulfill its function at all expected system voltages, no additional taps are needed. However, additional taps should be considered to allow for future uncertainties. Graphs similar to Fig 6 should be developed to determine the number of taps and their ratings. Taps in increments of 2 1/2% are usually specified. Tap increments in the range of 1 1/4% and 2 1/2% are typical.

Carrying the earlier example further, Figs 10, 11, and 12 provide graphs for system voltages of 362 kV, 345 kV, and 328 kV for various taps. When the system voltage is expected to vary between 345 kV and 362 kV, then only two transformer taps, 23 kV–336.4/345 kV or 24 kV–351/360 kV, could ever be used. If the system voltage is expected to vary as low as 328 kV, an additional tap or two is required, as shown in Fig 11. These additional taps, if specified, should be chosen to provide capability in the most likely voltage direction. As stated previously, high-voltage taps higher than 95% of the maximum system voltage may increase the cost of the transformer.

5.3.6 Winding Current Rating

ANSI/IEEE C57.12.00-1987 [8] does not require a transformer to deliver rated output at secondary voltages below the secondary voltage rating. The current ratings of the windings of the selected transformer must be calculated based on rated output at rated tap voltages. This means the lower than rated voltage taps will have higher than rated current ratings to deliver rated output.

If the required current ratings exceed those of a standard transformer for the selected MVA size, then the UT specifications must state the actual requirements.

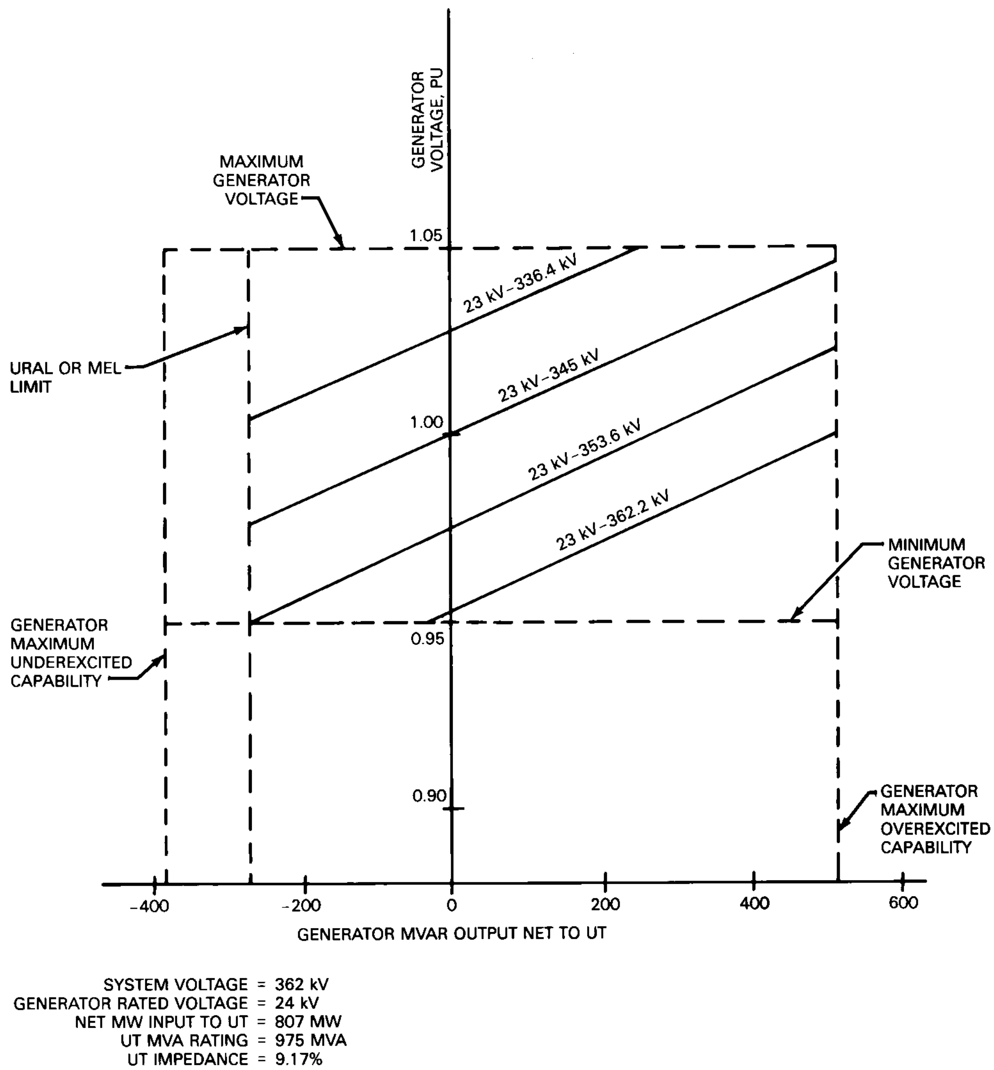


Figure 10— Generator Reactive Capability Limits for Various Tap Settings and a 362 kV System Voltage

