Issues to Consider when Substituting Large Power Transformers in Generating Stations

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***Abstract*—For availability reasons, many generating utilities keep in storage custom designed spare transformers, readily available and identical to their critical large power transformers. However, in case an exact replacement is not available, the only option the generating utility has is to search for a substitute transformer that, as a minimum, is able to offer a temporary solution. The purpose of this paper is to indicate the most important aspects to be considered when checking the interchangeability of such substitute transformer, based on authors' experience and on various standards requirements.**

***Index Terms*—power plants, power transformers.**

I. Introduction

THE power transformer is a reliable device, yet not failure-free. It has no moving parts, consequently neither the typical faults of rotating machines. On the other hand, the large transformers are oil-immersed and suffer from other faults, mainly chemically or electrically related. A transformer internal fault may be very difficult to locate and to repair. In many cases, the owner may decide that it is faster and cheaper to buy a new transformer than to repair an old damaged one. Even when the repair is worthwhile, it may last for many months.

Almost all large transformers used in power plants are custom-designed. Keeping in storage suitable spare transformers is a common practice, for the purpose of avoiding long unplanned outages and high economic losses. In case an exact replacement is not available, the only option the generating utility has is to search for a substitute transformer that, as a minimum, is able to offer a temporary solution than may introduce some operational constraints. The goal of this paper is to mention the most important aspects to be considered when checking the interchangeability of such substitute transformer. The discussion is based on the various requirements included in relevant American and European standards.

The most common generating station arrangements are shown in Fig. 1: a unit generator-transformer *block* configuration, and a unit generator-transformer with generator breaker. The vital large transformers in a power plant are the *unit step-up/main/generator transformer* (UT), the *auxiliary transformer* (UAT) and the *station service/reserve transformer* (SST). A failure of any one of these transformers may lead to unit shutdown or start-up unavailability.

II. General Layout

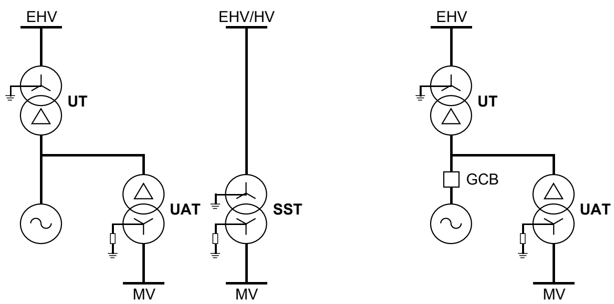
The UT may consist of a single three-phase unit, two half-size three-phase units, or three single-phase units. This is the most evident aspect to consider when a substitute transformer is needed.

When designing a new plant, the selection among these alternatives is generally based on consideration of some form of strategic reserve, as well as available space. Two half-size transformers may be selected in place of a single full-size transformer in order to reduce the cost of the spare. For similar reasons, a generator transformer may be made as a bank of single-phase units. Normally the cost, mass, and loss of such solutions are larger than for a single three-phase transformer; however, they may be preferable if transport size or weight limits apply. The three single-phase transformers provide independent magnetic circuits (see Section XI below), representing high magnetizing impedance for zero-sequence voltage components. Therefore, a delta equalizer winding is normally provided, implemented by external connection between phase units.

Some layouts may pose other complications, like UAT with three-winding design.

III. Dimensions and Weight

Any physical size and weight limitations should be checked, for example for installation on an existing foundation. Special installation space restrictions may influence the insulation clearances and terminal locations on the transformer.



a) Unit generator-transformer block configuration

b) Unit generator-transformer with generator breaker

Fig. 1. Common generating station arrangements.

UT and UAT are connected to the generator through isolated phase bus ducts. The high/extra high voltage terminals of the UT may be connected to gas insulated switchgear. The medium voltage connections to plant auxiliaries are also normally done via rigid, non-segregated phase bus bars or cables. All these aspects must be checked and solved when looking for a transformer replacement.

IV. Rated Frequency

In the unlikely situation a transformer designed for a different frequency is considered, the following applies. The rated frequency radically affects the transformer design and operation. The general formula of voltage e induced by a variable flux ϕ in a coil with N turns is $e = -N\,d\phi/dt$. Assuming a sinusoidal flux $\phi = \Phi_m \cos \omega t$, the induced voltage becomes $e = \omega N \Phi_m \sin \omega t$. Its rms value will be, in terms of core cross section A and flux density B_m [1]:

$$E = 2\pi/\sqrt{2}\, f N \Phi_m = 4.44\, f N A B_m. \qquad (1)$$

According to (1), operating at 50 Hz a transformer designed for 60 Hz means that the same voltage can be achieved only by a substantial increase in the flux density. The core iron will become heavily saturated, the excitation current will rise and also the hysteresis losses (proportional to the area of the hysteresis loop), which could severely overheat and damage the laminations. A 50 Hz transformer needs roughly 12% more iron in its core than a 60 Hz unit, and also more winding turns.

