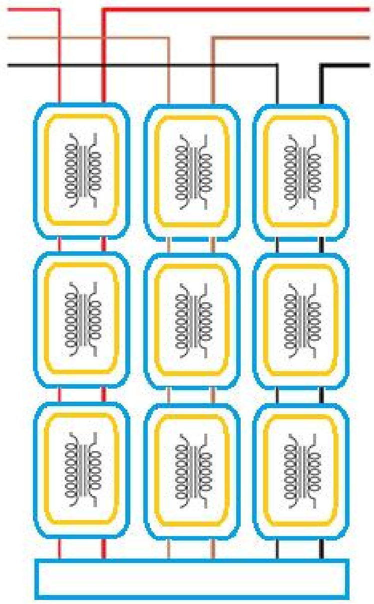
ABB Inc.
FINAL TECHNICAL REPORT



Novel Concept for Flexible and Resilient Large Power Transformers

Award:	DE-OE0000854
Lead Recipient:	ABB Inc.
Project Title:	Novel Concept for Flexible and Resilient Large Power Transformers
Principal Investigator:	Parag Upadhyay
Team Member	University of Tennessee, Knoxville, TN
Date of Report:	March 30, 2018

Table of Contents

EXECUTIVE SUMMARY

Failure of large power transformers (LPTs) having power rating of 100 MVA or greater can lead to wide-spread and long-term interruption of electric service. LPTs are typically custom-made and difficult to replace with procurement lead times of one year or more. Furthermore, their large size and weight make them difficult to transport, often requiring special permitting and equipment, which can add to costs and delays. These critical components are vulnerable to aging and damage from extreme weather events like hurricanes or flooding, as well as potential physical attack, electromagnetic pulses, and geomagnetic disturbances. In the event of an emergency with multiple LPT failures, manufacturers may struggle to meet the demand for replacements in a timely manner.

Since LPTs are generally tailored to customer specifications, units are not readily interchangeable, and their high costs prohibit extensive spare inventories. This feasibility study investigates a flexible and adaptable LPT design solution which can facilitate long-term replacement in the event of both catastrophic failures as well as scheduled replacements, thereby increasing grid resilience.

The scope of this project has been defined based on an initial system study and identification of the transformer requirements from an overall system load flow perspective. The majority of large power transformers are rated between 100 MVA to 600 MVA. There are about 500 voltage combinations and distinctive designs (from 69 kV to 500 kV) having a wide range of short circuit impedance values. However, the majority of transmission networks and sub-stations adopt only a few voltage categories and are covered by a limited range of short circuit impedance. As a result of sensitivity and load flow analyses having shown the dominance of line impedance compared to transformer short circuit impedance, a reasonable range of impedance values can be used without threatening system stability. The flexible modules are designed for the main voltage combinations and for a minimum required impedance, with common basic insulation levels (BIL) set to accommodate all voltage categories. The voltage ratio and impedance of the assembled transformer can be fine-tuned using a proprietary process.

The proposed modular, flexible solution includes only twelve common designs, two for each of six power ratings, adaptable to variable voltage as needed from 69 kV to 500 kV. Different combinations and winding interconnections of these twelve different modules address the complete power range and voltage range in the scope of this project. Each phase of the three-phase LPT design is built up using three or four modules, with each module made up of winding blocks on a common core that can be interconnected as needed depending on the required voltage levels.

High level design and analysis have been completed on thirty test cases covering the complete power and voltage range selected for the project. Characteristics including losses, costs, transportation weight, and short circuit impedance of the flexible solution are compared with the equivalent, conventional, three-phase solution. The initial cost of the flexible transformer solution is higher. However, the total cost of ownership calculation has been modified to factor in downtime and lead time to account for resiliency, speed of restoration, and transportability. Most of the evaluated test cases indicate benefit to the customer with the modified cost of ownership equation. A detailed design and field demonstration are recommended as next steps to validate the benefits of this novel, flexible transformer solution.

ACCOMPLISHMENTS

Design objective	**Accomplishments**
Reduction in lead time	Modules and associated auxiliary components are standardized and flexible, which can be kept as inventory by utilities and quickly manufactured.
Easier to transport	Modules are designed to be small and light enough (<42 tons from state highway limits) to be easily transportable by semi-trailer trucks
Fast deployment / installation	Modules are designed such that there is minimal manual onsite configuration.
Multiple high side and low voltages	This objective is accomplished.
Multiple power levels	There are six designs at different power ratings for each of the two types of modules (only 12 module designs in total) to accommodate from 100 MVA to 600 MVA and 69 to 500 kV at either side of the transformer.
Variable/flexible impedance	Modules have been designed to achieve base impedance and interconnected to achieve desired power and voltage ranges. Additional customization of impedance is available to match the impedance requirements of the installation location for the system needs.
Long term replacement	Modules are designed and operated to deliver overall integrated performance with long lifetime similar to conventional designs. Additionally, failed individual module can be selectively replaced one at a time (while the other blocks are still functional).
Energy Efficiency	Modules are designed to match the targeted efficiency and thermal load derived from the lifetime requirements.
Cost-effectiveness	The module designs trade-off the resiliency benefits for increased upfront hardware cost of the transformer system as demonstrated in the modified value proposition.

