Specifying HV/MV Transformers at Large Sites for an Optimized MV Electrical Network

White Paper 258

Revision 0

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Executive summary

Generally, large industrial site designs use standard specifications of the HV/MV transformer which leads to oversizing and a higher cost of the MV primary and secondary electrical distribution system. This paper introduces the factors to consider when specifying the HV/MV transformer and raises awareness of the impact of short circuit impedance (z_t) on the cost of the HV/MV transformer and the MV electrical distribution installation (MV switchgear and cabling). Finally, a case study of a large date center is presented to show how a reduction in the total cost of ownership (TCO) can be achieved. NOTE: this technical white paper is aimed at electrical engineers who are specifying HV/MV transformers for large industrial and data center sites.

Introduction

Electrical utilities use four types of networks topologies to deliver electrical energy to the different types of load centers. The main network characteristics are presented in **Table 1**.

Table 1
Network characteristics of the four utility network topologies used to deliver energy to load centers

Network Type	Function	Nominal Voltage (typical range)	Main topology	Typical Availability
Extra High Voltage (EHV) transmission	Transport bulk power over long distances	800kV < Un < 220kV	Meshed	99.99999%
High Voltage (HV) sub-transmission	Distribute power to main consumption centers (cities, large industrial sites, and infrastructure sites)	220kV < Un < 52kV	Meshed	99.9999%
Medium Voltage (MV) distribution	Distribute power within urban and rural areas	52kV < Un < 7.2kV	Open Ring and Radial	99.99%
Low Voltage (LV) distribution	Distribute power to residential customers	400V	Radial	99%

The voltage level selected to connect large industrial and infrastructure site loads depends on:

- Network voltage level available at the site
- Maximum power demand requirements, including future expansions
- Short circuit current level required for “direct on line” (DOL) starting of large MV motors

Figure 1 indicates that loads in the range of 20 to 100 MVA will be connected to the HV sub-transmission network at voltages between 66 kV to 150 kV. The actual connection voltage will vary country by country since electrical utilities adopted different voltages when they constructed their networks more than 50 years ago.

Industrial sites such as mines, oil & gas refineries, paper mills, cement plants, as well as large infrastructure sites like major airport hubs (e.g. London Heathrow, Paris CDG, New York JFK, etc.) have always been connected to the utility HV sub-transmission network since their installed power exceeds 20 MVA. More recently, XL data centers built by Web Giants (e.g. Google, Amazon, Facebook) and large colocation and telecom companies (e.g. Equinix, Interxion, Telefonica, etc.) could be considered as being “large infrastructure” installations as they are connected to the HV sub-transmission network.

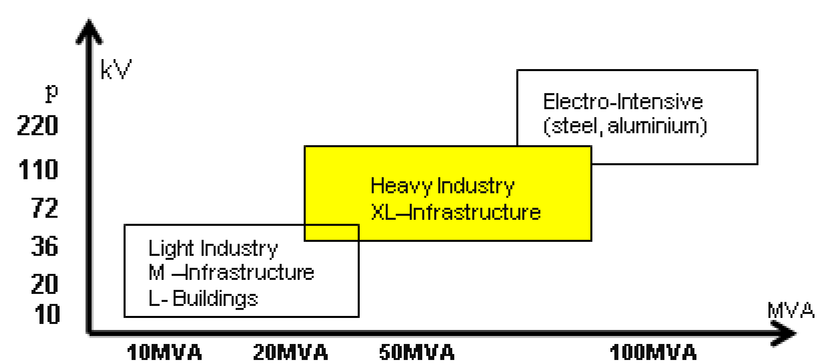


Figure 1
Electrical utility network voltage connection of large loads (> 20 MVA maximum demand)

This paper intends to raise awareness among these groups of end users on how to specify the key parameters of the HV/MV transformer to optimize the total MV distribution network cost. **Particular emphasis is put on the choice of HV/MV transformer short circuit impedance (z_t) value as it has the highest impact on the cost and performance of the site MV electrical installation.** The paper focuses on 3 phase HV/MV oil-filled transformers.

A synthesis of IEC and ANSI/IEEE standards guidelines applicable to HV/MV oil-filled transformers is provided. The different philosophies of both standards and the impact they have on the customer specifications in the USA and the rest of the world (RoW) are explained and illustrated with an example of a typical 40 MVA, 132 KV/11 KV, DY11 oil-filled transformer.

Finally, the paper shows a comparative analysis of the combined cost of HV/MV transformer, MV switchgear and MV cabling for a typical large data centre (80 MVA installed capacity) for different values of HV/MV transformer short circuit impedance (z_t). **The analysis clearly illustrates that specifying the right z_t value in the design phase is key to optimizing the cost and performance of a large site's MV electrical installation.**

General considerations

The main parameters that define the electrical performance of a 3 phase HV/MV oil-filled transformer are:

- Primary and secondary rated voltage (U_{1r} and U_{2r})
- Nominal apparent power (S_n) with the associated cooling method (natural or forced)
- Vector group (e.g. Dy 11)
- Short circuit impedance z_t in %
- Regulation range and type
- Frequency
- Losses

Important ancillary items required to complete the HV/MV transformer specification, such as connection systems (bushing, cable), the use of a conservator, Buccholz relay, temperature monitoring, dissolved gas monitoring equipment, noise requirements (no-load, load and/or total noise), and special insulating fluid will not be discussed in the paper as they only impact the HV/MV transformer cost.

Metering location

In most countries the end user requiring an HV network connection has to enter into a negotiation with the local electrical utility to fix the cost of the connection from the site to the point of common coupling. The utility is likely to propose their standard type of HV/MV substation.

The "metering point" divides the electrical plant ownership between the utility and the end customer. Utilities specify and purchase the metering CT and VT, as well the kWh meter used for billing. They also supply the back-up circuit breaker that will disconnect the end user installation from the HV grid in case the HV circuit breaker on the end user side fails to clear a fault within its own network.