When operating frequency is 60 Hz in contrast to a 50 Hz design, there is too much iron in the core. The hysteresis losses will be higher than the designed value (because iron volume and increased frequency), thus decreasing the efficiency. More importantly, the eddy currents losses will heat up the laminations, because they tend to increase as the square of the frequency. Operation of a 50 Hz rated transformer at 60 Hz may be sometime possible, but it may have to be derated from its nameplate MVA rating [2], depending on the new versus rated voltage.

V. MVA Rating

The substitute transformer rated MVA is obviously a first parameter to consider. When a new plant is designed, the UT rating is chosen to ensure that it will not represent a bottleneck of unit capability, under any possible operating condition. However, a substitute UT poses a different perspective: using a smaller MVA rating than the original one means generating unit derating, nevertheless it is normally preferable to a complete shut-down, taking into consideration the long time needed to obtain an exact replacement.

In the case of a transformer (especially UT) substitution, it is essential to pay attention to the differences among the various standards about the definition of rated power. The IEC 60076-1 [3] definition implies that rated MVA is the apparent input power, received when rated voltage is applied to the primary winding and rated current flows through the terminals of the secondary winding; the output power is, in principle, the rated power minus the power consumption in the transformer (active and reactive losses). Differently, by the North America conventions (IEEE C57.12.80 [4]), the rated MVA is the output power that can be delivered at rated secondary voltage.

If the transformer nameplate mentions a certain rated power and if it was designed in conformity with the American standards, the significance is that its primary (connected to the generator) would be able to receive a higher than rated power. If for instance, the UT impedance is 15%, it should be able to accept a primary MVA higher up to about 15% than the rated one, including load and magnetizing losses (in the worst conditions of lagging power factors). Exact values can be obtained by using the equivalent circuit of the transformer. Contrarily, such intrinsic capability will not be available in transformer exhibiting the same rated MVA, but designed to IEC requirements. The situation inverts under leading power factors (Mvar absorbed from the system) but this is a less likely regime, especially when a substitute transformer is involved.

A transformer may be able under some limitations to carry loads in excess of nameplate rating. In the case of a substitute transformer, the expected regime is a long-time emergency loading that may persist for months. Both IEEE and IEC have standards specially dedicated to such loading aspects (IEC 60076-7 [5], IEEE C57.91 [6]). The application of a load in excess of nameplate rating involves accelerated ageing and risk of premature failure, for instance: deterioration at high temperatures of conductor insulation, other insulation parts and oil, overheating of metallic parts, increased gassing in the oil, high stresses in bushings, tap-changers, connections and current transformers, brittleness of gasket materials. In general, the larger the transformer the more vulnerable.

Both above mentioned standards give similar maximum temperature limits that should not be exceeded in case of long–time loading beyond the nameplate rating: current 1.3 per-unit, winding hot-spot temperature 140 ºC (instead of 120 ºC at normal loading), top-oil temperature 110-115 ºC (instead of 105 ºC at normal loading). The increased ageing rate due to a hot-spot temperature of 140 ºC is 17.2 times higher than normal for upgraded paper insulation and 128 times higher than normal for non-upgraded paper insulation [5].

VI. Rated Voltages

Finding a substitute transformer with suitable primary and secondary rated voltages is a challenging task, difficult to be selected intuitively. Additionally, a transformer design for a certain voltage determines the size of the core and has a significant impact on the overall transformer size and cost.

The system and transformer medium/high/extra high voltage ratings are well standardized and correlated in ANSI C84.1 [7] and IEC 60038 [8]. However, the generators standards do not specify standard series, neither preferable values for the rated stator voltage. The generator stator voltage rating is normally fixed by agreement, and in many cases it is simply the generator manufacturer decision, according to its available design. Therefore, it is quite difficult to match between UT/UAT primary rated voltage and generator rated voltage.

Section VII deals in details with transformers having rated voltages lower than expected operational voltages. Contrarily, it may be possible to use transformers with rated voltages higher than the operational ones, providing that the rated current will not be exceeded. Practically in such case the substitute transformer might be oversized and then unsuitable, because of larger core size and longer insulation distances.

