OPTIMIZED HIGH-VOLTAGE ARCHITECTURES FOR LARGE SCALE INDUSTRIAL ELECTRIFICATION

Paper No. EUR25_30

Shailesh CHETTY
Shell Global Solutions
Grasweg 31, 1031 HW
Amsterdam
Netherlands

Abstract - Traditionally, electrical infrastructure designs prioritized reliability, availability, and operational flexibility. However, as industrial processes shift towards green energy, electrical demands have surged fourfold, complicating designs and increasing CAPEX allocation to electrical infrastructure. Despite a decrease in overall energy consumption, electricity usage and infrastructure loading are rising. Significant upgrades, renewals, or extensions of electrical infrastructure are often required to meet these demands.

To adapt, we must shift from traditional conservative designs to leaner ones that still meet process needs. This paper highlights an EHV/HV to MV design approach and how architecture selection with power transformers can improve CAPEX and OPEX. It discusses the application of transformers and adaptable architectures for large-scale electrified industrial complexes and upstream green hydrogen projects (>250MW).

Index Terms — Electrification, Design, Transformer, Transformer life, CAPEX, OPEX, Optimization

I. INTRODUCTION

The entire energy ecosystem is undergoing a radical transformation. It is important to note that attractive electricity prices are not consistent throughout the year, especially when compared to fossil energy (natural gas), due to the intermittent availability of renewable energy resources.

This means that strategizing a decarbonization plan becomes increasingly complex when aiming for optimal economics. Planners must consider factors such as project CAPEX, energy (electricity, natural gas) prices, the CO_2 footprint of energy (electricity, natural gas), availability, and reliability, which can result in multiple scenarios.

As an initial read, references [1] and [2] introduce readers to methods for decarbonizing an industrial facility and outline a three-step approach to achieve this goal. This paper highlights the requirements for the high voltage side of electrical infrastructure and proposes a strategy for planning high voltage receiving substations to meet large scale electrification needs.

NOMENCLATURE

AIS	Air-Insulated Switchgear
BESS	Battery Energy Storage System
CAPEX	Capital expenditure
EHV	Extra High Voltage
GIS	Gas-Insulated Switchgear (GIS)
gH_2	Green hydrogen
gNH_3	Green ammonia
ONAN	Oil Natural Air Natural
ONAF	Oil Natural Air Forced
OFAF	Oil Forced Air Forced
OPEX	Operational expenditure
RAM	Reliability Availability Maintainability
TCO	Total cost to ownership
TES	Thermal Energy Storage

II. DEMAND DRIVERS IN ELECTRIFICATION AND THEIR ARCHITECTURAL REQUIREMENTS

A. Demand drivers for Electrification

There are several demand drivers contributing to the increasing demand for electrical energy. These drivers span various sectors and applications, each contributing to the overall growth in energy consumption. Some of the most significant demand drivers include:

1. EV Mobility
2. Electrification of Industrial Processes
   a. Electrification of large compressor or pump (replacement of gas / steam turbines with motors)
   b. Electrification of utilities (process heat, steam etc.,)
   c. Electrification of core processes (e-cracker, e-SMR, e-furnace)
3. Power-to-X (gH_2 and gNH_3)
4. Carbon Capture Systems
5. Hyperscale Data Centres

B. Addressing these drivers – the challenge ahead

Traditionally, remote and some energy-intensive industrial processes have relied on in-house power generation and operated off-grid / island-mode. However, as clean electrical energy becomes a key enabler for systematically decarbonizing facilities, there is a significant shift in the energy value chain. In these scenarios, new and upcoming facilities are more likely to be grid-connected, making high voltage receiving end substations a critical part of the infrastructure.

It is important to recognise that many existing electricity networks were not originally designed to support the scale of modern industrial load centres. When grid capacity is insufficient to transfer electricity from generation sources to end users, congestion occurs, resulting in extended lead times for new connections and ultimately hindering the pace of the energy transition.

To support this transition, industrial electrical systems are increasingly incorporating energy storage solutions, either power-to-power systems such as BESS or power-to-heat systems like TES. However, integrating these technologies necessitates higher-capacity (MVA) intake substations. This adds complexity to the design process, requiring careful analysis and optimisation to align with load characteristics and minimise overall electrical infrastructure costs.

C. Architectural needs

Electrical designs are generated to meet specific reliability, availability, and maintainability requirements. The electrical architecture needs for each demand driver differ. In traditional industrial facilities, achieving high levels of Reliability, Availability, and Maintainability (RAM) often involves implementing 100% redundancy in the electrical power system network, particularly for essential services.

However, as the overall energy demand shifts increasingly toward electrical loads, redundancy strategies are evolving. Instead of defaulting to full (100%) redundancy, designs are now tailored to meet specific site RAM requirements more efficiently.

This approach mirrors practices in process systems, where 2x100% redundancy is typically considered cost-prohibitive. Instead, configurations such as N+1 or N are adopted based on RAM analysis. A similar rationale can be applied to the architectural design of electrical power systems.

Redundancy can be categorized at different levels:

a) System-level redundancy: Built into the product itself, such as an additional module providing hot standby capability.
b) Power distribution network-level redundancy: Implemented through the main electrical infrastructure to ensure continuous power supply to critical electrified loads.

This layered approach allows for more cost-effective and RAM-optimized electrical system designs.

Table I summarizes the electrical architecture needs for various demand drivers.