5.3.7 Overexcitation

It is not likely that one high-voltage tap will allow full generator utilization over the full range of expected system voltages during the life of the UT. It is likely that more than one tap will be found desirable, as shown in Fig 9. A lower rated tap will allow the generator to absorb VARs for a lightly loaded system, while a higher rated tap will allow the generator to produce VARs for a mature, heavily loaded system. Use of a particular tap may change as the system grows or changes significantly.

Overexcitation can occur when the UT is operating on one of the lower taps and the system voltage increases beyond 105% of that tap's rating. For instance, assume the transformer in Fig 9 is operating on the 23 kV–336.4 kV or 24 kV–351 kV tap and the transmission system is operating in the 345 kV to 353 kV range. Now assume that for some reason the transmission system voltage increases to 360 kV. It can be seen that the transformer secondary now has 107% voltage, which is 2% overexcitation.

Methods for achieving suitable overexcitation characteristics for the transformer system should be evaluated economically.

5.4 Summary of Parameter Selection

1) Select highest high-voltage tap rating as 5% below the maximum expected system voltage.
2) Choose transformation ratio equal to 95% of system maximum expected voltage divided by generator rated voltage.
3) Estimate impedance as manufacturer's standard value.
4) Estimate megavoltampere rating.
5) Calculate and draw graphs similar to Fig 6 for the maximum expected system voltage and with the transformer set on its highest high-voltage tap.
6) Review the impedance for stability and short-circuit requirements, and make new selection or range of acceptable impedances.
7) Review megavoltampere rating estimate.
8) Redraw graphs from Step 5.
9) Repeat previous steps to fine-tune the parameters.
10) Determine if the selected high-voltage rating is adequate for all expected system voltages. If not, draw graphs similar to Fig 9–12 as required and select additional taps.
11) Determine excessive winding current requirements.
12) Determine overexcitation requirements.