OBJECTIVE

The objective of this work is to investigate the feasibility of a novel approach to construct, transport, install, and service large power transformers. The effects of the proposed system on LPT lead time, efficiency, cost, impedance matching, transportation, and lifetime are considered. The results from the project provide a thorough understanding of the potential value for the customer and a conclusion regarding the best manner in which the system can be implemented.

SCOPE OF WORK

The following scope has been defined for the project:

1. Market, power system analysis data, and existing studies and data were utilized to derive requirements and technical specifications to cover the widest practical range of LPT installations.
2. ABB's internal design tools were utilized to evaluate various designs and design trade-off curves, including investigation of the likelihood and impact of technical and manufacturing risks.
3. System modeling software was used to evaluate the impact of mismatched impedance and the benefits of flexibility and resiliency.
4. All design and cost evaluation results were incorporated into a modified value proposition developed for the customer and used to select the final design to propose for next stage demonstration.

DETAILS OF PROJECT ACTIVITIES

The goal of this effort is to address the needs of the US energy delivery system - security, reliability, and resiliency - by creating a blueprint for future LPTs that can quickly and effectively replace a variety of existing, aging LPTs. This project was organized into the seven main tasks listed below.

Task 1 Project Management and Planning

Task 2 Power System, Site, and Requirement Specifications

Task 3 Design Specification Optimization

Task 4 Customer Value Proposition

Task 5 Unit Design and Evaluation

Task 6 Evaluating of Variable and Mismatched Impedance

Task 7 Final Design Selection

The description of the work from each of the tasks is summarized below.

TASK 1: Project management and planning

The initial Project Management Plan (PMP) was defined and updated subsequently with minor project revisions to provide sufficient detail to plan, carry out, and report all project activities. The quarterly updates, final project review, and final project reporting are the primary parts of this task.

TASKS 2 & 3: Power System, Site, Transformer Requirement Specifications and Design Specification Optimization

The scope of these tasks were to identify market and application requirements, including applicable standards, and average and existing ranges for values including voltage, power, impedance, short circuit, and other characteristics and use this input to optimize specifications for the modular transformer designs.

Following a failure, transformers need to be replaced in the minimum possible time to improve grid reliability and profitability. There are many requirements involved for determining a transformer design flexible enough to be usefully applied as a potential replacement unit across a wide variety of locations within the US power grid.

1. Power and voltage ratings
2. Performance matching – efficiency and percentage short circuit impedances
3. Material availability, supply chain management
4. Production complexity
5. Transportation
6. Compatibility with other power transformer components and systems
7. Installation
8. Testing and commissioning

In addition to the above requirements, the transformer cost and lifetime also impact the total cost of ownership. After studying the power system and the transformer market, ranges of some important specifications for the specific design were determined. It is feasible to have a candidate design for a future flexible LPT with the following variable features:

- High voltage ranging from 115 kV to 500 kV and low voltage ranging from 69 kV to 230 kV
- Power level ranging from 100 MVA to 600 MVA (three single-phase units are envisioned, each rated from 33.3 to 200 MVA)
- Controllable impedance in addition to the designed impedance
- Transportable blocks with maximum weight of about 25-40 metric tons (a challenge for 200 MVA, 500 kV)

This report focuses on the voltage, power and short circuit impedance ranges.

2.1 Transformer categories

There are three main types of power transformers based on their role in the grid.

1. Generator Step–Up (GSU) transformers – usually having high voltage ratios
2. Network transformers – (transmission and sub-transmission) – usually used for interconnecting two different systems with unequal bus voltages (often one winding type autotransformers)
3. Sub-station transformers (Step-down) – usually higher turns ratio

Transformers can be further categorized based on their voltage levels and location in the transmission and sub-transmission network as given in Figure 1.