Ideally, it is desirable for a generator to be able to absorb Mvar to its limit when the system voltage is at its highest expected level and to produce Mvar 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 may have to be made by selecting the appropriate tap rating to meet the most likely operating condition. It is important to note that the reactive power consumed by the UT will absorb a significant part of the generator Mvar output under most conditions.

IEEE C57.116 [9] recommends selecting the main parameters of UT (rated voltages, rated MVA, impedance, and over-excitation) by portraying graphically their effect under various operation conditions. While this method is mainly dedicated to a new plant project, it may be also used in case of a substitute transformer. A typical graph (Fig. 2) shows the change in generator voltage with generator reactive load, for various constant transmission system voltages. The graph allows predicting the Mvar capability (both lead and lag) at any given system voltage, keeping the ±5% generator voltage limits, as required by IEEE C50.12 [10], IEEE C50.13 [11] and IEC 60034-1 [12].

The example in Fig. 2 was built on a spreadsheet using equations based on transformer phasors diagram [9]. For a potential substitute transformer, such graphs should be drawn for any available tap/ratio at anticipated MW, and analyzed in order to choose the most suitable tap voltages (according to the forecasted system voltage profile) that will pose minimum restrictions to unit operation: range of available Mvar, synchronization ability, etc. Of course, a substitute transformer may not allow a full range of loading; normally some limitations (e.g. in reactive capabilities) may be acceptable.

References [13] and [14] propose other graphs, more complete but also more complex, which take in consideration additional restrictions, such as: generator maximum excitation limit, generator under-excited reactive ampere limit, UT limits (at lower than rated tap voltage), turbine MW limit, and auxiliary bus-bars (motors) voltage limits. Such graph shows the reactive power transferred to/from the grid (at UT high voltage side) as a function of system voltage, and forecast the area of allowable operation. This graph can be also obtained in a spreadsheet using suitable equations (Fig. 3).

VII. Overvoltage Limits

The purpose of this section is to show how low the substitute-transformer rated voltages may be in order to withstand the highest expected voltages on its terminals.

The standards define the maximum winding voltage based on the insulation withstand capability (in IEC 60076-3 [15] it is called the highest voltage for equipment, while in ANSI C84.1 [7] it is the maximum system voltage).

According to (1), the ratio between the voltage and frequency (V/Hz) of the system to which the transformer is connected determines the nominal flux density at which the transformer operates (assuming the number of turns at a particular tap will remain constant). Normally, the transformer is economically designed to operate at as high as possible flux density, while avoiding saturation of the core. System frequency is normally controlled within close limits; thus, the system voltage is the main factor responsible for over-fluxing (over-excitation). When the V/Hz ratios are exceeded, saturation of the magnetic core of the transformers may occur, and stray flux may be induced in non-laminated components that are not designed to carry flux. This can cause severe localized overheating in the transformer and eventual breakdown of the core assembly and/or winding insulation.

As mentioned before, the IEC 60076-1 [3] definitions imply that rated voltage is applied to primary winding, and the voltage across the secondary terminals differs from rated voltage (defined in no-load condition) by the voltage drop/rise in the transformer. Contrarily, by IEEE C57.12.00 [16] the rated output is delivered at rated secondary voltage; according to IEEE definition, allowance for voltage drop has to be made in the design so that the necessary primary voltage can be applied to the transformer (at a secondary load lagging power factor of 0.80 or higher). For instance, a UT with a impedance of 15% (typical range: 13–17%) designed according to IEEE shall withstand continuously primary voltages as high as 110% of the rated value when fully loaded at a power factor of 0.80 (value calculable using the transformer equivalent circuit). Such hidden capability will not be available in the case of a transformer which follows the IEC requirements.

According to IEC 60076-1 [3], a transformer shall be capable of continuous operation up to 105% voltage or V/Hz (the standard meaning is per each winding). IEC 60076-8 [17] adds that this is not meant to be systematically utilized in normal service, but should be reserved for relatively rare cases of emergency service under limited periods of time. IEEE C57.12.00 [16] defines the over-flux capability in a different way: secondary voltage and V/Hz up to 105% of rated values when load power factor is 0.80 or higher (lagging). Taking into account the previous considerations, this additional requirement may result in 10-15% primary overvoltage (and over-excitation) for a fully loaded generator step-up transformer built under IEEE. Fortunately, generators are only capable of continuous operation until 5% above or 5% below their rated voltage, by [10]-[12] (i.e. V/Hz until 105% at generator base) so the above overvoltage capabilities are rarely exploited. For UAT and SST the impedance is usually smaller than for UT, they often work not fully loaded and the primary voltage will normally not rise by more than a few percentage points for a secondary increase of 5%.