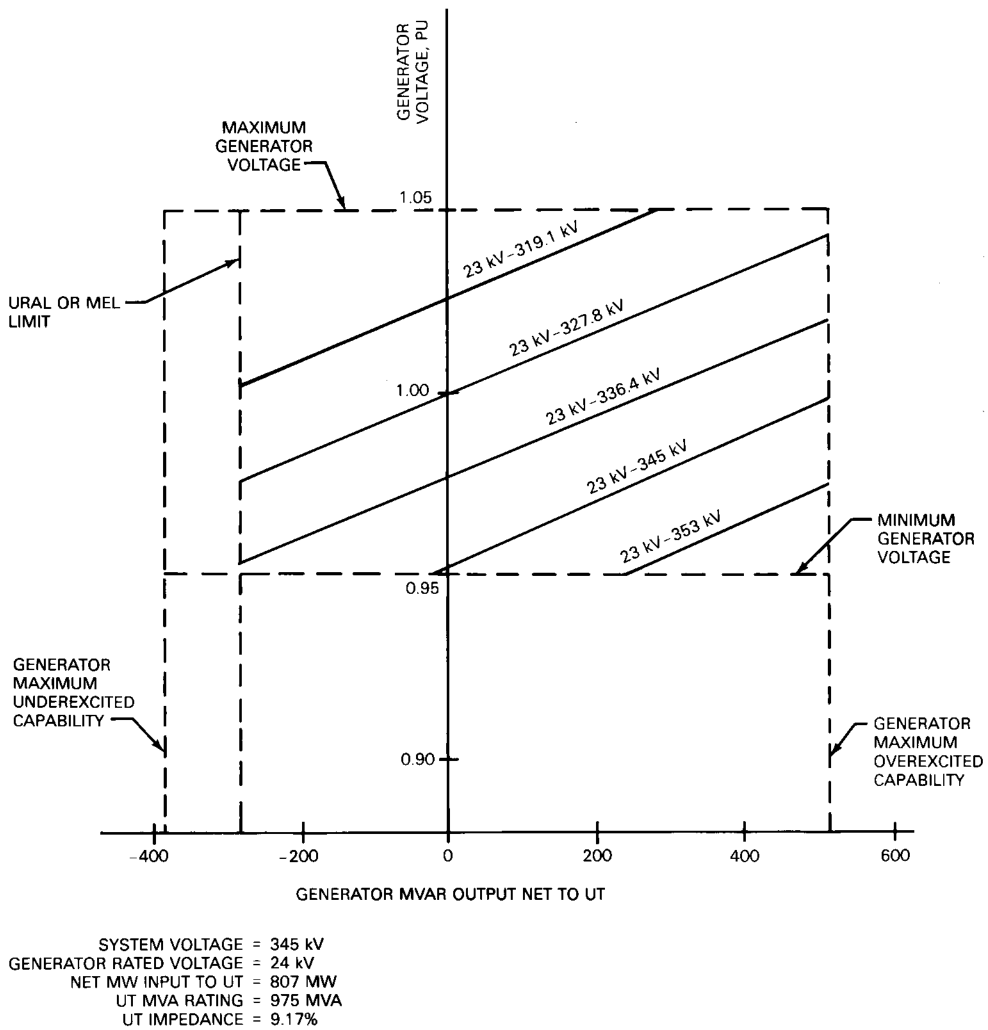
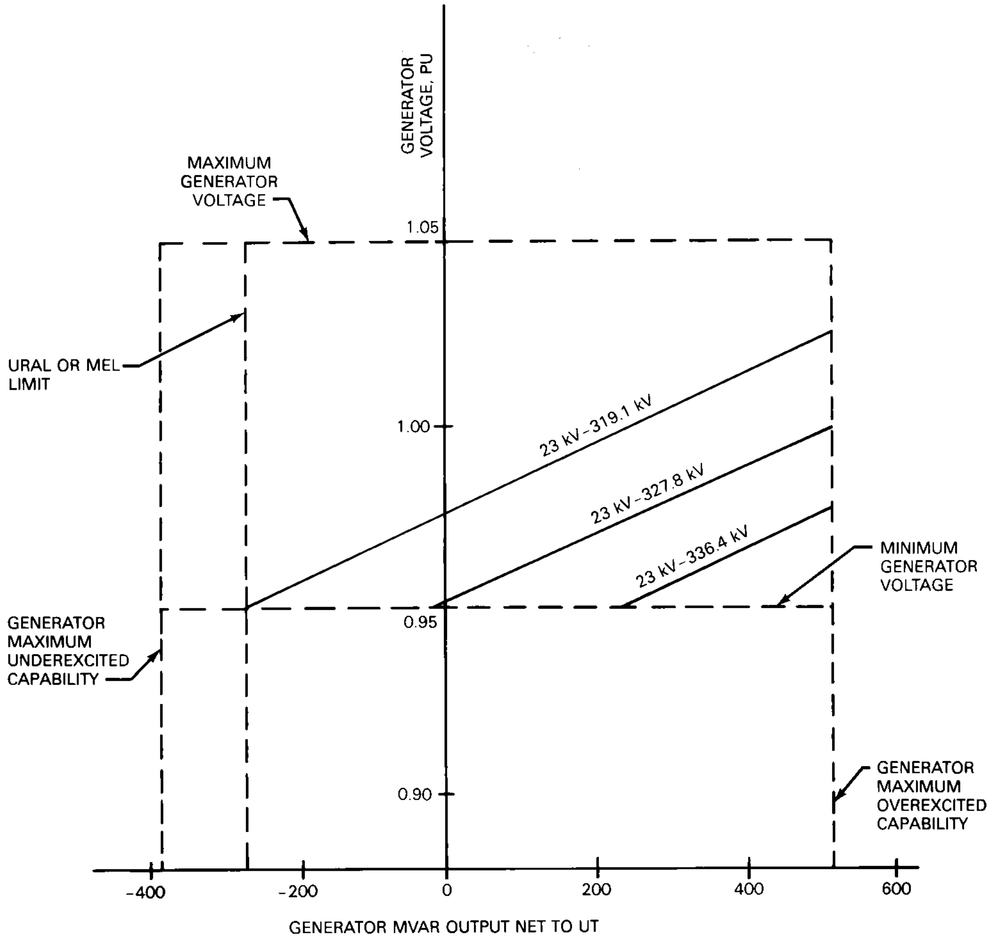


Figure 11— Various Tap Settings and a 345 a kV System Voltage

5.5 Spare, Leased, or Alternative Unit Transformer

Frequently, it is necessary to determine if a UT (either existing or planned) is usable for a certain generating unit. The plotting of graphs similar to Figs 10–12 will show this information in an understandable manner.



SYSTEM VOLTAGE = 328 kV
GENERATOR RATED VOLTAGE = 24 kV
NET MW INPUT TO UT = 807 MW
UT MVA RATING = 975 MVA
UT IMPEDANCE = 9.17%

Figure 12— Generator Reactive Capability Limits for Various Tap Settings and a 328 kV System Voltage

6. Selection of Parameters of Unit Auxiliaries Transformer

The UAT serves to supply all or part of the power plant auxiliaries load with its primary winding connected directly to the generator bus. The selection of parameters is, therefore, similar to that for the UT with respect to the generator system (see Section 5).