TABLE I
ELECTRICAL ARCHITECTURE NEEDS

Megatrend	MW Needs	Redundancy Needs	HV/EHV
EV Mobility	Charging stations as high as 10 MW	System level	N
Electrification of large compressor or pump	MV Drives reaching up to 100 MW	System & power network level	Y
Electrification of utilities	Utilities proportion depend on industrial facility	System & power network level	Y
Electrification of core processes	Could start from 200MW to a few GW's	System & power network level	Y
Power-to-X	Could start from 200MW to a few GW's	System & power network level	Y
Carbon Capture Systems	500 MW – 1 GW	System level	Y
Hyperscale Data Centres	500 MW – 1 GW	System & power network level	Y

III. KEY ELEMENTS FOR PLANNING AN OPTIMIZED HIGH VOLTAGE BACK BONE IN LARGE FACILITIES

Primary Network – Source / Generation

The electrical energy demands of an industrial site are met through a combination of onsite or offsite generation, with or without the support of public utilities.

1) *Onsite generation: A*n electrical network, self-supporting, no coupling to the public network and could be of below combinations:
   a) Combined cycle power plant (Power Only)
   b) Combined heat and power plant (Power & Heat)
2) *Offsite generation*: Similar to onsite system however energy is transferred from a different site via overhead lines or cables to the industrial facility (over-the-fence).
3) *Public Utility:* A public utility network is generally available and can be used in conjunction with onsite generation. This availability enhances energy security for consumers.

For this paper, we explore optimization areas for a large industrial network that is 100% supplied by a public utility. High voltage electrical systems design and optimization are inherently multi-dimensional. Achieving successful optimization requires a comprehensive approach that involves the following elements:

Element #1 : Demand Plan, site layout and accessibility
Element #2 : Power distribution, operation criticality and redundancies
Element #3 : Design standardization, with minimum customization to meet local rules

Depending on the project scenario, the end user might be responsible for installing transmission links or using public utility infrastructure to tap into power sourced through a Power Purchase Agreement. In the first scenario, the end user has full control over the infrastructure, but the design must adhere to guidelines set by transmission authorities.

A simplified approach is illustrated in Fig.1(a), showing the entire high voltage (HV) system divided into two bricks: one connected at grid-specified voltages, and the other transformed to the main backbone for the industrial facility.

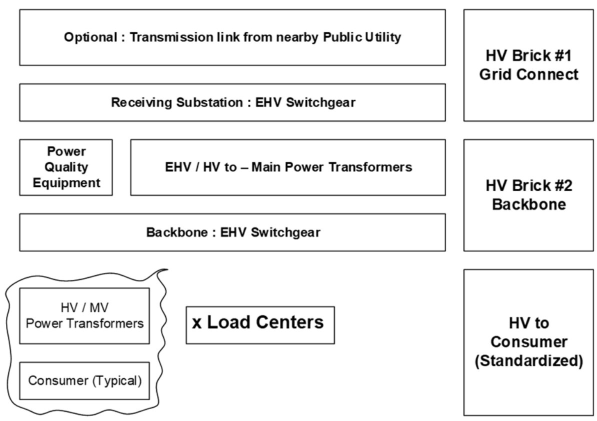

Fig. 1 Overall block diagram of electrical distribution network

In the design process, we can have two sets of high voltage switchgears: one for the receiving substation, indicated as HV Brick #1, and the other at the transformed voltage, indicated as HV Brick #2.

We now explore the various elements that influence design decision-making and are directly related to system optimizations.

A. Element #1

Demand Plan

The following steps are taken to establish demand plan for power system

1) Establishing power demand

Estimating power demand can be complex, especially when the system includes energy storage such TES and/or BESS. In both storage scenarios, electrical energy is required as input, with the output being electricity for BESS and heat for TES.

Normal and peak loads are two important factors needed to size electrical systems. Load demands are estimated for all possible operating scenarios during the planning stage.

Load = (Electrified Load) + (Utilities Load) + (Charge Rate of Electrical Energy for Energy Storage in TES*) + (Charge Rate of Electrical Energy for Energy Storage in BESS*)

*The charge rate needs to be considered in peak demand requirements for the grid, but can be ignored for normal demand.

Some other critical questions for load planning are:

a) Where are the major load centres?

b) What types of load (e-furnace, e-boiler, large drives, electrolyzer etc.)?

c) How much power is required at various phase of project ?

d) What are desired (acceptable) levels of outage frequency and power quality ?

e) Preferences such as centralized or de-centralized power distribution ?

2) Choice of Critical parameters: Receiving Voltage & Short Circuit Current

Rated voltage is a critical parameter, primary (grid connection) voltage is defined by facility MW definition and local utility guidelines. Selection of voltage can be challenging sometimes, as it is also tied with grid rules, expansion plan, availability of grid infrastructure near site.

The choice of short circuit current for electrical systems at the receiving (intake) substation is largely influenced by public utility connection rules and its expansion plan.

Note that for a chosen receiving voltage level provided by the utility, short circuit parameters are generally specified by utility interconnection requirements, leaving no opportunity for optimization. However, optimization scenarios are possible in situations where multiple voltage levels are available.

In some cases there could be more than one possible system short circuit level specified by the utility (Table II), hence in early planning stage, when details are not available, it is advised to select a lower value for system design and higher value for equipment CAPEX. Thus leaving scope to power system engineer to optimize further during detail engineering.

Some questions which are worthy to be raised during this stage :

a) Is project definition fully firm or we might foresee a future expansion, and how will it affect the network?

b) Public Utility options for receiving load connection and its waiting periods

c) Public Utility rules for a short-term overload, and its impact to selected parameters

d) Public Utility assurances for outage frequency

e) Availability of time-limited, reduced-availability grid connections at lower cost and/or faster availability

Site layout and accessibility

Site location plays a crucial role in making critical decisions related to project optimizations. Grid components are large structures that are often transported via road, rail, or shipped from other parts of the world.