Another aspect related to an overvoltage condition is whether the UT and UAT will be subjected to load rejection. Sudden loss of load can subject these transformers to substantial overvoltage. If saturation occurs, substantial exciting current will flow, which may overheat the core and damage the transformer. A sudden unit unloading during a fault may be caused by the clearing of a system fault and, hence, the machine may be at the ceiling of its excitation system; the unit transformer may be excited with voltages exceeding 130% of normal [18], [19]. With the excitation control in service, the over-excitation will generally be reduced to safe limits in a few seconds; with the excitation control out of service, the over-excitation may be sustained and damage can occur (unless dedicated V/Hz protection exists). Both IEC 60076-1 [3] and IEEE C57.12.00 [16] allow continuous operation at *no load* at a voltage or V/Hz up to 110% of the rated values. For the particular case of transformers connected directly to generators

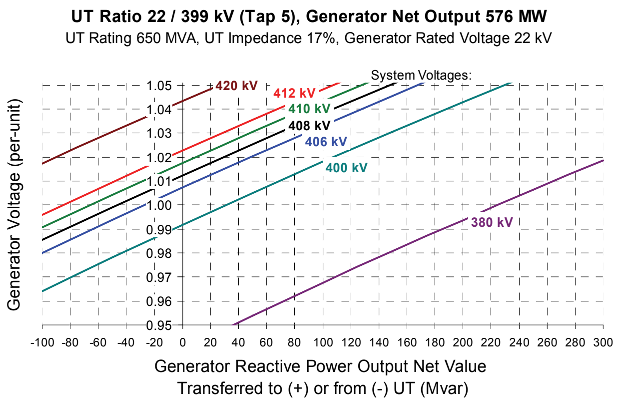


Fig. 2. Change in generator voltage with generator reactive load for various system voltages.

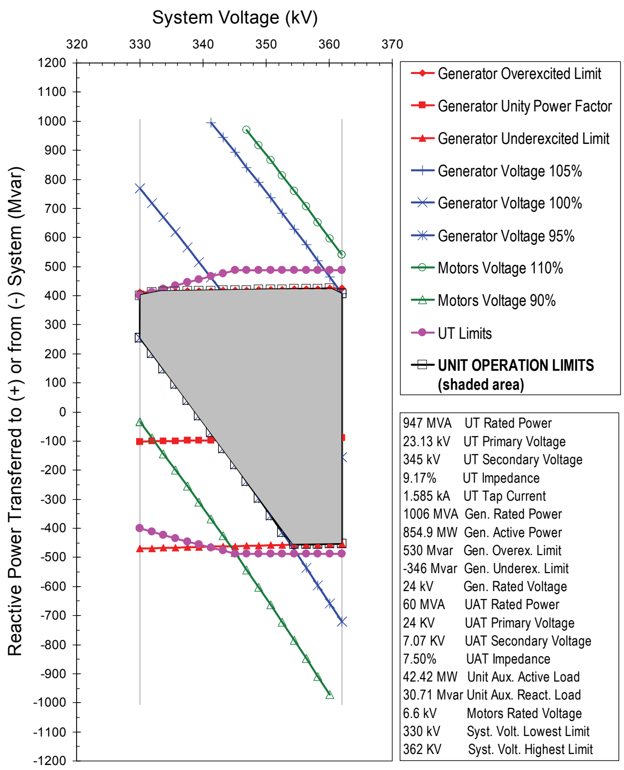


Fig.3 Reactive power transferred to/from system as a function of system voltage (operation area limit).

in such a way that they may be subjected to load rejection (i.e. configurations without generator breaker), [3] has an additional requirement: to be able to withstand 1.4 times rated primary voltage for 5 seconds.

VIII. Connection Arrangement and Phase Displacement

Normally the high voltage system is grounded, leading the UT's high voltage windings to be star connected, with the neutral often solidly grounded. The reason for this is mainly related to equipment insulation level and system protection requirements. The significant consequence as regards the transformer high voltage windings is the possibility to use non-uniform, cheaper insulation systems (i.e. the neutral terminal insulation is designed with a lower insulation level than assigned for the line terminals). On the other hand, it is convenient to have the low voltage windings delta connected (the delta circuit provides a path for third-order harmonics of the magnetizing currents, thus reducing the voltage waveform distortion; it also stabilizes the neutral point potential in the case it is left ungrounded). The most common connection / angular (phase) displacement used for large UTs is YNd1 [9], [14], however YNd11 is also encountered (Fig. 4).