In general, utilities prefer to provide metering on the MV side of the transformer. However, in some countries the end user can request to have the "metering point" on the HV side of the transformer, as illustrated in **Figure 2**. In this arrangement, the end user has a lower kWh tariff but has to specify and purchase the HV/MV transformer and HV switchgear. The end user would also have the responsibility for the maintenance of the HV installation in this case.

Although initially there is a higher capital investment, the end user can expect pay back between 3 to 5 years as the price of kWh as an HV customer is significantly lower than the MV tariff. Furthermore, the end user can further benefit by choosing an HV/MV transformer specification that cost reduces the total cost of its MV distribution installation. This specification needs to be done very early in the project as the HV/MV transformer is an engineered to order (ETO) item with typically the longest lead time (usually 6 to 8 months).

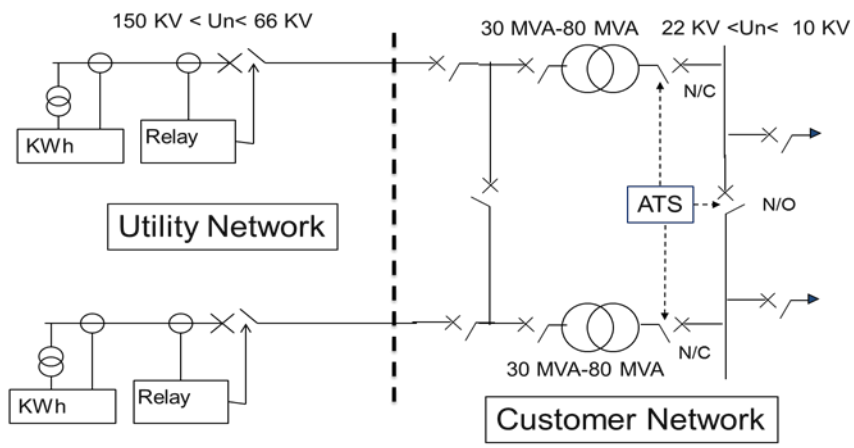


Figure 2
HV/MV substation with HV utility metering for connection of a site with installed power > 30 MVA

HV/MV transformer specification

Transformer short-circuit impedance

The transformer short circuit impedance (z_t) is a fundamental value measured, guaranteed, and reported on the nameplate for all transformers in percentage (%). However, many people specify transformers without fully understanding the impact of this key parameter on the total cost of the MV installation.

The magnitude of z_t is the voltage drop caused by the transformer leakage impedance at full load current, expressed in % of the rated voltage. It can also be represented as the % of the rated primary voltage (U_{1r}) that has to be applied (U_{1sc}) to circulate full load current (I^2R) when the secondary winding is under short circuit condition (see **Figure 3**). For this reason z_t is also referred to as "short circuit voltage impedance" and expressed as[1]:

$$z_t(\%) = (U_{1sc} / U_{1r}) \times 100$$

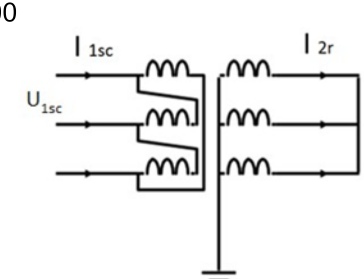


Figure 3
Basic circuit used to measure transformer short circuit impedance z_t in %

[1] A. Naderian Jahromi, J. Faiz and H. Mohseni, A fast method for calculation of transformers leakage reactance using energy technique, IJE Transactions B: Applications, Vol. 16, No. 1, April 2003

Life Is On Schneider Electric

The short circuit impedance z_t is determined by the leakage flux which depends on the winding characteristics and the leakage flux magnetic path. These are parameters that can be varied during product design engineering by choosing different coil designs and geometries.

Physically, the short-circuit impedance relates with the leakage inductance (L_{lk}) of the energized winding added with the leakage inductance of the shorted winding(s) (scaled according to the turns ratio).

Accurate calculation of leakage inductance for a given design requires 3D magnetic field computations using finite element method. However, it is possible to have an estimation of leakage inductance using different analytics methods (See **Footnote 1**). Among these methods the one named "energy method" presents the most accurate evaluation of the leakage inductance. The equations given by this method are shown and used below for the evaluation of the short circuit impedance z_t.

We know that short circuit transformer impedance (Z_t) in ohms is given by[2]:

$$Z_t = \frac{z_t(\%)}{100}\frac{{U_{1r}}^2}{S_n}$$

And[3]

$$Z_t \cong X_t = 2 \cdot \pi \cdot f \cdot L_{lk}$$

…where R_t is neglected as the $X_t >> R_t$ for large transformers.

Hence, from these equations above and also considering the leakage inductance (L_{lk}) given by the following equation[4] (see **Figure 4**):

$$L_{lk} = 2\pi\mu_0 N^2 * \left(\frac{D_1 \ e_1}{3} + \frac{D_2 \ e_2}{3} + D_{12} \ e_{12}\right) * \frac{1}{H} \quad (4)$$

…we obtain the short circuit impedance of the transformer[5]:

$$z_t(\%) = K * \left(\frac{D_1 \ e_1}{3} + \frac{D_2 \ e_2}{3} + D_{12} \ e_{12}\right) * f * (NI)^2 * \frac{100 * n_c}{H * S_n} \quad (5)$$

Where:

z_t = transformer short circuit impedance (%)
K = coefficient
D_1, D_2 = average diameters of respectively MV, HV windings (mm)
D_{12} = average diameter of the gap between the windings (mm)
e_1, e_2 = thickness of MV and HV windings respectively
e_{12} = gap between the windings (mm)

[2] Robert M. Del Vecchio Bertrand Poulin Pierre T. Feghali Dilipkumar M. Shah Rajendra Ahuja, Transformer Design Principles : With Applications to Core-Form Power Transformers, Second Edition, Edition 2, CRC Press, 2 June 2010

[3] Standard IEC 60076-8 - Power transformers – Application guide, 1997

[4] C57.12.10-2010 - IEEE Standard Requirements for Liquid-Immersed Power Transformers