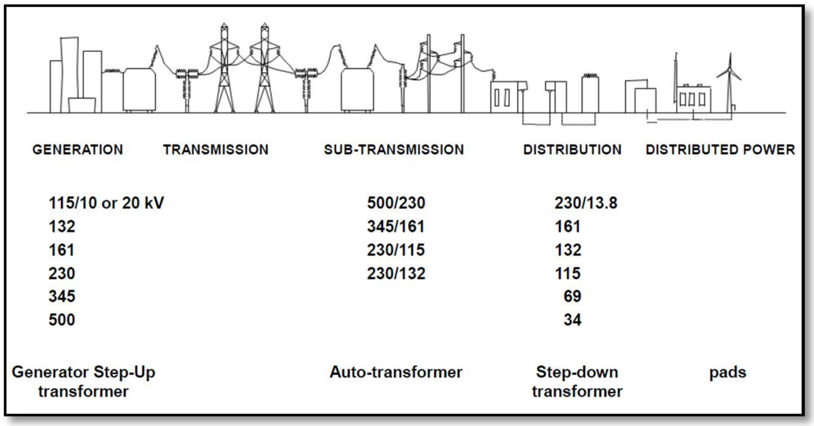


Fig. 1 Transmission and sub-transmission network voltage overview [1]

In addition to the above categories of operation and location, transformers are also differentiated based on number of windings: one-winding (autotransformers), two-winding, and three-winding power transformers. For this study, transformers are categorized according to the voltage levels of the windings, combining some voltage levels close to each other to an integral value for simplification. For example, the voltage level of 13.8kV and 13.2kV are both categorized as 13kV.

The two-winding and three-winding transformer categories are listed elsewhere. Usually each transformer order requires a custom design for a given lot, making it very difficult to generalize the design.

2.2 Statistics of transformer installations and their ratings

Based on the power system model and transformer category, the impedances and ratings of the transformers are analyzed for the three US interconnections. The entire list of the two-winding and three-winding transformers are tabulated. Per unit short circuit impedances are also listed in the same reference to derive mean values and standard deviations. The data is sorted based on MVA ratings, and all transformers having power ratings greater than 100 MVA are listed for two-winding and three-winding transformers. The results of this summary are summarized, including high voltage/low voltage/tertiary voltage combinations, number of units, and the range of power ratings for those transformers. Some of the HV/LV combinations are repeated for two and three-winding transformers as encircled in Figure 2. Considering the scope of the project, the minimum LV voltage rating is 69 kV. For detailed ratings and additional details please consult the reference report from an earlier UTK/DOE study [2].

2.3 Summary of major transformer installations and their specification needs

The United States' electrical grid consists of over 360,000 miles of transmission lines, including approximately 180,000 miles of high-voltage lines, connecting to over 6,000 power plants, and more than 3,500 substations with more than 5,500 power transformers [1]. Referencing a publically available example, American Electric Power's (AEP's) transmission network of about 37,000 HV circuit miles includes about 5,600, 16,000, and 10,600 miles respectively of 345, 138, and 69 kV lines [5]. These three voltage levels account for 87% of the AEP HV circuit miles. Various transformer voltage combinations are also observed based on the transmission line voltage specifications in the US power grids shown in Figures 2 and 3. These figures represent present and future transformer voltage rating requirements covering a majority of the US transmission network.

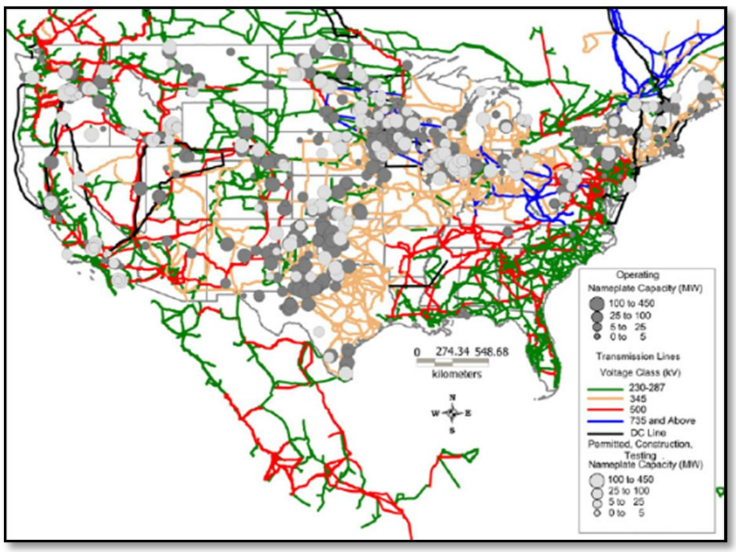


Fig. 2 US transmission line network with substation nameplate ratings [3]