It is common practice, in serving large unit auxiliaries load, to use dual UATs, as shown in Fig l, to satisfy the load demand. This alternative, in addition to improved availability benefits, provides a divided load current that can help to maintain fault currents within acceptable limits for connected switchgear.

Another configuration utilizes a three-winding design that may provide secondary voltages at different levels to two separate auxiliaries buses. In still another configuration of the unit-connected design, a generator breaker can be employed to permit the back-feeding of plant auxiliaries buses through the UT and the UAT. One benefit of this design is the mitigation of thermal short-circuit duty that the UAT is subjected to as a result of the energy available under the fault decrement curve (see 7.2). In the generator breaker configuration, consideration of voltage regulation on the auxiliaries bus must include the extremes. The UAT connection to a generator that is operating at its maximum voltage output can be selected such that the corresponding auxiliaries bus voltage at no load is 110% of its rating. In the back-fed configuration, the minimum voltage requirements of plant auxiliaries must be met when considering minimum system voltage and the effective impedances of both the UT and the UAT. A brief discussion on the selection of major parameters for UATs is provided in the following paragraphs. For more detailed information, refer to Chapter 9, "Transformer and Voltage Regulation," of *Electric Power Service System for Generating Stations*, a guide developed under IEEE PGC Project P666.[4]

6.1 Voltage Rating and Tap Range

Conventional design practice is to match the primary UAT winding voltage rating with the rated generator voltage. This permits the normal ±5% generator voltage variation to be matched by the standard rated output requirement for the transformer at ±5% of its rated secondary voltage. It is common practice to specify taps above and below the rated connection. In some cases, selection of a high-voltage winding rating at as much as 5%; below the generator rating is made. In such instances, it is important to investigate the possibilities of transformer overexcitation.

6.2 Impedance

As stated for impedance selection for the UT, limitations for acceptable voltage regulation and the necessity to bring short-circuit currents within design limits are primary considerations for the selection of UAT impedance. In most cases, first priority should be given to obtaining the lowest practical impedance so as to provide adequate voltage regulation for auxiliaries buses. Other considerations, such as fault-current limitations and limiting high-circulating currents resulting from out-of-phase load transfer, must be dealt with in selecting impedance alternatives that will not compromise this first priority. Development of a diagram for the UAT similar to Fig 8 is useful in the identification of voltage and impedance characteristics.

6.3 Megavoltampere Rating

The MVA rating selected should allow for the maximum expected auxiliaries load demand corresponding to the highest expected output of the generator. This MVA should also coordinate with the MVA ratings of the connected equipment, such as switchgear bus work, switches, etc. The MVA rating should also include a reasonable future load growth of about 20% in the auxiliaries loads. In most cases, auxiliary loads are not firmed up to a desired level at the time of procuring the UAT. This means allowance should also be made in determining MVA rating for last-minute load adjustments. Triple-rated transformers may be best suited for UAT applications due to overall economics of losses (transformer and cooling equipment) associated with the varying loading of the UAT.

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[4]This is in a final balloting process.

6.4 Phase Relationship

Because of the connections of the UT and the SST, it may be necessary to use a nonstandard phase relation ship for the UAT (for example, high voltage lagging low voltage by 30°). It should be noted that this connection may be obtained using a standard transformer (see ANSI/IEEE C57.12.00-1987 [8,] Section 4.3).

7. Transformer Overcurrent Considerations

7.1 Unit Transformer Faults

The standard mechanical force and the thermal short-circuit requirements described in ANSI/IEEE C57.12.00-1987 [8] are normally satisfactory for UTs.

For a fault on the system [location (1) in Fig 1,] the fault current through the UT will be limited to the fault contribution from the generator. The maximum fault contribution from the generator is determined by the generator subtransient reactance. The value of this reactance varies from 15% to 25% on the generator base. Since the UT MVA rating approaches the generator MVA rating, it is apparent that the fault current through a UT designed and built in accordance with ANSI/IEEE C57.12.00-1987 [8] will be considerably less than its through-fault capability.

For a fault on the generator side of the UT, the maximum fault contribution through the UT is determined by its own impedance and system equivalent impedance.

7.2 Unit Auxiliaries Transformer Faults

The standard mechanical force and the thermal short-circuit requirements described in ANSI/IEEE C57.12.00-1987 [8] are normally not satisfactory for certain types of through faults on UAT.