Site constraints can influence the selection of major equipment:

1) EHV/HV Switchgear: AIS or GIS

There are two primary types of high voltage switchgear technologies: Air-Insulated Switchgear (AIS) and Gas-Insulated Switchgear (GIS). AIS uses air as the primary dielectric medium, while modern GIS employs non-SF_6 gas, offering a more compact, reliable and environment friendly solution.

GIS offers several advantages over AIS for a premium price, including lower life cycle costs, higher availability, a smaller footprint, and ease of transport. A detailed summary can be found in section 2 of [3].

2) Power Transformers

Transporting high-power transformers to remote sites via rail or road poses significant logistical challenges, primarily due to dimensional constraints. These limitations must be carefully considered during the specification phase, as key parameters—such as MVA rating, cooling method, impedance, and losses not only affect electrical performance but also directly influence the physical dimensions of the transformer.

At the extra-high voltage (EHV) level, the use of single-phase transformers can offer logistical and operational advantages. By standardizing the physical dimensions of these units, it becomes feasible to maintain a single spare transformer on-site, thereby enhancing system reliability and reducing downtime in the event of a failure. In certain scenarios, autotransformers may also be a viable option, subject to manufacturing feasibility for the specified MVA and voltage ratings.

A detailed analysis of how transformer technical parameters impact overall dimensions and performance is presented in Section IV. For further guidance on procurement strategies and best practices, readers are referred to CIGRE Technical Brochures [4], [5], and [6], which provide comprehensive insights into transformer specification and acquisition processes.

B. Element #2

Power distribution, operation criticality and redundancies

Operation criticality and necessary redundancies directly impact the power distribution concept. At this stage, the system is viewed as a whole, encompassing HV Brick #1, the Main Power Transformer, and HV Brick #2. The major question to address is justifying the added cost to maintain process continuity. These concepts are illustrated in Figure

2.

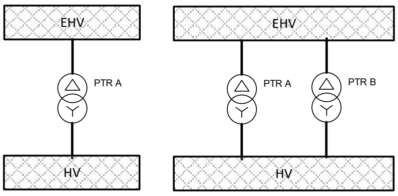

Fig. 2(a) Radial (left) and 2(b) dual redundant (right)

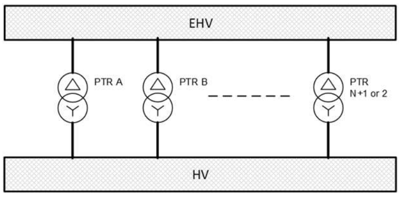

Fig. 2(c) N+1/N+2 configuration

Choice of HV architecture : circuit / switching arrangements

Various circuit and switching configurations are available for high-voltage substations, and the selection process is guided by multiple factors, including reliability of power supply, spatial constraints, capital expenditure, and operational and maintenance costs. The optimal arrangement is typically a balance between technical performance and economic feasibility.

A prominent example where high availability is critical is in hyperscale data centres. These facilities are engineered with robust electrical infrastructure and advanced automation systems to ensure uninterrupted operation. In this context, substation and power system designs must adhere to stringent reliability standards, often aligned with Tier classifications. Tier III systems are required to be concurrently maintainable, allowing maintenance without service interruption, while Tier IV systems must be fully fault-tolerant, capable of sustaining operations even in the event of multiple failures.

A detailed discussion of the various EHV/HV switching configurations and the criteria for their selection is provided in Section III. C.

Choice of Main Power Transformers

Main power transformers are critical assets in high-voltage substations, and their sizing is a key design consideration due to their substantial CAPEX. Selecting the appropriate redundancy strategy is essential to balance reliability with cost-effectiveness. Common redundancy configurations for large power transformers at grid-connected substations include “N (no redundancy), 2N (fully redundant), N+1 or N+2 (partially redundant)”.

While higher utilization (load) factors are generally preferred to reduce initial investment, it is crucial to incorporate adequate design margins. These margins ensure operational flexibility and system resilience during contingency scenarios. Detailed transformer sizing methodologies are discussed in Section IV. & V.

C. Element #3

Design standardization, with minimum customization to meet local rules

It is understood that upstream connection electrical parameters depend on grid rules, however design methodology such as transformer arrangement and high voltage backbone are up to the system designer to achieve the intended safe process operation within project timelines.

Grid Code Compliance: The design must comply with grid codes. Assessment studies are conducted using RMS or phasor analysis domain software, and detailed instantaneous switching and voltage insulation coordination in EMTP domain software. Compliance with the Grid Code in all scenarios is required for grid connection.

From the facility, at EHV level short circuit contribution is not expected to be significant from loads (e.g., process heating, 1Q Mega MV Drives) other than large directly-connected synchronous / induction machines. However, in-house energy sources such as gas and steam turbine generators, BESS contribute to short circuit current.

Table II summarizes typical practices adopted by energy (utility) companies when establishing power connections to industrial facilities. It outlines the applied voltage levels and short-circuit current parameters at the receiving EHV (Extra High Voltage) substation, based on the facility’s load demand.

TABLE II
VOLTAGE & SHORT-CIRCUIT CURRENT PARAMATERS WITH REFERENNCE TO LOAD CAPACITY

Size	Load Limit of Receiving Substation	Voltage Level	Short Circuit Current
Extra Large	> 1000 & up to 2500 MVA	400 kV	50 kA or 63 kA
Large	> 500 & up to 1000 MVA	220 kV	40kA or 50 kA
Medium	>160 & up to 500 MVA	132 kV	25 kA or 31.5 kA or 40 kA
Small	Up to 160 MVA	66 kV	31.5 kA

A variety of bus switching architectures are employed in EHV and HV substations, each offering distinct advantages in terms of service continuity, maintenance availability, and operational flexibility. The selection of an appropriate configuration is a critical design decision and is typically guided by the specific functional role of the substation within the power system.