[5] Standard IEC 60076-1- Power transformers – General, 2011

f = frequency of network (Hz)
NI = ampere-turns of HV or MV winding
n_c = number of columns of stacked transformer
H = height of HV windings (mm)
S_n = transformer nominal apparent power (kVA)

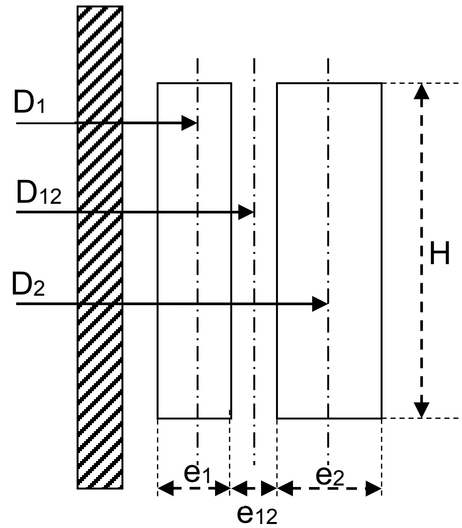


Figure 4
Axial structure of simple 2 windings

In order to receive a quotation, customers have to specify the value of z_t in % as well as other key parameters that define the transformer specification (V_{1r}, V_{2r}, S_n, connection group, etc.). The manufacturer will try to achieve the most cost effective transformer design by adjusting:

- Winding geometrical parameters:
  - number of turns (z_t is proportional to the square of the number of turns),
  - height (z_t is proportional 1/height),
  - gap between windings,
  - winding diameter
- Resistive part of the winding (for resistive part of short circuit impedance z_t)

The magnitude of z_t has a major impact on the performance of the MV electrical network, namely:

- Magnitude and waveform of the short circuit current in the secondary side
- Voltage drop under load conditions, also known as “voltage regulation”
- Magnitude of magnetizing inrush current
- Capacity to share load between two or more transformers connected in parallel

Impact of “z_t” on MV short circuit current

The maximum short circuit current that a transformer can deliver on its secondary winding is under the 3 phase MV fault (I_{sc}) and can be calculated from its rated power (S_n), secondary rated voltages (V_{2r}), and z_t in % (see **Figure 5**) in two steps:

Step 1- Calculate secondary rated current[6] (I_{2r})

$$I_{2r} = \frac{S_n}{U_{2r}\sqrt{3}}$$

Step 2- Calculate the three phase short circuit current I_{sc}[7]

$$I_{sc} = \frac{100}{z_t(\%)} \times I_{2r}$$

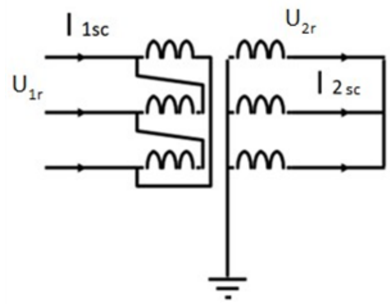


Figure 5
Calculation of 3 phase short circuit current (I_{sc}) in a delta-star connected transformer

The HV/MV transformer specification will impact the downstream short circuit current magnitude I_{sc} as well as the transient waveform determined by the X_t/R of the transformer, where X_t is equal to the transformer short circuit impedance (see equation (3)) and R is the winding resistance.

For all large power transformers, the reactive part of the series impedance is much larger than the resistive part. X_t is typically 5% to 20% and R is less than 1%[3]. The Xt /R ratio is lower for smaller transformers and low voltage transformers.
If the ratio Xt /R > 14, the installation will be outside the limits used to test MV circuit breaker short circuit interruption performance in accordance with IEC standard 62271-100. In this case, it is necessary to consult the MV circuit breaker manufacturer to verify if the device is capable of withstanding the peak current and the level of asymmetry (DC component) at contact separation when Xt /R > 14; see an example in **Figure 6**.

[6] ADEME – Distribution transformer and energy efficiency – in French, www.ademe.fr, 2012

[7] IEC 60076-5 standard - Power transformers – Part 5: Ability to withstand short circuit, 2006

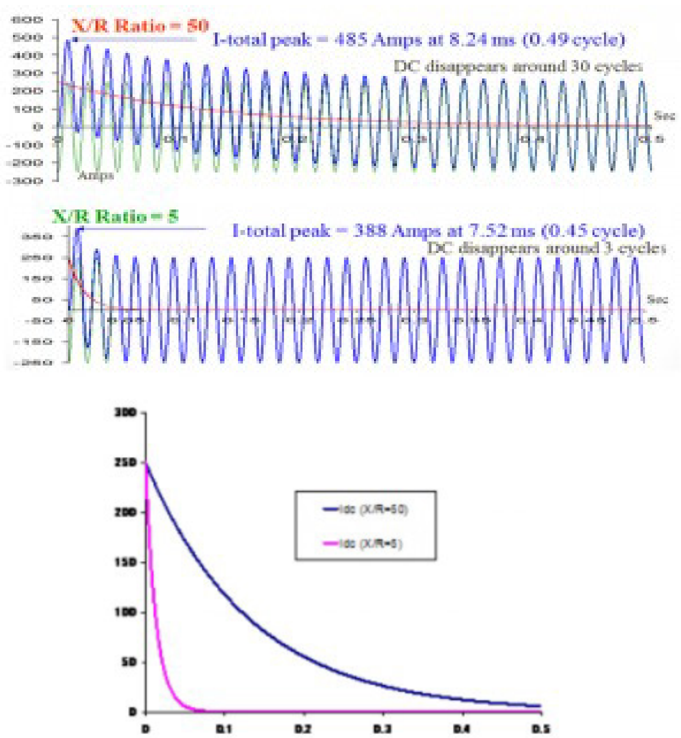


Figure 6
Short circuit current for different X_t /R ratios – top image shows AC and DC waveforms and bottom images shows the DC component