The through faults that are of interest are three-phase faults on the secondary of the UAT [location (3) in Fig 1]. For those cases where a generator breaker is not used, the UAT may be subjected to a more severe through-fault duty than similar transformers in network applications because:

1) The direct-current decrement is less than in network applications.
2) The short-circuit duration. is not limited to 10 cycles to 20 cycles, as in the case for network transformers, but may be as long as 10 s to 20 s.
3) Depending on the generator loading prior to the fault, the UAT may have a voltage of up to 125% of its rated voltage imposed on it during the short, circuit.

The UAT must be designed to mechanically and thermally withstand the environment in which it operates. The energy available under the fault decrement curse can be a major factor in the determination of the mechanical and thermal requirements of the UAT.

The short-circuit current on the UAT. consists of two parts. Up to the point of system breaker and generator exciter field tripping, the root mean square (rms) symmetrical value is relatively constant, any alternate-current decrement being more or less compensated for by increased field current through the action of the voltage regulator. Once the protective system operates, the system breaker opens and the field of the generator exciter is tripped. Opening of the system breaker removes the load from the generator and interrupts the fault contribution from the system. Assuming the generator was fully loaded prior to the fault, the generator terminal voltage will rise to a value determined by the shape of the generator saturation curve, the magnitude of the field current before the exciter was tripped, and the short-circuit current, that flows in the UAT. For rated prefault load, this voltage rise can be as much as 25% of rated voltage. This explains the sudden rise in short-circuit current when the system breaker is tripped.

Once the field of the exciter is tripped, this current will now start decaying at a rate largely determined by $T'_{do,}$ the generator direct axis transient open-circuit time constant. This is shown in Fig 13 (a). T'_{do} can range from 3.5 s for two-pole (3600 rpm) generators to 8 s for four-pole (1800 rpm) generators.

Figure 13 (a) shows a symmetrical rms fault current that flows through the UAT during a three-phase fault at location (3) in Fig 1. F_1 is the fault current magnitude at the instant the fault occurs. The system breaker and the generator field excitation trip at t_r second(s). The fault current rises to $F_{2,}$ corresponding to the increased generator voltage due to full-load rejection at time t_r and decays nonlinearly from this level, as shown in Fig 13 (a). This nonlinear decay curve can be replaced by the straight-line decay shown in Fig 13 (a) if the integrated I^2t under the straight-line curve equals that under the nonlinear curve. This can be approximately achieved if a straight line is drawn to intersect the time axis at time t_r+ $2T'_{do}$ seconds. Thus the total fault duration (T_F) in seconds is approximately

$$T_F \cong (t_r + 2\tilde{T}_{do}\ldots)"$$

where

t_r = the time delay between fault inception and the full-load rejection that results due to tripping of the system breaker and the generator exciter field.

Typically, t_r is in the range of 6 cycles–60 cycles., The 6 cycles represent a high speed system breaker opening and the 60 cycles represent backup clearing time for the system breaker for a failed station auxiliaries bus breaker during a three-phase fault on the station auxiliary bus.

The maximum current asymmetry occurs at the inception of the, fault, and it depends upon the fault X/R ratio. Therefore, the highest asymmetrical rms current results at the instant the fault occurs. This means the highest. mechanical force is exerted on the UAT at this time. However, the maximum symmetrical fault occurs at the time of full-load rejection and decays to zero over the several seconds that follow. A relatively smaller change in the symmetrical fault current at full-load rejection results in a considerably lower asymmetry factor. Thus, the magnitude F_2 as shown becomes a major factor in determining the thermal duty required for the UAT. An integrated I^2t value of the curve of Fig 13 (a) represents the thermal energy the UAT will be subjected to under a three-phase fault condition.

Figure 13 (b) shows a plot of asymmetrical-fault current versus time, typical of a transformer designed to meet the requirements of ANSI/IEEE C57.12.00-1987 [8.] Since, in general, the generator direct axis transient open-circuit time constant of all large modern generators exceeds 2 s, the short-circuit withstand capabilities provided by ANSI/ IEEE C57.12.00-1987 [8] *are not adequate for UAT applications.* This can be seen easily by comparing the current versus time curves of Fig 13.

The user specifications should include a current plot similar to Fig 13 (a) for the transformer designer to adequately account for the mechanical (F_1) and thermal (I^2t under the curve) duties. The nonlinear decay curve can be approximated as discussed above.