As outlined in [7], a weighted evaluation method is proposed to support configuration selection based on the substation's application. The methodology assigns weighting factors to three primary performance criteria:

1. Service Security
2. Availability During Maintenance
3. Operational Flexibility

These criteria are evaluated for the following typical substation types:

1. Substations interfacing directly with power generation facilities
2. Interconnection substations within the transmission network
3. Step-down substations (also referred to as grid supply substations)

The sum of the weighting factors for each substation type is constrained to 100%, ensuring a balanced and comparative assessment of design priorities. This structured approach facilitates a more objective and application-specific selection of bus configurations, aligning technical performance with operational requirements.

During the design phase, a systematic assessment is conducted to evaluate various substation architecture options against the minimum RAM requirements of the industrial facility. Multiple configurations may satisfy the defined RAM criteria; in such cases, the final selection is made based on project-specific considerations, including cost, space constraints, and future scalability.

As per reference [7], during design evaluation stage, below factors can be considered for step-up/down substations during design evaluation:

Step-down substation	Service Security	Availability during Maintenance	Operational Flexibility	Sum
Weight factor	0.3	0.3	0.4	1.0

Table III. provides commonly adopted architectural practices for step-down substations, reflecting industry norms and design preferences aligned with RAM performance expectations. For further reading, a detailed guidance can be found in reference [7].

Table III. architectural practices for step-down substations

TABLE III
SWITCHING BUS CONFIGURATION

Load	Circuit Configuration	Voltage Level
Extra Large	✓ 1½ breaker scheme ✓ Ring bus ✓ Double Main with Double breaker	400 kV
Large	✓ Double Main ✓ Double Main & Transfer bus ✓ Double Main with Double breaker	220 kV
Medium	✓ Main & Transfer bus ✓ Double Main	132 kV
Small	✓ H-connection ✓ Single bus ✓ Single bus with Sectionalized busbar ✓ Main & Transfer bus	66 kV

IV. THE POWER TRANSFORMER PUZZLE

The application of power transformers from a network design perspective can be highly complex, as their specifications can be influenced by various factors. This section discusses several key parameters that power system engineers can select and specify to optimize transformer performance and integration within the network.

A. Impedance & Active Loss

Transformer impedance represents the greatest impedance in the power system network, directly impacting the fault current that can flow into the industrial network. Therefore, care must be taken when defining impedance, ensuring it aligns with tapping position and the voltage profile.

Table IV summarizes the impact of transformer impedance

TABLE IV
High Impedance vs Low Impedance

Parameter	High Impedance	Low Impedance
No Load Loss	Lower	Higher
Load Loss	Higher	Lower
Mass	Lower	Higher
Short Circuit forces (internal)	Lower	Higher
Height	Shorter windings	Taller windings
Current Density	Lower	Higher

Transformer losses are a critical parameter, influencing CAPEX and OPEX. Active losses mainly consist of no-load and load losses, while reactive losses are directly related to transformer impedance. Actual losses are based on the utilization profile of each transformer.

Firstly, a load profile for industrial facility is estimated based on the intended process operation. For flexible operating assets, different scenarios (for load profiles) are possible due to factors such as demand planning, seasonal variations, and the availability of cheaper electricity. Generally, transformers at the EHV/HV receiving substation level experience fewer fluctuations from downstream process variations. However, it is still possible to encounter different load profiles.

From the load profile, based on the network arrangement and operation, we can determine the utilization profile of each main power transformer. The total active and reactive power loss during transformer operation is calculated from the sum of no-load losses and load losses at a specific load factor (or utilization profile). The no-load loss component is load-independent, whereas the load loss component is directly related to the square of the loading factor.

$$P_{NLL} = P_O + P_{CO}$$

$$L_f = \frac{S_L}{S_R}$$

$$kW_L = P_{NLL} + \left(L_f\right)^2 \times P_{LL} \qquad (1)$$

$$kvar_L = Q_0 + \left(L_f\right)^2 \times Z_t \times S_r \qquad (2)$$

where

L_f	is loading factor
P_O	is the no load losses measure at rated voltage and rated frequency, on the rated tap
P_{CO}	is the electrical power required by the cooling system for no load
P_{LL}	is the measured load loss at rated current and rated frequency on the rated tap corrected to the reference temperature
S_R	is the rated power of the transformer on which P_{LL} is based
S_L	is the actual loading of transformer
Q_O	is no-load loss (reactive) measure at rated voltage and rated frequency, on the rated tap
Z_t	is the transformer impedance
kW_L	are active losses at a specified load factor

$kvar_L$	are reactive losses at a specified load factor

Thus,

- ✓ Operating transformer at higher load factors, will attract higher active losses.
- ✓ Transformers with higher impedance can significantly contribute to reactive losses at the EHV level, thereby impacting grid intake power factor.
- ✓ Additionally, it is worth noting that restricting transformer loading to 80% could be attractive as the variable load component is kept under 64% (i.e., $80\%^2$).

Every transformer achieves its highest efficiency at a specific loading point, which can be influenced by the purchaser during the preparation of transformer specification and datasheets. However, minimum energy efficiency requirements for large power transformers are regulated. Currently, the EU Ecodesign Regulations for Transformers – Tier 2 (2021) are applicable. These regulations ensure that transformers meet minimum efficiency requirements, expressed in terms of the Minimum Peak Efficiency Index (PEI) [8].