Impact of "z_t" on MV voltage regulation

The magnitude of the voltage drop as the transformer load current increases is directly proportional to Z_t, but it is also affected by the power factor (cos Φ) of the load and the transformer load losses (LL)[8].

$$\Delta U = (U_r \ \cos\varphi + U_x \ \sin\varphi) * n + (1/200) * (U_x \ \cos\varphi - U_r \ \sin\varphi)^2 * n^2$$

ΔU = voltage drop (% of rated voltage)
Ur , Ux = resistive and reactive components of voltage impedance z_t (%)
Cos φ = power factor given by the transforme
n = loading factor of transformer (p_u)

$$U_r = \frac{100 * LL}{S_n}$$

$$U_x = \sqrt{{Z_t}^2 - {U_r}^2}$$

LL = transformer on load losses (kW)
S_n = transformer rated apparent power (kVA)

If the transformer load varies the output voltage will be adjusted as close as possible to the secondary rated voltage (V_{2r}) using the on load tap changer (OLTC) acting on the primary winding to change transformer voltage ratio.

[8] IEEE C57.12.10-2010 - IEEE Standard Requirements for Liquid-Immersed Power Transformers

Designing a transformer that meets the required short circuit impedance value

The value of z_t is determined by the leakage flux, which depends on the winding ampere-turns and the leakage flux path. The transformer designer has to choose the type of windings, the geometric relationships between them to achieve the required z_t magnitude within a certain range.

To obtain a high z_t value the designer chooses windings with a higher number of turns (N), low height (H) and a wide gap between the windings. Transformers with high z_t are attractive because they reduce MV short circuit current. However, there are undesirable affects created by higher leakage flux, such as:

- losses due to eddy currents circulating in the tank and windings
- higher winding current density
- poor voltage regulation

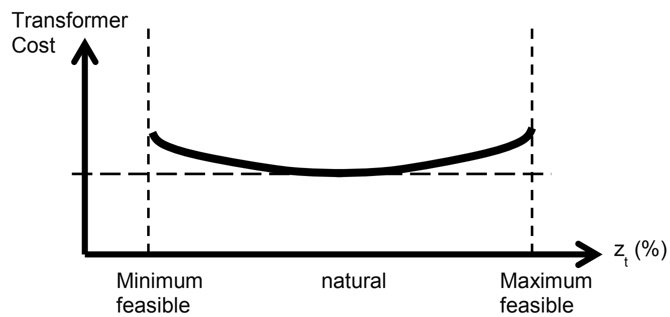
The "flat" windings required to achieve high z_t magnitude increase the magnitude of the primary winding inductance, which results in a higher inrush current during transformer energization and a higher DC component in the MV short circuit current. Manufacturing the "flat" coils needed to achieve the high z_t is expensive because it uses a complex technique known as Continuously Transposed Conductors (CTC), which requires building an assembly with insulated rectangular wires that are transposed at each turn.

To design a transformer with low z_t value the designer will choose "tall" windings with a low number of turns (N) and a narrow gap between windings. Transformers with low z_t magnitude are attractive because they have good voltage regulation required when starting MV motors direct on line (DOL). However, their most undesirable affect is the increase of the MV short circuit current magnitude. This leads to high forces between conductors (Force ~ I^2) which requires more copper section, additional spacers, and an increased number of clamps to avoid the winding displacement during a fault condition. These elements result in a higher cost and inherently lower reliability of the transformer.

In practice, the range of z_t values has upper and lower limits determined by the feasibility to manufacture it. The minimum z_t value is determined by the capacity of the clamping system to withstand the electro-mechanical forces caused by the short circuit current. The maximum value is determined by the feasibility to build "flat" coils reliably, as well as the unacceptability of higher levels of losses.

Every transformer has a "natural z_t" value which is the best compromise between cost and feasibility. This is reflected in **Figure 7** that applies for any transformer of a given value of S_n, U_{1r}, and U_{2r}.

Figure 7
Variation of transformer cost vs short circuit impedance value for a given value of S_n, U_{1r}, and U_{2r}



The global market for HV/MV transformers is ruled by two main standardization bodies:

- International Electrotechnical Commission (IEC)
- American National Standard Institute/ Institute of Electrical & Electronic Engineers (ANSI/IEEE)

Although power transformers applications and technology are virtually the same in any country, there is a significant difference in the philosophy of IEC and ANSI/IEEE standards in the way they deal with the specification of short circuit impedance. This has resulted in different market habits in the USA versus the rest of the world, although in theory, there is no technical reason for this divergence.

IEC 60076-5 standard

This standard identifies the requirements of power transformers to sustain without damage the effects of a high currents generated by a short circuit in the secondary winding for a duration of 2 seconds. On this basis it defines the minimum z_t value for a given range of HV/MV transformer nominal apparent power Sn without any reference to primary and secondary rated voltage as illustrated in **Table 2** below:

Table 2
Minimum z_t values according to the IEC 60076-5 standard

S_n (MVA)	Minimum z_t
6.3 to 25	8%
25 to 40	10%
40 to 63	11%
63 to 100	12.5%

IEC Standard does not provide a “recommended value” for z_t. Instead, it says that the z_t specification is subject to an agreement between the end user and manufacturer.

IEEE C57.12.10 standard

This standard written by the Institute of Electrical & Electronic Engineers (IEEE) and published by ANSI uses a different philosophy as it provides a “recommended” value of z_t for a range of primary winding lightning impulse voltage withstand known as Basic Insulation Level (BIL), which effectively corresponds to the rated primary voltage U_{1r}. It also takes into account whether the transformer is equipped with an on-load tap changer (OLTC) or not. IEEE C57.12.10 standard identifies two types of power transformers according to rated primary voltage (category I < 69 kV and category II between 115 kV and 765 kV). An excerpt of the voltages that are of interest in this paper is shown in **Table 3** below.