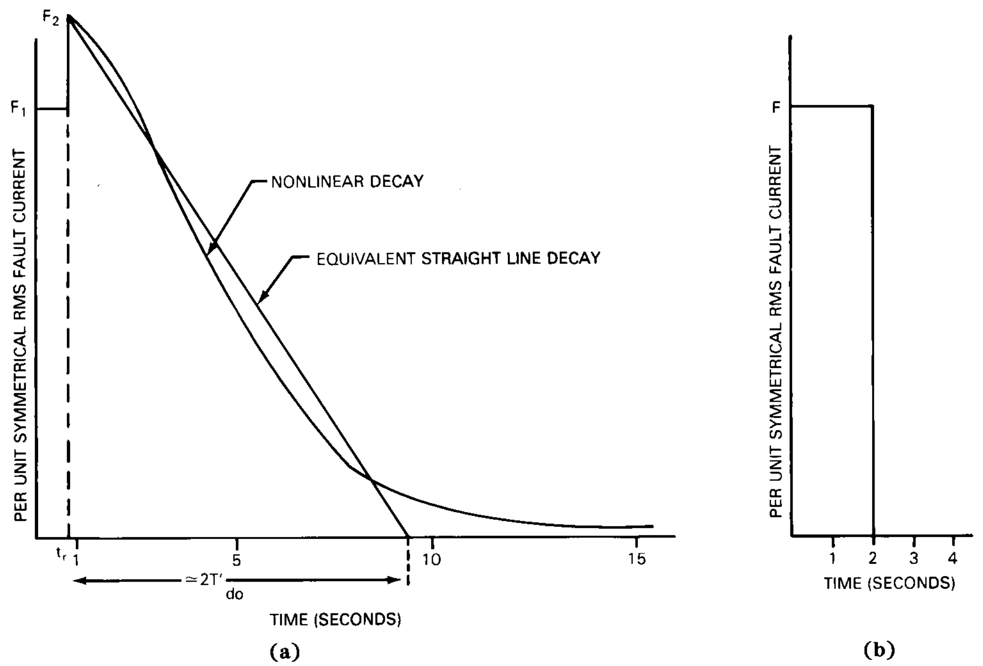

Figure 13— Unit Auxiliaries Transformer Fault Decrement Curve

7.3 Fast Load Transfer-Mechanical Considerations

A fast transfer of load from the UAT to the SST may under certain conditions result in high-circulating currents flowing through the two transformers that could exceed the mechanical design capability of one of them. If the two source voltages as shown in Fig 1 are sufficiently out-of-phase and the circuit breakers (3) and (5) are closed at the same instant of time, a circulating current will flow. The magnitude of the circulating current will be a function of the difference in source voltages and the impedances of the UAT and the SST. The calculations for the circulating current can be refined by adding system impedances in series with the impedances for the UAT and the SST. Generally, system impedances are relatively small and have no significant effect.

From the vector relationship of E_t and E_s in Fig 14, the expression for I_c in Fig 14 can be represented as follows:

$$\overline{I}_c = \frac{\overline{E}_t - \overline{E}_s}{\overline{Z}_u + \overline{Z}_s} = \frac{\overline{E}_c}{\overline{Z}_u + \overline{Z}_s}$$

for $|E_t| = |E_s| = E$ and $|Z_u + Z_s| = Z$

$$|E_c| = E\sqrt{2 - 2\cos\phi}$$

and $|I_c| = \dfrac{E\sqrt{2 - 2\cos\phi}}{Z}$

The following parameters are defined for the above expression and the parameters shown in Figs 14-16.

E_t = generator voltage
E_s = system voltage
E_c = vectorial difference between the two source voltages (E_t and E_s)
f = phase angle difference between two source voltages
I_c = circulating current
Z_u = impedance of UAT
Z_s = impedance of SST
E_{UAT} = voltage across Z_u or UAT = $| I_c| \cdot | Z_u |$
E_{SST} = voltage across Z_u or SST = $| I_c| \cdot | Z_s |$
Z_m = motor short-circuit impedance
E_m = internal voltage of motor
R = ratio of Z_u to Z_s

For example, consider the following parameter values. The transformer impedances are expressed in per unit (pu) on the same MVA base:

Z_u = 0.04 pu (reactive)
Z_s = 0.08 pu (reactive)
Z = 0.12 pu
f = 180°
E = 1.0 pu

Substitution of these values into the above expression yields I_c = 16.66 pu.

The fault-current capability of the UAT is 1/0.04 = 25 pu, while for the SST it is only 1/0.08 = 12.5 pu. As can be seen, the maximum allowable current for the SST is exceeded by (16.66/12.5–1) or 0.33 pu. This translates into a transformer design that requires $(1.33)^2$ or 1.77 times the mechanical strength of a standard transformer design.

The assumption that the phase angle difference between the two source voltages is 180° provides the maximum value for the circulating current, assuming that each source voltage is equal to 1.0 pu. Current values could be higher if the voltage were higher or lower in the case of a lesser angular difference. It is possible to experience large phase-angle differences if the E_s bus [Location (6)] is electrically distant from the system bus of location (1) in Fig 1.