For similar reasons, commonly the UAT primary windings (connected to the generator side) are delta connected, while the secondary ones are star connected through a current-limiting resistor. The most common connections used for UAT are Dyn11 [14] or Dyn1 [9] (Fig. 5). According to IEEE C57.12.00 [16], in Yd or Dy transformers the low voltage shall lag the high voltage by 30°; the connection Yd1 for step-up transformer matches this standard, while Dy11 for step-down transformers does not; however, a standard Dy1 UAT with phase sequence externally reversed on both sides, as explained below, is equal to Dy11. The IEC standards do not have such restrictions.

If the UT is YNd1 and the UAT is Dyn11, the medium voltage auxiliary system has zero-phase shift compared with the high/extra high voltage system (Fig. 1a). During unit start-up or shut-down, the medium voltage busses fed from the UAT and SST secondary windings are briefly paralleled (by the *fast transfer* scheme), so both must be in phase. Additionally, the high and extra high voltage systems are always in phase so the SST must produce zero-phase displacement and therefore, usually it is a star-star as YNyn0 transformer. In same cases it will have a delta-connected tertiary winding, for the reasons mentioned above. For modern transformers, it is matter of the grid configuration and/or protection requirements whether the SST is provided with a delta tertiary or not.

The connection configurations and phasor groups are drawn in Fig. 4 and 5 according to IEC 60076-1 conventions [3]. Since that standard mentions that terminal marking on the transformers follows national practice, Fig. 4 and 5 use the American practice - IEEE C57.12.70 [20].

If the original transformer should be replaced by a non-identical substitute, matching the three-phase connections and phase-angle relations may be a complicated or even an impossible task. Normally it is not possible to substitute a UT or UAT having the vector group number 11 with a vector group number 1 transformer (or the opposite); the reason was explained above: these two transformers link between two rigid phasor systems. Only in the case of a unit equipped with generator breaker (Fig. 1b), it may be possible to use a YNd11 UT instead of a YNd1 one (or contrary) assuming no rapid transfer is performed to other auxiliary bus-bars. However, such substitution will affect the secondary circuits (at least the differential protection) and changes will be required in relays settings and/or matching by intermediate transformers. It is recommended to check also any potential influence on synchronizing circuits; it is a good practice to use supervision sync-check relay with two or three phase-sensing circuits.

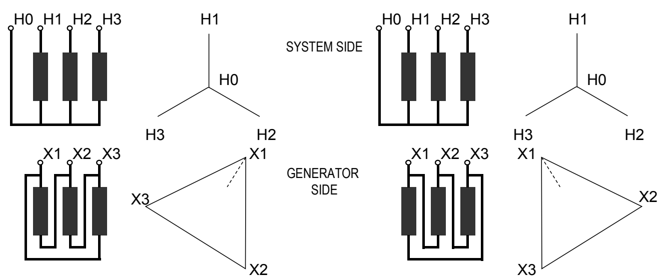
Theoretically, it is possible to keep the original vector group while using a different group transformer. For example, an UAT with vector group 11 may be used in place of an original device with vector group 1 (or inverse), by reversing the phase sequence on both sides of the transformer. Such change is shown in Fig. 6a: as viewed from the external line connections, the Dy11 transformer became a Dy1 one. Unfortunately, the rigid isolated phase bus bars on the generator side and non-segregated bars on medium voltage side will not allow such cross-connections in most cases.

The substitution may be complicated by the transformer layout terminal marking and sequence. According to IEEE C57.12.70 [20], the terminals are marked as in Fig. 7a, i.e. the H1 lead is brought out as the right-hand terminal as seen when facing the high voltage side. Other countries may use different standards; for instance, the English practice is to locate the high voltage terminals from left to right when facing that side [21]; the German DIN 42402 rule is the terminals are arranged from right to left as viewed from the low voltage side [22] (Fig. 7b). For instance, if an UAT designed according to the German standard with a vector group Dy11 is installed in place of an original UAT designed according to an American one, without any change in the external connections, it will externally appear as a Dy1 transformer (Fig. 6 b).

Taking in account both vector group and terminal sequence aspects, an Yd1 American transformer is interchangeable with a European Yd11, without any external modifications.