Table 3
Recommended z_t values according with IEEE C57.12.10 standard

BIL	Recommended z_t without OLTC	Recommended z_t with OLTC
350 kV	8%	8.5%
550 kV	9%	9.5%
750 kV	10%	10.5%

It is interesting to notice that IEEE C57.12.10 makes no link between transformer nominal apparent power (S_n) and short circuit impedance (z_t), which in practice are strongly dependent as shown in the first equation above. The IEEE standard z_t recommended values are close to the IEC minimum values.

A small footnote in IEEE C57.12.10 indicates the z_t value can be subject to agreement between the end user and manufacturer, effectively allowing users to choose any z_t value that is feasible to manufacture.

USA vs. the Rest of the World

The different philosophies of IEC and ANSI/IEEE standards have generated a noticeable gap between the z_t values commonly specified in the USA market compared to the countries using IEC standards which leads to lower values of z_t in USA market. This results in higher level of short circuit current and hence more expensive HV/MV transformer and MV installation in North America compared to countries using IEC standards (other parameters than z_t remaining the same).

Additional aspects of specifying HV/MV transformers

Although HV/MV transformer z_t has the highest impact on cost and performance of the electrical network in a large site, it is also important to understand the elements to take into account when specifying other HV/MV transformer parameters.

Transformer overload capacity and life expectancy

Overload capacity is determined by the oil temperature and hot spots. Oil temperature should be kept below 100°C during operation while the average winding temperature should remain below 85°C for standard paper insulation.

Copper and eddy current losses are converted into heat which increases the temperature of active parts (core & windings), construction parts (clamps, tank) and the mineral oil. This heat has to be dissipated by the cooling system. The cooling intensity can be increased proportionally to the rated power by using radiators (natural air flow) or boosting it by the use of fans (forced air flow), or oil pumps that cool the oil directly (forced oil flow). The notations used in the liquid-immersed transformer cooling method specification are shown in **Table 4** below:

Table 4
Transformer cooling methods

Internal cooling medium	Circulation mechanism for external cooling medium	External cooling medium	Circulation mechanism for external cooling medium
O= oil, fire point ⩽ 300 °C	N=natural	A=air	N=natural convection
K= insulating liquid, fire point > 300 °C	F=forced	W=water	F=forced circulation (fans, pumps)
L= insulating liquid, no measurable fire point	D=forced & directed		

Hot spots occur in certain parts of the windings when the current density is high. There will be a significant reduction of the transformer expected life if the hot spot exceeds 120°C. Hence, rate of loss of life is doubled for every 8°C over 120°C, but also there is a gain in lifespan when the temperature is less than 120°C.

The transformer is considered to have reached the end of life if the paper insulation characteristics have deteriorated to the extent where the probability of failure becomes unacceptable. Modern on line monitoring equipment based on dissolved gas chromatography are a very effective way to have an early warning in case of insulation deterioration as the result of hot spots.

Transformer losses

They are classified as no-load losses (NLL) and load losses (LL). No load losses are generated by the working flux interaction with the transformer magnetic core. They include hysteresis and eddy current losses which are dependent on:

- Voltage (dramatic increase with voltage as flux density reaches saturation)
- Frequency
- Magnetic core design (steel properties, lamination thickness, mass)

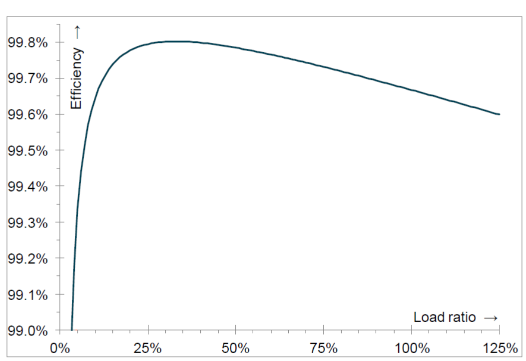
Most transformers are always energized therefore the no-load losses are always present and they are independent of the choice of z_t. Load losses are current dependent and can be of two types:

- Ohm losses: current flowing through the windings causes resistive heating of the conductors (are proportional to I^2 R, where R is the winding resistance)
- Stray losses: generated by penetration of stray leakage flux in the steel tank and shields and inside the windings and connections, which will give rise to eddy currents and converted to heat

All these parameters will vary for high z_t designs due to the transformer geometrical modifications (increase or decrease of the losses) but generally we could have an increase of the losses for a higher z_t. This is found in the case where we are looking for the minimization of the transformer cost, but is possible by design to keep the same level of the losses independent of the z_t increasing (with a small additional cost).

All these elements should be taken into account by considering the transformer total cost of ownership (TCO), a calculated function of the capital cost and total cost of losses over a determined time period. Most customers specify low loss transformers to achieve their energy efficiency targets, which could pose a limit to the z_t maximum value. The global efficiency of the power transformer is also dependent on the load ratio (see **Figure 8** for a medium power transformer) and the power factor.

Figure 8
Variation of transformer efficiency vs load ratio



Eco-design EU directive

European Union (EU) is implementing its "20-20-20" program by 2020 with the main aim to:

- Reduce greenhouse gas emissions by 20%,
- Reduce energy consumption by 20%,
- Have renewable energy represent at least 20% of total energy production

One major topic concerns reducing the power transformer losses that represents today about 2.5% of total EU energy consumption. Directive 2009/125/EC of the European Parliament established a framework for the setting of "EcoDesign" requirements for energy related products. The directive imposes two major objectives on transformers:

- Reduce electrical losses (1st step in 2015/ 2nd step in 2021)
- Clarify and make performance indicators more visible:
    - The minimum A_o, C_k or B_k classifications for transformers from 25 kVA to 3150 kVA
    - Minimal PEI ratio (Peak Efficiency Index) for power transformers, see **Tables 5 and 6**

Table 5
Minimum PEI ratio for oil immersed power transformers

Rated Power (kVA)	Phase 1 (01/07/15) Minimum PEI	Phase 2 (01.07.21) Minimum PEI
3150 < Sr ⩽ 4000	99,465	99,532
5000	99,483	99,548
6300	99,510	99,571
8000	99,535	99,593
10000	99,560	99,615
12500	99,588	99,640
16000	99,615	99,663
20000	99,639	99,684
25000	99,657	99,700
31500	99,671	99,712
40,000	99,684	99,724