The methodology for calculating the PEI for medium and large power transformers is based on the below formula [8]

$$PEI = 1 - \frac{2(P_{NLL})}{S_r\sqrt{\frac{P_{NLL}}{P_{LL}}}} \qquad (3)$$

All newly manufactured transformers are required to comply with Tier 2 efficiency standards. Adherence to these stringent regulations ensures compliance with the Peak Efficiency Index (PEI), a key performance metric. While meeting PEI targets transformer designers carefully optimize critical design parameters, including operating flux density, current density, and the selection of high-grade core materials, among others. This optimization not only enhances energy efficiency but also contributes to improved lifecycle performance and reduced operational losses.

B. Transformer Capitalisation of losses with CO_2 flavour

Transformer losses incur costs and are generally considered during the evaluation process when purchasing. For many years, purchasers adopted a simpler approach by specifying a minimum efficiency, primarily based on the local market's economics. This approach set a minimum bar during purchase, allowing manufacturers the freedom to innovate and offer effective solutions. Consequently, transformer procurement evolved into a practice known as evaluating the total cost which includes impact of transformer losses over its life.

This approach considers the following factors:

1. Initial cost (equipment cost)
2. Loading pattern impacts, such as average load factor or utilization profile
3. Discount rate
4. Energy cost and mid-point energy cost

As discussed in earlier section, it is possible to have several transformer designs (offers form transformer OEM's) respecting PEI guidelines. The methodology adopted for calculating the Total Cost of Ownership (TCO) for a transformer is detailed in [9] and is expressed in simplified equation as below :

$$TCO = IC + A \times (P_{NLL}) + B \times (P_{LL} - P_{CO}) \qquad (4)$$

where

IC	is the initial cost of the transformer; this cost may include installation costs such as foundation and erection costs (requires a more sophisticated evaluation)
A	is the factor representing the cost of capitalisation of no-load losses in cost per kW
B	is the factor representing the cost of capitalisation of the losses due to load in cost per kW

Also note that, power consumption related with transformer cooling (fans) are included in P_{LL}.

Increasingly, designs are incorporating CO_2 emissions over the entire project lifecycle. The emissions related with energy consumption are evaluated by arriving at transformer losses over its lifetime with the associated emission factor for the energy that is lost [12]. In developed economies, an established CO_2 tax structure must also be considered, making designs more inclusive with regard to sustainability and thus providing a more meaningful TCO.

C. Cooling

In power transformers, oil serves two primary functions: insulation and cooling. The heat generated within the transformer is absorbed by the surrounding oil and subsequently transferred to either atmospheric air or water. This heat transfer is crucial for maintaining the temperature within acceptable limits for the insulation class, thereby reducing thermal degradation and extending the transformer's lifespan. Power transformers can be subclassified into three categories based on their required MVA rating. By specifying a combination of cooling modes, such as OFAF, ONAF, and ONAN, their design can be optimized to achieve multiple ratings.

1. Lower Power Transformer ($S_R \leq 50MVA$), Generally, ONAN type of cooling, benefiting users with lower maintenance and no external constraints such as auxiliary power for fans. During the design stage, a future provision for fans can also be considered, which can increase the transformer rating while respecting the guaranteed temperature rise.
2. Medium Power Transformer ($50 < S_R \leq 150MVA$). A combined rating (ONAN/ONAF) is considered, with ONAN capability up to about 75% of the ONAF rating (from an operational point of view, transformers might still be operated under ONAN conditions).
3. Large Power Transformer ($S_R \geq 50MVA$). Either have higher number of radiators with ONAF cooling or adapt to three-stage approach by having OFAF. The three-stage approach in the cooling system provides optimized transformer configurations: ONAN cooling covers up to 60% of full load, ONAF cooling covers between 60% and 80% of full load, and OFAF cooling covers from 80% to full load.

D. Transformer Life – Thermal Aging Principles

A distribution transformer is typically expected to remain in service for a minimum design life of 25-30 years. Transformers which are part of step-down substation (Grid supply substation) are expected to operate for 40 years. This extended lifespan can be attributed to various design specifications, operating load patterns, and operational practices. Consequently, the operating life of large transformers can exceeds their design life due to its actual loading patterns and strict maintenance practices.

Transformer loading is a critical parameter, as internal heat is generated during operation and must be dissipated. Heat transfer occurs in two main areas: from the core to the oil and predominantly from the winding to the oil via its insulation. Transformers are designed so that at least one side of each insulated coil can transfer heat directly to the oil. Within the transformer, the heat transfer rate is proportional to the insulation's thermal conductivity and exposed surface area, and inversely proportional to the insulation thickness.

There are two possible options on the type of conductor insulation which are non-thermally and thermally upgraded paper. The main constituent of these materials is cellulose, an organic compound molecule made up of a long chain of glycosidic rings, typically ranging from 1400 to 1600 for new material. The degree of polymerization (DP) is the average number (n) of glycosidic rings in a cellulose macromolecule, which ranges between 1100 and 1400 for unbleached soft wood kraft before processing.

Studies have shown that tensile strength is closely related to the degree of polymerization (DP). As a paper ages during operation, the DP decreases. When the paper's DP reaches 200, it is considered to be of poor quality, marking the "end of life" for such insulating material [10] & [11].