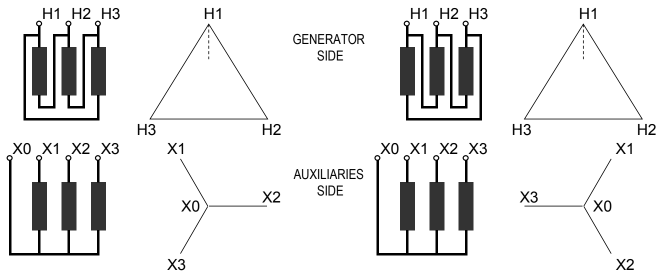
IX. Taps and Tap-Changer

The original transformer may be equipped with on-load tap-changer or de-energized tap-changer. Normally a substitution for a limited period of time with a fixed turns-ratio transformer will be possible in an emergency. When choosing the most suitable tap of the substitute transformer, it is indispensable to check whether it is a full-power tapping (e.g. suitable for a current equal to the rated power divided by the tap voltage).



a) YNd1 b) YNd11

Fig. 4 Most common connection/phase displacement used for UTs.



a) Dyn11 b) Dyn1

Fig. 5 Most common connection/phase displacement used for UATs.

By IEEE C57.12.00 [16], whenever a transformer is provided with de-energized taps, they shall be full capacity taps. Transformers with on-load tap-changer shall be capable of delivering rated MVA at the rated voltage and on all taps above rated voltage. However, for taps below the rated voltage, they shall be capable of just delivering the rated current related to the rated voltage (i.e. these taps may be of reduced MVA, unless specified otherwise). By IEC 60076-1 [3] all taps shall be full-power taps, except when specified otherwise.

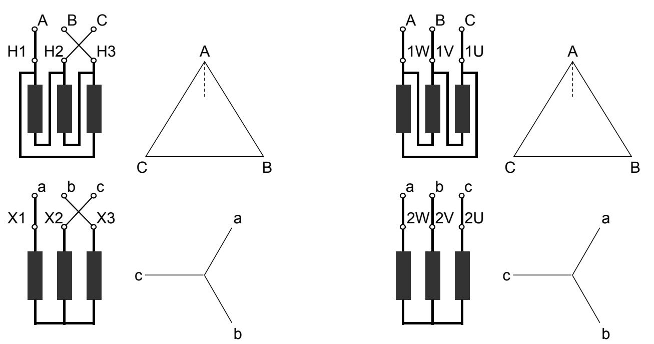
Almost all transformers used in power plants are at least equipped with de-energized tap-changers. Sometimes, especially in case of units equipped with generator breakers, it is difficult to ensure the unit auxiliaries suitable voltage under any operation regime. To overcome this problem, UAT with on-load tap-changer may be required. In some cases, UT or SST are equipped with on-load in place of de-energized taps to allow for large variations in transmission system voltage.

X. Impedance

When designing a new plant, the selection of transformer short-circuit impedance (in fact the reactance, the resistance being negligible for large transformers) is subject to conflicting demands: low enough to limit the voltage drop and to meet stability requirements, but also suitable high to set the system short circuit levels according to economic limitations of the switchgear and other connected plant. If a generator breaker is used, regulation of the UAT with the generator offline should also be considered. These aspects should be also considered for a replacement transformer.

Since reactance is a result of leakage flux, low reactance is obtained by minimizing leakage flux and doing this requires a large core and an expensive transformer. Conversely, if high reactance can be tolerated, a smaller core can be provided and so a less expensive transformer.

It should be noted that since the rated MVA (S) appears in the numerator of the expression for percentage impedance ($z_{\%}$) calculated from its ohmic value (Z_{ohm}), the value of percentage impedance tends to increase as the transformer rating increases:



a) Dy11→Dy1
By reversing the phase sequence on both sides of the transformer

b) Dy11→Dy1
By using a substitute transformer with different terminals layout

Fig. 6. Modifications of transformer phase displacement.

a) American practice (IEEE C57.12.70)

b) German practice (DIN 42402)

Fig. 7. Transformer layout terminal marking.

$$z_{\%} = Z_{ohm} \text{ x } S / U^2. \quad (2)$$

That means that large MVA at low impedances may require significant bulky transformers, and permissible transport limits of dimensions and weight may be reached. It is at this stage that the use of single-phase units may need to be considered.

XI. Unbalance when Using Single Phase UT

In addition to all the issues discussed in this paper that must be considered when selecting a substitute transformer, single-phase transformer replacement from a three-phase step-up unit introduces an additional concern: generator neutral current unbalance.