Table 6
Minimum PEI ratio for oil immersed power transformers

Rated Power (kVA)	Phase 1 (01/07/15) Minimum PEI	Phase 2 (01.07.21) Minimum PEI
3150 < Sr ⩽ 4000	99,348	99,382
5000	99,354	99,387
6300	99,356	99,389
⩾ 8000	99,357	99,390

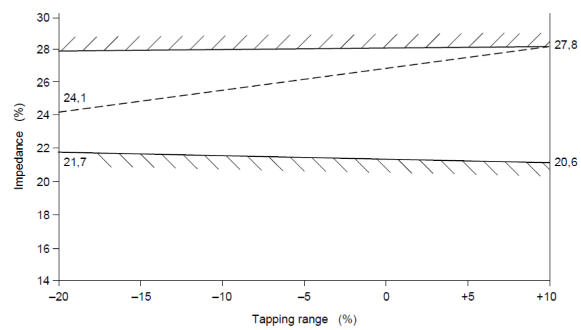
On load tap changer (OLTC)

On Load tap changers (OLTC) are designed to change the transformer voltage ratio under load. They can vary the primary winding number of turns in, for example[9] (±4) steps of ±2.5 % each. It is important to provide OLTC if the installation load varies regularly, and particularly if a transformer with a high z_t is chosen as it will help compensate the poorer voltage regulation inherent to this type of design.

Also the z_t impedance is done for the nominal tap, the variation of its value has to be considered in the power system design. For transformers with no tappings exceeding a voltage variation of ±5 % from the principal tapping, the short-circuit impedance of a pair of windings shall be specified at the principal tapping only. This one could be precise in ohms per phase Z or in percentage terms z referred to the rated power and rated voltage of the transformer[9].

For transformers with tappings exceeding a voltage variation of ±5 % from the principal tapping, impedance values expressed in terms of Z or z shall be specified for the principal tapping and the extreme tapping(s) exceeding 5 %. On such transformers, these values of impedance shall also be measured during the short-circuit impedance and load losses test. An example of the short circuit impedance variation vs plot number is done in the **Figure 9**.

Figure 9
Short circuit impedance variation vs tapping range (plot number)



Example transformer design

This typical example of HV/MV transformer specification was chosen to illustrate the points above.

U_{1r} = 132 kV +/- 10 % with 550 kV BIL
U_{2r} = 11 kV
S_n = 40 MVA
Connection group: Dy11
NLL = 25 kW
LL = 158 kW

The nominal current on the 11 kV side will be I_{2r} = (40 x 106) / ($\sqrt{3} \times$ 11x 103) = 2 100 A. The minimum value of z_t recommend by IEC standard is 10%, which will give a short circuit current of 21 kA on 11 kV. The “natural” z_t value that gives the optimized cost and electrical performance is 14%, which will give a short circuit current of 15 kA on the 11 kV side. The maximum z_t value, considering industrial capabilities, according to some manufacturers, is around 18%, which will give a short circuit current of 11.6 kA on the 11 kV side.

If the same transformer was specified according to the guidelines of IEEE C57.12.10 the z_t value of 9.5% will be chosen in accordance with the 550 kV BIL

[9] Standard IEC 60076-1- Power transformers – General, 2011

and the need for OLTC for voltage adjustment. This will give a short circuit current of 22 kA.
The difference in MV short circuit current between IEC and ANSI/IEEE installations becomes even larger for HV/MV transformers with a nominal power of S_n > 40 MVA. This is because IEC standards will recommend an increase in z_t proportional to S_n, while ANSI/IEEE standard will keep the same z_t value as it is only dependent on BIL (hence, the rated primary voltage U_{1r}).

Impact of operational practices on short circuit current level

Most HV/MV substations feeding a large site have a 2N architecture; that is, each of the two transformers is designed to take the full load. Under normal conditions the substation is operated with the MV bus section circuit breaker normally open (N/O) and the transformer incomer circuit breaker normally closed (N/C) so that the site load is shared between the two HV/MV transformers (see **Figure 2**).

In case one of the HV/MV transformers becomes unavailable, the automatic transfer switch (ATS) will automatically open the incomer and then close the bus section MV circuit breaker after a time delay < 1 sec. Following a short supply interruption, the total site load will be fed by just one HV/MV transformer. As the ATS ensures that both transformers are never operated in parallel, the short circuit current rating of the MV network is sized based on the fault current contribution of just one transformer.

Some industrial installations with large MV motors operate both HV/MV transformers in parallel (i.e., bus section circuit breaker normally closed) in order to minimize the voltage drop on the MV busbars when large MV motors start in a direct on line fashion. Even if this is a temporary arrangement, the MV distribution network is sized for the total fault current contribution of both transformers together.

In the U.S. market the arrangement shown in **Figure 2** is known as a "main-tie-main". In the US, the common use of transformers in parallel and the use of HV/MV transformers with a lower z_t, result in MV short circuit current levels that are significantly higher than in the rest of the world. This fact becomes apparent when comparing ANSI and IEC MV circuit breaker market share data by rated short circuit current (see **Figure 10**). Only 25% of the U.S. MV circuit breaker market is < 25 kA rated short circuit current level while in the "Rest of World" this proportion increases to 65 %. Equally, the largest proportion of US MV switchgear market is 40 kA (> 50%) and there is even a small portion of application that uses 63 kA short circuit current while this performance is rarely requested in IEC installations.