Table V indicates the expected insulation life at aging temperatures of 80°C, 90°C, 98°C, and 110°C, Table A.2 from [10]

TABLE V
EXPECTED LIFE OF PAPER UNDER VARIOUS CONDITIONS

Paper type / ageing temperature		Expected life years			
		Free from air and 0,5 % moisture	Free from air and 1,5 % moisture	Free from air and 3,5 % moisture	With air and 0,5 % moisture
Non-thermally upgraded paper at	80^0C	97.3	26.6	8.9	14.7
	90^0C	29.3	8	2.7	6.4
	98^0C	11.7	3.2	1.1	3.4
	110^0C	3.2	0.9	0.9	1.4
Thermally upgraded paper at	80^0C	151.9	81	39.9	19.4
	90^0C	67.8	36.1	17.8	9
	98^0C	36.7	19.6	9.6	5
	110^0C	15.3	9.6	4	2.2

For further reading, refer to Figure 4 and Figure 5 of reference [10] for the expected life of non-thermally and thermally upgraded paper and its dependence on moisture, oxygen, and temperature.

Generally, for oil-type transformers, the purchaser and manufacturer agree on a transformer life at a hot spot temperature of 98°C. In this case, intentionally lowering the loading point can reduce stress on the transformer, thereby improving its lifespan. Alternatively, a cost-effective way to further enhance its life is by specifying thermally upgraded paper.

V. SYSTEM OPTIMIZATION OF A GW SCALE PROJECT

Optimization is a multi-faceted approach. Some projects focus primarily on CAPEX, while others are driven by strict timelines. However, a truly successful project balances and optimizes CAPEX, OPEX, and timelines. This holistic approach ensures that resources are used efficiently, costs are managed effectively, and project deadlines are met, resulting in a well-rounded and successful outcome.

For large projects, typically two to three concepts for main power distribution are generated and are weighed on different factors as mentioned below:

1) CAPEX: This includes the upfront costs for purchasing and installing equipment such as transformers, switchgear, and cables.
2) Costs Associated with Process Interruption: These are the costs incurred due to power outages or interruptions, which can affect productivity and lead to financial losses.
3) OPEX, Operational Costs: This encompasses maintenance costs for equipment, routine operation expenses, and administrative costs.
4) OPEX, Operational Losses from Electrical Equipment: These losses occur due to inefficiencies in transformers and other equipment (e.g., energy dissipated in conductors)

A. Optimization of CAPEX via project decisions

In certain projects, CAPEX can be optimized through modularization and standardizing equipment ratings, which can lead to more competitive offers from original equipment manufacturers (OEMs). It is important to note that while some individual equipment costs may be higher in these cases, the overall project costs are optimized.

B. Optimization through network design

Optimization through network design is a crucial step in the overall system design process. During this phase, fundamental concepts of electrical design are evaluated alongside alternative architectures, considering both mid-term and long-term power demand projections.

The outcomes of this step may suggest the selection of higher voltage levels, adjustments to short circuit current within the power system network, and the ideal placement of power quality (PQ) equipment, among other considerations.

C. Power System loss

Overall power system loss is an effective indicator for measuring network performance, as it ensures that the system's operational expenditures (OPEX) remain within benchmark figures.

Loss optimization is conducted through multiple design iterations, involving changes to the following parameters:

- ✓ System nominal voltage (Higher voltages imply lower current, thereby reducing load losses, which are proportional to the square of the current).
- ✓ Power distribution principles (single link running at

full capacity incurs significantly more losses compared to a dual link with 50% shared power).

✓ Transformer sizing, losses and impedance (note : impedance requirements can be influenced to maintain fault levels within acceptable limits).

D. Transformer Sizing

The transformers are a critical piece of equipment, where a significant portion of network losses occurs. As per the equations indicated in IV. A. selection of transformer size and its loading factor is critical for overall optimization.

Evaluations get even more complicated during early stage of projects, especially energy costs scenarios. energy inflation rate, and years of intended operation.

Transformer arrangements can generally be configured in either a radial or redundant format. Radial systems are chosen when power interruptions are acceptable, while redundant systems are preferred in all other situations to ensure reliability. To maintain process continuity, the design should incorporate redundancy at an affordable project cost, as conceptually illustrated in Figure 2.

Consider a scenario where a group of N transformers is intended to operate in parallel to supply an electrical load of S_L. In this case, the size of each transformer would be $\frac{S_L}{N}$. However, this approach lacks contingency, as the failure of one transformer would result in a process interruption. As discussed in Section IV. C. , applying various cooling arrangements to transformers can enable them to achieve higher ratings. By carefully selecting the initial load limit factor, we can achieve an optimal combination. This concept is illustrated through the following hypothetical example.

Sizing approach:

$$Sum\ of\ Installed\ MVA = MVA_S = \frac{S_D}{LLF} \quad (5)$$

$$Transformer\ Size = S_{TR} = \frac{MVA_S}{N} \quad (6)$$

$$MVA\ at\ Source\ @\ \text{N-1} = (N-1) \times S_{TR} \quad (7)$$

$$MVA\ at\ Source\ @\ \text{N-2} = (N-2) \times S_{TR} \quad (8)$$

$$Transformer\ loading\ (operating) = \frac{(S_{TR} \times N_{OP})}{S_D} \quad (9)$$

Where:

N : Number of installed transformers (no's)
N_{OP} : Number of transformers in operation (no's)
S_D : Power demand of sub-system (in MVA)
LLF : Load limit factor (in %age)

Case Definition:
Case #1 : 3 Transformers operated in Parallel
Case #2 : 4 Transformers operated in Parallel
Case #3 : 5 Transformers operated in Parallel

If a system to be designed, to be able to feed power during one (1) contingency with least CAPEX then case#2 of TABLE VI.B is enough. However if the system demands to be able to feed power during single(1) contingency and at the same time allow under to do maintenance then case#3 of TABLE VI.A is needed.

i.e., when we choose an LLF=60%, considering Case#3 configuration, as per TABLE VI.A, under normal operating condition, each transformer is loaded to 60%, under "N-1" operating scenario loading goes up and reaches to 75% and reaching to a 100% under "N-2" scenario.