Neutral current of the main generator is monitored in many power plants, in particular those with large generating units. Neutral current can be the result of a ground fault on the generator stator windings, on the circuit (isolated phase bus or cables) between the generator and UAT(s) and UT, or on the delta-connected windings of the UT or UATs. Upon exceeding certain amplitude, the generator neutral current alarms and might also trip the unit, by an overcurrent relay in the neutral circuit, or, by an overvoltage relay connected across the neutral resistor.

A slightly different turns ratio and/or different impedance (resulting in different regulation) between the substituted transformer and the other two will result in voltage unbalance and thus, negative sequence voltages and currents. This condition will not lead to an increase in generator neutral current, although it introduces other problems discussed elsewhere in this paper. However, different winding capacitances to ground between the substituted and the other two transformers will result in an increase in neutral generator currents, with possible adverse impact on the protective scheme of the generator neutral.

Fig. 8 shows the typical arrangement of a large generator grounded at the neutral via a single phase grounding transformer with a resistive load connected to the secondary winding, sized to reduce any fault current to about 15 to 25 Amps. The sizing of the neutral resistor is a simple calculation that can be found in any good book on generator protection or in the standard IEEE C62.92.2. It is mainly dependent on the value of the capacitance to ground of the generator as well as all other equipment connected to its stator leads. Fig. 8 shows the capacitances to ground of all windings and the isolated phase bus for each of the three phases. In the figure, the capacity to ground of the UT and UAT(s) are lumped in a single delta-connected component.

Under normal conditions, all the capacitances to ground are balanced among the phases and the neutral current is very close to zero. However, if a substitute one-phase transformer is installed with different capacitance, the circuit becomes unbalanced, and the neutral current will grow. Finding the value of the unbalanced current requires solving the unbalanced circuit by any of several available methods. One such method requires the delta connection of capacitors to be replaced by its wye (star) equivalent. All series resistances and reactance are neglected. Then, Fig. 8 can be simplified to the circuit shown in Fig. 9. In the circuit, all the variables are vector quantities, with exception of R_r which is the grounding resistance referred to the primary side. Voltages are assumed balanced and generator / isolated phase bus capacitances to ground equal in each phase. Given that the capacitance reactance to ground is much higher than the series impedance of the windings/buses, these last are disregarded. Following, and using superposition, the total neutral current I_N can be calculated by solving for each phase a circuit as shown in Fig. 10 (example for phase A) and then summing together.

Following the calculation of the neutral unbalanced current, proper setting of the neutral protection can be done.

XII. Overcurrent Considerations

The mechanical force and the thermal short-circuit requirements described in transformer standards are normally satisfactory for UTs.

However, the UAT must be designed to mechanically and thermally withstand the environment in which it operates. The standard requirements for network applications may be not be adequate for certain types of three-phase through-faults on the secondary of the UAT, because of the following: slower dc component decrement, longer short-circuit duration, possibility of higher primary voltage subsequent to breaker trip (load rejection) in *block* schemes [9].

Another eventuality is the fast transfer of load from UAT to SST (or vice-versa), which may lead, under certain conditions, to high-circulating currents flowing through the two transformers exceeding their mechanical design capability [9].

In general, examination of the aforementioned requires consulting with the manufacturer.

XIII. Secondary Circuits

When using a substitute transformer, the protection circuits may be required to be modified because the transformer's rated power changed, and/or bushing current transformers have different turns ratio, and/or differing secondary current or burden capabilities, etc.

Substitute-transformer's bushing current transformers, with different rated secondary current, ratio or burden than those of the original one, may lead to saturation and wrong operation of the differential protection. If the turns ratio or vector group of the alternative transformer is different from the original unit, it should be taken into account regarding current transformers ratio and connections. Some differential relays (mainly numerical) can internally accommodate the phase shift of the transformer, or differences in these ratios. Other relays (mainly electromechanical) do not have this versatility, and pose difficulties or need external auxiliary current transformers.

In case of transformer replacement it is important to verify adequacy of the transformer over-excitation protection. Often, protection and output limiting functions are provided in the generator excitation equipment, but it is a good practice to apply additionally separate V/Hz protection. The curves that define generator and transformer V/Hz limits should be coordinated to properly protect both. When the transformer rated voltage is equal to the generator rated voltage, the same V/Hz relay that is protecting the generator may be set in such a way that also protects the transformer. In some cases, however, the rated transformer voltage is lower than the rated generator voltage and common protection may not be applicable; in such a case, it is desirable to provide supplementary protection for the transformer.