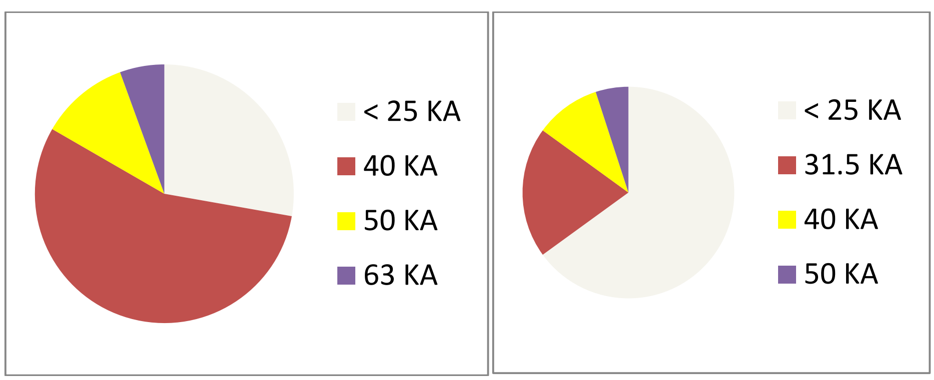


Figure 10
A comparison of MV circuit breaker market split by short circuit current rating. Left chart shows U.S. market with ANSI/IEEE standard. Chart on the right shows RoW using IEC standard.

The cost of the MV electrical distribution installation increases dramatically when the MV short circuit current magnitude exceeds 25 kA (see **Figure 11**), as it depends the copper section used in switchgear and cabling, as well as the reinforced clamping required to withstand the electromechanical forces, both of which are I^2 dependent.

In many cases, we have observed the HV/MV transformer, MV switchgear, and the cabling are all specified and ordered separately. Often the z_t value requested in tender documents results in a MV short circuit current level slightly above 25 kA, forcing the use of 31.5 kA rated MV switchgear. **Our experience is that customers are unaware that significant cost saving could have been achieved by marginally increasing the HV/MV transformer z_t value specified.**

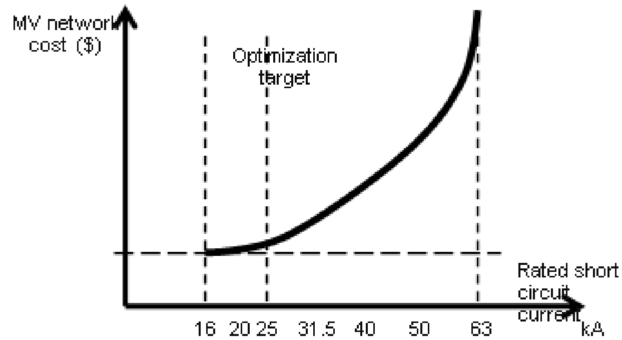


Figure 11
Cost of MV switchgear and cables as a function of rated short circuit current

Large colocation data center case study

An example of optimized large data center (IEC type) for colocation companies with an emphasis on redundancy, time to market (TTM), and the initial capital expenditure (CapEx) is presented below. The data centre is to be built out in twelve increments of 3.8 MW blocks. The data centre is designed for a maximum demand of 80 MVA, which requires a connection to the electric utility's high voltage (HV) sub-transmission network. Depending on the country, the supply voltage can vary from 90 kV (e.g. France), to 110 kV (e.g. Finland), and up to 132 kV (e.g. UK). The total power of 80MVA is provided via redundant 2N 40 MVA transformers and electrical distribution architecture presented in **Figures 12 and 13**. A comparative TCO analysis is conducted in the following few paragraphs with two different scenarios defined as:

a) Case 1: 4 x 40 MVA transformers with a z_t = 12 % 132 kV/10 kV with a power system I_{sc}=31,5 kA, close transition
b) Case 2: 4 x 40 MVA transformers with a z_t = 17 % 132 kV/10 kV with a power system I_{sc}=25 kA, close transition

We assume both transformers have the same losses (same PEI) as compliant with the EcoDesign rules mentioned previously.

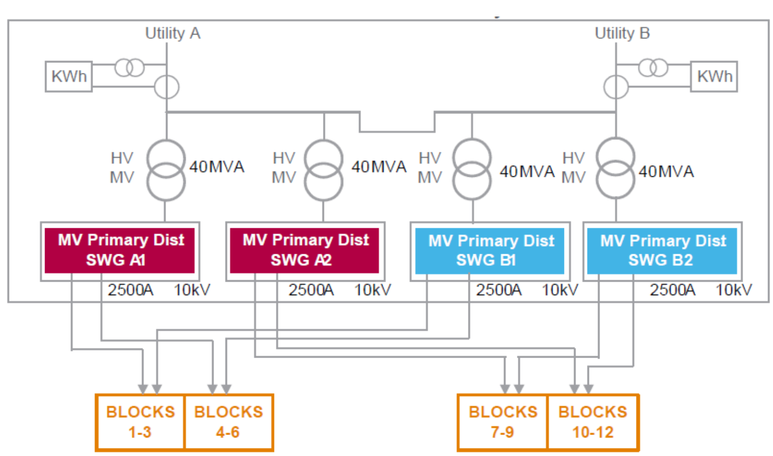


Figure 12
HV/MV Substation and Primary MV Distribution for the case study

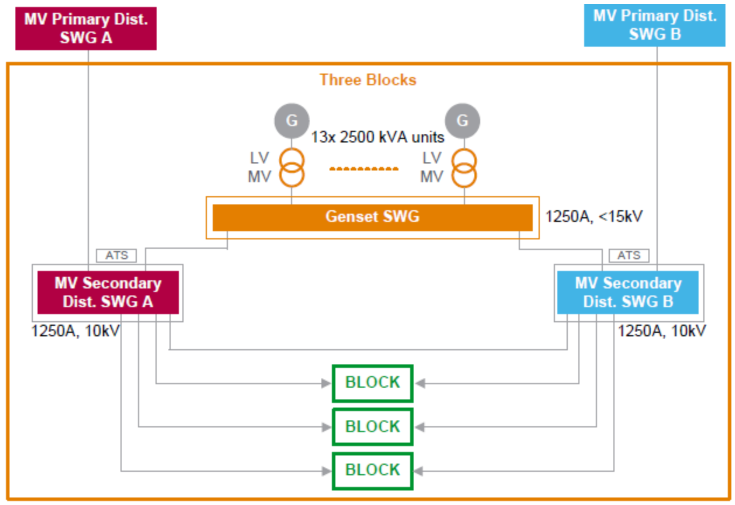


Figure 13
Secondary MV distribution for the case study (here represented only for 3 IT blocks)