Table VI provides guidance on transformer size for different cases

TABLE VI
GUIDANCE ON NORMAL LOADING FACTOR WITH REFERENCE TO SELECTION OF INTAKE SUBSTATION

Description	Case #1	Case #2	Case #3
Sum of all MVA of Transformer needed (p.u.)	1.67	1.67	1.67
Nameplate of each transformer (p.u.)	0.56	0.42	0.33
(N-1) Operation, loading on running transformer (%)	90%	80%	75%
(N-2) Operation, loading on running transformer (%)	180%	120%	100%

TABLE VI.A : Tabulations at Load limit factor = 60%

Description	Case #1	Case #2	Case #3
Sum of all MVA of Transformer needed (p.u.)	1.52	1.52	1.52
Nameplate of each transformer (p.u.)	0.51	0.38	0.30
(N-1) Operation, loading on running transformer (%)	99%	88%	83%
(N-2) Operation, loading on running transformer (%)	198%	132%	110%

TABLE VI.B : Tabulations at Load limit factor = 66%

When designing a system to ensure power supply during a single contingency with minimal CAPEX, Case #2 from Table VI.B is sufficient. However, if the system needs to maintain power supply during a single contingency while also allowing for maintenance, Case #3 from Table VI.A is required.

Transformer loadings for Case #3 from Table VI.A (Load Limit Factor (LLF) = 60%)

following scenarios apply:

- Under normal operating conditions, each transformer is loaded to 60%.
- Under an "N-1" operating scenario (one transformer out of service), the loading increases to 75%.
- Under an "N-2" operating scenario (two transformers out of service), the loading reaches 100%.

Case #3 from Table VI.A ensures better longevity of transformer life, contingency handling and maintenance capabilities while optimizing the system's performance.

Let us apply Table VI numbers to design a sub-system to feed 1 GW in a multi GW facility. Overall facility as it is in few GW's, they would be connected at EHV level generally >=400 kV.

For a low CAPEX combination (Case #2 from Table VI.B), the required transformer size is 380 MVA (0.38 * 1000), with four transformers operating in parallel. In contrast, for a high CAPEX configuration with provision for double contingency (Case #3 from Table VI.A), the required transformer size is 330 MVA (0.33 * 1000), with five transformers operating in parallel.

A quick recap of Section IV.C outlines the loading limits for various cooling options:

- ✓ Option 1: ONAN: 100%
- ✓ Option 2: ONAN/ONAF: 80/100%
- ✓ Option 3: ONAN/ONAF/OFAF: 60/80/100%

The cost per MVA for power transformers substantially decreases as we move from Option 1 to Option 3. Therefore, specifying Option 2 or Option 3 can be beneficial. In realistic scenarios where demand can fluctuate, Option 3 (60/80/100%) is particularly attractive as fans and pumps are not in operation during transformer normal operation (i.e., the transformer's actual loading is within 60% of its nameplate), this further reduces transformer lifecycle costs.

The holistic way to look at the transformer system is a TCO approach. Actual load losses in a transformer are proportional to its loading. With loading factor limit set at 60% ensures active and reactive losses are within 40% (=60%^2), however for Case #3 configuration would require an EHV & HV bay which is significant as well. Let us understand how both options perform :

Project Parameters (test case):

Bank Rate of interest	5 %
Life expectancy of operation	40 years
Cost of energy	0.06 $/kW
Annual increase in Energy Price	1 %
CO_2 Emission Factor	0.30 kg/kWh

Transformer Arrangement:
Option 1 : 4 No's of 380MVA, loading factor 66%
Option 2 : 5 No's of 330MVA, loading factor 60%
Assumption : Transformer initial cost : 20,000 $/MVA

Table VII provides TCO analysis for two combinations

TABLE VII
TRANSFORMER TCO WITH CO_2 CONSIDERATIONS

Parameter	Option 1	Option 2	Option 1	Option 2
Scenario for CO_2 Tax ($/tonne)	**50**	**50**	**100**	**100**
CO_2 Emission (tonne/year)	1437	1084	1437	1084
Cost of CO_2 Emission (k$)	2874	2168	5748	4336
Capitalization Factor				
A	11223	11223	11223	11223
B	4889	4040	4889	4040
Total cost of Ownership, of each transformer (k$)	16611	13398	19485	15566
Total Transformer Package cost (M$)	66.44	66.99	77.94	77.83
(relative in %age)	()	0.83%	0.14%	()
Cost of EHV + HV Bay (M$)	()	1	()	1
Effective Cost (M$)	66.44	67.99	77.94	78.83
(relative in %age)	()	2.33%	()	1.14%

From the above evaluation, results indicate that by considering the CO_2 cost component, selecting Option 2 does not significantly increase the project cost and also offers the benefit of higher power availability.

E. Reactive Power – Grid Requirements – Operational Cost

The need of reactive power is primarily driven by system loads and as well as transformers connected with the system. Generally, transformer impedance at utilization end is selected based on system performance pertaining to networks ability to start large motors and to keep electrical system fault levels to a desirable level.

Recalling architectures which are indicated in Fig. 2, fault level constraints are higher for systems in main-tie-main configuration and with operating scenario where both transformers are also operated in parallel. In such cases there is a tendency to specify for higher transformer impedance, however it can lead to increased consumption of Var's by transformer

Currently, utility companies in some developed economies impose penalties for inductive reactive energy supplied by the transmission network, with charges varying between peak and off-peak hours. Therefore, special care must be taken when selecting transformer impedance. Under normal conditions, sizing transformers at a higher loading factor can lead to significant consumption of reactive VARs, necessitating additional mitigation equipment such as STATCOM.