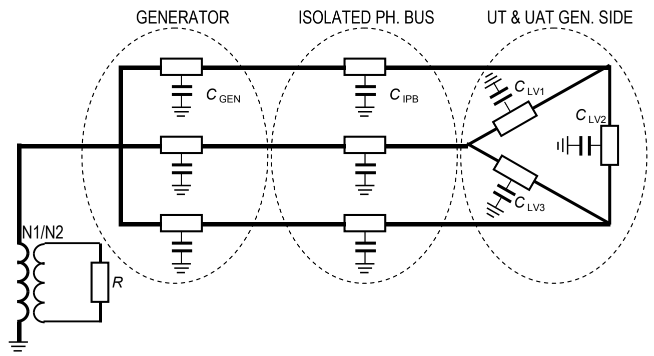


Fig. 8 Equivalent Circuit of the generator, isolated phase bus, and the delta-connected windings of the UT and UATs.

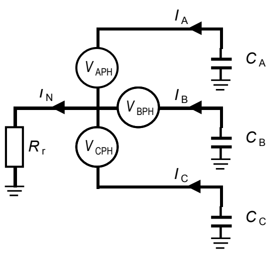


Fig. 9 Simplified circuit for calculating the unbalanced neutral current.

XIV. Additional Considerations

Additional aspects that should be checked when deciding for a transformer substitution are:

- Details of type and arrangement of terminals, for example connections to overhead line, isolated phase bus, or cable box or gas insulated bus bar.
- Isolated phase bus ducts with accompanying strong magnetic fields may cause high circulating currents in transformer tanks and covers which may result in excessive temperatures when corrective measures are not included in the design.
- Unusual voltage conditions including transient over-voltages, resonance, switching surges, etc. which may require special consideration in insulation design.
- Derating due to high harmonic load current.
- Unusual environmental conditions (altitude, special cooling air temperature, explosive atmosphere, etc.).
- Details of auxiliary supply voltage (for fans and pumps, tap-changer, alarms, etc.).
- Sound-level restrictions.
- Losses level (usually not relevant in case of an emergency situation transformer substitution).

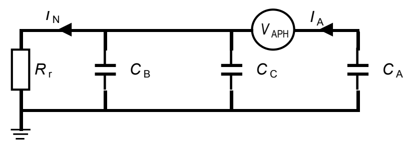


Fig. 10 One of the three circuits to be solved for calculating the neutral unbalance current.

XV. Conclusions

The large transformers used in power plants have particular characteristics and specific custom designs. Keeping in stock spare transformers identical to the critical ones in operation is an expensive strategy; however it ensures the lowest risk. The advantageousness of this policy increases in the case of multiple standardized generating units (one example of interchangeable generator transformer is detailed in [23]).

Checking the suitability of a different substitute transformer is a complex task. As a first feasibility check, confirm the transformer rated frequency fits your grid, preliminarily look for an available transformer ratio close to the ratio of secondary system voltage to generator rated voltage (about ±5%), and roughly appreciate the transformer largeness, heaviness and available power.

Following is a partial list of the main parameters that must be checked:

- UT secondary tap voltage should not be lower than 95% of the grid's maximum expected voltage (this value typically equals the rated system voltage).
- UT primary (low) voltage should not be lower than 95% of generator rated voltage for transformers designed according to IEEE C57.12.00, and not lower than generator rated voltage for

transformers designed according to IEC 60076-1.

- UAT primary voltage should normally match the rated generator voltage; a lower voltage (up to 95% of generator rating) may be possible only after investigation of the risk for over-excitation.
- Check connection and phase displacement suitability.
- Analyze MVA rating suitability. If taps below the rated voltage shall be used, check their MVA capability.
- Transformer rated voltages higher than the expected operating ones mean mandatory reducing the MVA to avoid exceeding the rated current.
- Check dimensions and weight suitability.
- Analyze the unbalance that may be introduced when replacing a single-phase transformer from an UT made of three sing-phase transformers.
- Estimate transformer short circuit impedance influences.
- Confirm through fault and fast load transfer capability in case of UAT/SST replacement.
- Verify the implications on secondary circuits (mainly protection and synchronizing).
- Thoroughly analyze the synchronizing and loading capabilities for any available tap, under various operation conditions, using graphs as in Fig.2 or Fig.3.
- In the eventuality of two units connected to the same bus, one of them having a substitute UT (with different MVA or ratio or impedance), the possible effect on generators different behavior should also be considered.

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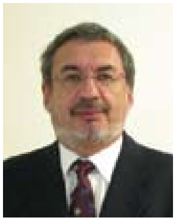
XVII. Biographies



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