Total Cost of Ownership (TCO) approach and assumptions

Using the definition of TCO as presented above (capital expense plus operating losses of a given period of time), we consider a comparative study period of 20 years, and assume that only the capital cost (transformers, MV equipment and cabling) and cost of electrical losses (transformers and cables) could be influenced by the modification of the transformer short circuit impedance and short circuit current withstand on the MV equipment. Hence the TCO for a 20-year period is defined as (total transformer yearly losses cost formula[6]):

$$TCO = Nr \times Tcapex + Nr \times Tylc \times 20 + Mcapex + Ccapex + Cylc \times 20$$
$$Tylc = Ec \times (NLL + LL \times Kf^2) \times 8760$$
$$Cylc = Ec \times CL \times 8760$$

Where:

Tcapex : transformer capital cost, [ ]
Nr : number of medium power HV/MV transformers
Tylc : total transformer yearly losses cost, [ ]
Mcapex : MV electrical distribution equipment capital cost, [ ]
Ccapex: MV cabling capital cost, installation included, [ ]
Cylc : total cables yearly losses cost, [ ]
Kf : transformer load factor
NLL : transformer no-load losses, [kW]
LL : transformer load losses, [kW]
CL : total cables losses, [kW]
Ec : energy cost, [/kWh]

a) Case 1: 4 x 40 MVA transformers with a z_t = 12 %
Transformer parameters:
U_{1r} = 132 kV +/- 10 % with 550 kV BIL
U_{2r} = 10 kV
S_n = 40 MVA
z_t = 12 %
Connection group: Dy11
NLL = 72 kW
LL = 120 kW

MV electrical distribution (equipment and cables) parameters:
Isc = 31,5 kA 1s or 3s

Un = 10 kV

b) Case 2: 4 x 40 MVA transformers with a zt = 17 %

Transformer parameters:
U_{1r} = 132 kV +/- 10 % with 550 kV BIL
U_{2r} = 10 kV

S_n = 40 MVA
z_t = 17 %
Connection group: Dy11
NLL = 72 kW
LL = 120 kW

MV electrical distribution (equipment and cables) parameters:
I_{sc} = 25 kA 1s or 3s
U_n = 10 kV

TCO over 20 years

The TCO analysis for both cases is presented below in **Figure 14**, showing a potential improvement of 14%.

Case	20 yr TCO [pu]	TCO % Improvement
Case 1 Zt = 12%, Isc = 32,5 kA	1	reference
Case 2 Zt = 17%, Isc = 25 kA	0,86	14%

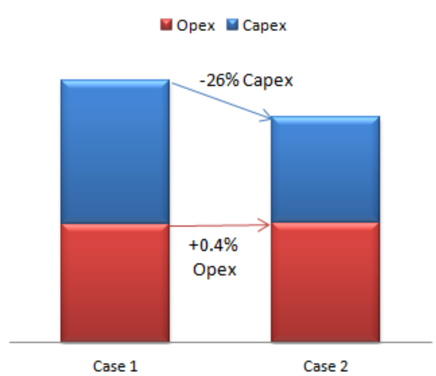


Figure 14
20 year TCO shows 14% overall cost savings using a higher impedance transformer and a lower short circuit current rating

Conclusion

End users in electro-intensive industries and large infrastructures require installations with electrical loads > 20 MVA that are connected to the utility HV transmission network. Their objective is to reduce the MV/LV electrical distribution network CAPEX in new sites, while simultaneously increasing the energy efficiency.

The optimal choice of HV/MV transformer specification, and particularly of short circuit impedance, has a major impact in the MV distribution network cost. This is clearly illustrated in the case of a typical XL data centre with 160 MVA installed capacity, where a CAPEX saving of 25% on the MV distribution installation and 14% TCO savings over a 20-year period can be achieved by optimizing the value of the HV/MV transformer short circuit impedance. Achieving this savings requires involvement of equipment manufacturers like Schneider Electric at the initial stage of the project design.

About the authors

Juan Tobias in 1977 obtained BSc in Electrical Engineering from Universidad del Sur (Argentina) and in 1984 received a PhD in Electrical Engineering from Strathclyde University (Glasgow, UK). In 1984 joined Buenos Aires electric utility company. In 1988 moved to UK to join Yorkshire Switchgear, Medium Voltage electrical equipment manufacturer. The company was acquired by Schneider Electric in 1989, where he held several positions in R&D, Product Marketing, Business Development Manager and Sales. In 2005 he moved to Schneider Electric corporate organization in France to take the position of Vice-President Market Development for Energy, Buildings & Infrastructure. In 2007 he was appointed Vice-President Strategic Marketing for MV Switchgear Business. Since 2012 he holds the position of Vice President- Segment Solution focusing on MV/LV electrical distribution for XL data centres, Oil & Gas and Mining applications. Since 2012 he has been a visiting lecturer at the Grenoble Graduate School of Business, teaching postgraduate students International Marketing Management and Innovation. He has authored over 40 international publications in the technical field of electrical power distribution.

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Daniel Radu was born in 1975 in Bucharest, Romania. He obtained a Ph.D. degree in Electrical Engineering, in 2004, from the University “POLITEHNICA” of Bucharest, Romania. From 1998 to 2002 he has been assistant professor of Electrical Engineering in the same University. Follow this was involved in research and teaching activity with Power Engineering Laboratory of Grenoble – LEG, France. He is currently with Schneider Electric, France, since 2006. His interests include shore connection systems, large data center applications, low and medium voltage power systems transient analysis, power systems modelling, LV and MV equipment and system design. He published more than 30 international papers in conferences proceedings and journals and several white papers in the field of Electro-Intensive Applications. He holds several patents in the field of power quality, frequency conversion applications and power systems. Also he participates as technical expert to TC18 & TC23 committees of IEC and is IEEE member since 2006.

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