Let us look at reactive power consumption for above options. Table 1 from IEC 60076-5 [13] provides guidance on minimum values of short-circuit impedance for transformers with two separate windings. Analysis is carried out for two set of values (14% & 18%) to show the impact of impedance parameter with regards to transformer reactive power consumption.

Power to be Fed (Connected at Transformer Secondary)	S_L	1000 MVA
Load Power factor (Transformer Secondary)	PF	0.95
Hence load requirement :		
	P_L	950 MW
	Q_L	312.25 Mvar

Table VIII summarizes reactive power consumption by transformer

TABLE VIII
REACTIVE POWER CONSUMPTION WITHIN TRANSFORMER

Parameter	Option 1	Option 2	Option 1	Option 2
Grid Connected Transformers, load factor	66%	60%	66%	60%
Impedance of Grid transformers EHV/220 kV	**14%**	**14%**	**18%**	**18%**
Reactive power consumption (per transformer)	23.17	16.63	29.8	21.38
Reactive power Consumption by Grid transformers	92.68	83.15	119.2	106.9
At EHV Metering Point				
Peq (MW)	950	950	950	950
Qeq (Mvar)	404.93	395.4	431.45	419.15
Seq (MVA)	1032.7	1029	1043.4	1038.4
PF	0.920	0.923	0.911	0.915

TABLE VIII illustrates that, even when a high load-side power factor of 0.95 is maintained at the HV backbone, the introduction of transformer impedance results in a measurable reduction in the power factor observed at the behind-the-meter point. This phenomenon underscores the critical importance of transformer impedance selection, particularly in systems subject to stringent grid compliance requirements.

In such contexts, where utilities impose penalties or tariffs for excessive reactive power consumption, careful consideration of impedance characteristics becomes essential. Optimizing transformer impedance not only supports regulatory compliance but also contributes to improved system efficiency and cost-effectiveness.

VI. CONCLUSIONS

As established industries transition toward electrified processes, a substantial increase in energy demand is anticipated. This shift necessitates a strategic and forward-looking approach to infrastructure planning—one that carefully considers energy availability, economic viability, and technical feasibility.

The capital intensity of electrical infrastructure in large-scale electrification projects underscores the importance of an optimized design methodology to ensure cost-effectiveness and long-term sustainability. In this context, the application of best practices and design principles, such as those outlined in CIGRE guidelines provides a solid foundation for the selection and configuration of high-voltage systems.

Furthermore, early-stage design optimization through the adoption of standardized substation architectures offers significant advantages. Standardization promotes a systematic and coherent design framework, enabling consistency across projects while reducing engineering complexity and lead times. When tailored to project-specific requirements and aligned with national and utility regulations, standardized designs enhance technical compliance, scalability, and maintainability.

Collectively, these strategies support the development of resilient, efficient, and future-ready electrical infrastructure capable of meeting the evolving demands of industrial electrification.

VII. REFERENCES

[1] Shailesh CHETTY, Kevin HUNG, Guillaume BRUANDET, “Conceptual Electrical Designs & Total Control System Concept for Green Hydrogen”, PCIC energy Conference Record, Europe, 2023

[2] Shailesh CHETTY, Renato FINOL, “Process Electrification and Application of Net-zero Power Hub Solution”, PCIC energy Conference Record, Middle East, 2022

[3] 2009, CIGRE Technical Brochures – 390, Evaluation of Different Switchgear Technologies (AIS, MTS, GIS) for Rated Voltages of 52 kV and above

[4] 2013, CIGRE Technical Brochures – 528, Transformer Procurement Process: Guide to Preparation of Specifications for Power Transformers

[5] 2013, CIGRE Technical Brochures – 529, Transformer procurement process: Guide to design review for power transformers

[6] 2013, CIGRE Technical Brochures – 530, Transformer Procurement Process: Guide to the Assessment of the Capability of a Transformer Manufacturer

[7] 2014, CIGRE Technical Brochures – 585, Circuit Configuration Optimization

[8] Commission Regulation (EU) No 548/2014 of 21 May 2014, https://eur-lex.europa.eu/eli/reg/2014/548/oj/eng

[9] IEC 60076-20 Power transformers – Part 20: Energy efficiency

[10] IEC 60076-7 Power transformers – Part 7: Loading guide for mineral-oil-immersed power transformers-voltage AC circuit-breakers

[11] 2007, CIGRE Technical Brochures – 323, Ageing of cellulose in mineral oil insulated transformers

[12] Dr. Bhaba P. DAS , Rob MILLEDGE, Ghazi KABLOUTI, “Investigating the impact of transformer capitalization factors on the carbon footprint”, Transformers magazine, Volume 9, Issue 4, 2022

[13] IEC 60076-5 Power transformers – Part 5: Ability to withstand short circuit

VIII. VITA

Shailesh Chetty holds a master's degree in Power Systems and Electrical Drives from Thapar University, India, and a System Engineering L1 from CESAME, France. Since 2023, he has been working as an Electrification Solution Integrator in Shell's Industrial Electrification Solutions team within Research & Innovation organization. His primary focus is to develop innovative solutions for electrification of industrial processes, Offshore DER integrations for applications in P2H, P2X, and data centres. Prior joining Shell, Shailesh gained valuable experience working on various projects with companies like Schneider Electric, Technip, and Areva T&D.
shailesh.chetty@shell.com