If one includes the effect of motors connected on the auxiliaries bus [Location (4) in Fig 1] in the previous analysis, it can be shown that their presence increases the circulating current discussed in the previous paragraphs. The effect of the motors can be shown by assuming that when circuit breakers (3) and (5) in Fig 1 are closed, the motors act as a parallel source to both the generator and the system, as shown in Fig. 15. By assuming that the voltage, E_m, produced by the motors is in phase with one or the other source, the maximum effect can be shown. If the motor is represented by its short-circuit impedance, e.g., Z_m = 0.2 pu (reactive) on the same MVA base as Z_u or Z_s, and if this is in parallel with the smaller of the two transformer impedances (Z_u in the example), then the maximum increase in the circulating current would occur. In the above example, then:

$$|I_c| = \frac{1.0\sqrt{2 - 2\cos 180°}}{\frac{(0.04)(0.2)}{(0.04 + 0.2)} + 0.08} = 17.65 \text{ pu}$$

This indicates that the maximum allowable current for the SST is exceeded by (17.65/12.5–1) or 0.41 pu. This corresponds to a transformer design that requires $(1.41)^2$ or 1.99 times the mechanical strength of a standard transformer design. If this type of operation is expected, requirements for operation in this environment shall be specified.

To eliminate the potential of this occurring on a fast transfer, one should ensure that breaker (5) closes only after breaker (3) has opened.

Figure 16 may be used to determine the overvoltage of a transformer that is fast transferred. In the example cited above, ratio R of the UAT impedance to the SST impedance is 0.5, and a 1.33 pu voltage appears across the SST during bus transfer (effect of motors neglected). Fig 16 shows the effect of varying the value of R in the same example. A higher Z_s unit is in a shutdown status. The voltage results in a higher overvoltage of the SST. Note that these curves are valid only if Z_s is greater than or equal to Z_u, that is, for $R \leq 1$. For R greater than 1, the voltage across the UAT becomes the larger voltage, and the same curves (Fig 16) can be used by replacing E_{SST} with E_{UAT} and redefining R as the ratio of the SST impedance to the UAT impedance.

If completeness is desired, the effects of the motor load, generator impedances, and station impedances should be included in the analysis. Motor impedance is in parallel with the impedance of the UAT, and thus its effect is to lower the impedance in series with the SST.

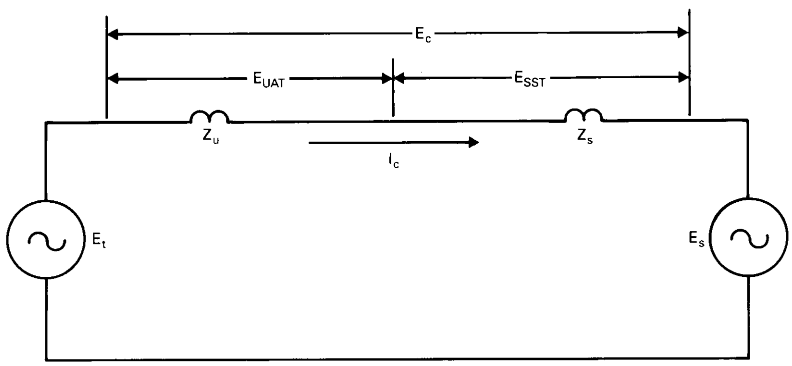

Figure 14— Equivalent Circuit Neglecting Motor Load

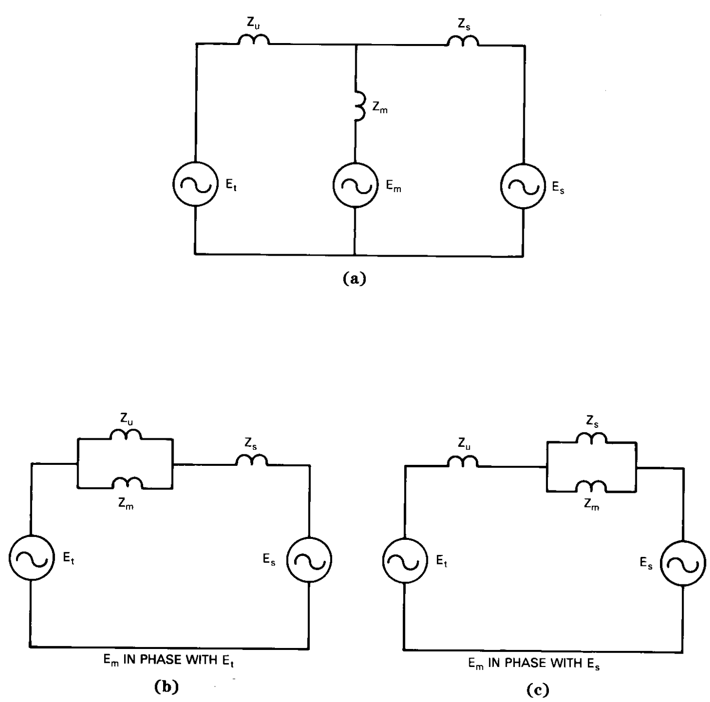

Figure 15— Equivalent Circuit With Motor Load

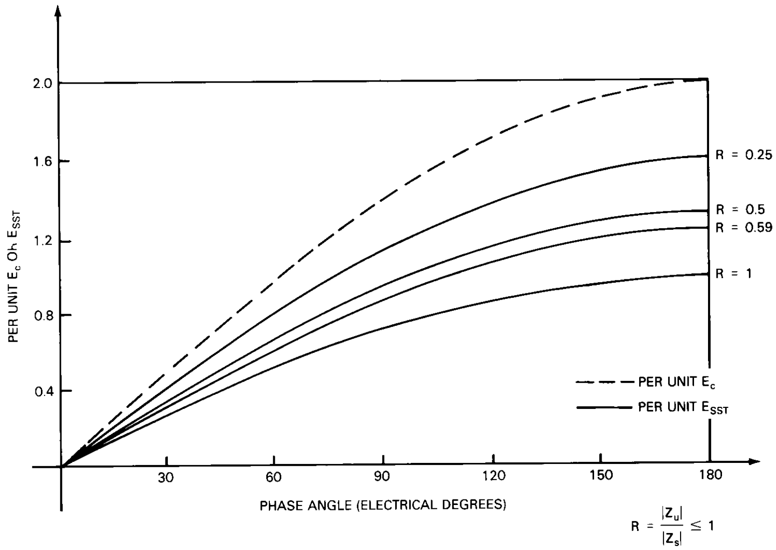

Figure 16— E_c as a Function of the Phase Angle(θ)

8. Load-Tap Changing Considerations

The range of voltage on UAT buses from the generator and the switchyard may be great enough to consider the application of load-tap changing capability for transformers that supply the unit auxiliaries system load. Particular attention should be paid to voltage conditions where generator breakers permit the back-feed of station auxiliaries buses when the range criteria for connected load should be evaluated under all conditions. Controlling the secondary voltage with the use of load-tap changing may be a consideration where the UAT loading alters bus voltages to the extent that auxiliaries would lie outside their acceptable operating voltage range without this control. Consideration should be given to manual operation or prevention of load tap-changer (LTC) operation during motor starting.

8.1 Load-Tap Changing Equipment

Various types of load-tap changing equipment and circuits are used, depending upon circuit parameters. LTCs are built with 8, 16, and 32 steps, with the trend in recent years being toward the larger number of steps so as to give a finer degree of regulation. The usual range of regulation is ±10% of the rated line voltage; however, 5% above and 15% below the rated primary voltage is often more suitable for UAT application. In addition to automatic load-tap changing capability, consideration should be given to remote manual operation. The 32 step, ±10% LTCs have wide acceptance and are considered standard for many applications.

8.2 Duty Considerations

The duties that load-tap changing transformers will experience for plant operation should be considered in definition operating requirements, including mechanical and thermal withstand capabilities. These duties include delayed clearing of generator decrement type short-circuits, motor starting inrush, and evaluation of inadvertent out-of-phase paralleling transients when transferring load from the UATs or the SSTs. Inclusion of these duties in the performance specifications should enable the manufacturer to design the equipment for the service intended.

8.3 Specifications

Load-tap changing equipment specifications should be consistent with the requirements of ANSI C57.12.30-1977 [2].

9. Overheating of Isolated Phase-Bus Duct Connections

High-current isolated phase bus ducts with accompanying strong magnetic fields may cause unanticipated circulating currents in transformer tanks and covers, bushings, and the bus duct itself. The losses resulting from these unanticipated currents may result in overheating if corrective measures are not included in the design. This overheating of transformer components depends upon the method of terminating the isolated phase bus duct at the transformer end. This problem could occur on a large UTs, either three phase or single phase.

By judicious selection of the location of the shorting plate on the bus duct, it is possible that heating of the transformer tank and other components due to induced eddy currents generated from currents flowing in the isolated phase bus can be minimized. Proper grounding of bus duct enclosure per manufacturer's recommendations should be followed.

Experience has shown that heating problems may exist at isolated phase bus duct connections in large UTs if left to chance. Therefore it is suggested that design coordination meetings be arranged between the bus duct manufacturer, the transformer manufacturer, and the user prior to the design of the bus duct. Nonuniform currents and the consequent flux need to be carefully calculated for the bus enclosure and their effects on the material in the transformer tank. In this way, the heating problem can be mitigated.