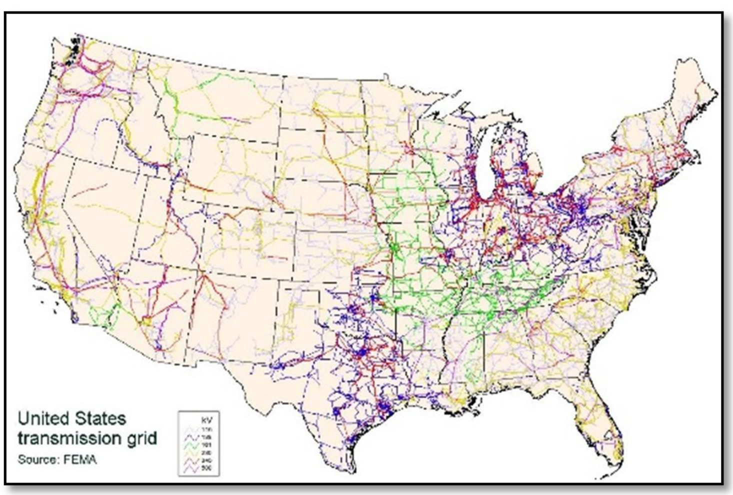


Fig. 3 US transmission line network with line voltages designated in kV [4]

More than 33% of US transformers are aged more than 50 years. Out of those 33%, about half (or roughly 1/6 of all US power transformers) are more than 60 years old [5]. The aggregate aging of assets contributes to an increased likelihood of transformer failure, potentially leading to sustained black outs in the regions served by these substations [6]. Consideration of such aging is an important part of any resiliency strategy for rapid repair and replacement. Table 1 represents various voltage combinations to support the transmission network.

Table 1 Example of various transformer voltage combinations [6]

HV Voltage (kV)	LV Voltage (kV)
138	69
230	115
115	69
161	69
230	69
230	138
161	115
230	100
161	138
138	115
230	161

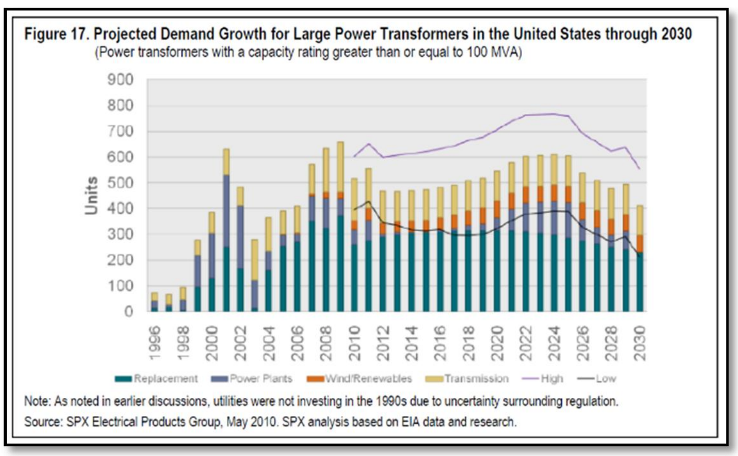


Fig. 4 Power transformer yearly unit need [7]

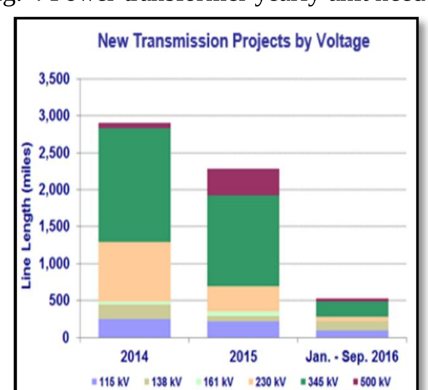


Fig. 5 Voltages of new transmission projects [7]

As per the grid infrastructure planning by AEP shown in Figure 4, the future demand growth will need more than 400 transformers each year, the majority of which will be either replacements or for future transmission projects. As high voltage transmission is more efficient, major additional grid installation projects will be at 115 kV, 138 kV, 161 kV, 230 kV, 345 kV and 500 kV as shown in Figure 5.

Table 2 Voltage ratings of transformers and number of substations in US power grids [8]

	Low Side							
High Side	345 kV	230 kV	161 kV	138 kV	115 kV	69 kV	35 kV	4 kV
765 kV	9	1	1	14	3	7	1	15
500 kV	3	107	16	43	69	43	3	153
345 kV	-	18	27	269	185	136	10	336
230 kV	-	-	87	226	628	422	56	528
161 kV	-	-	-	44	162	336	14	158
138 kV	-	-	-	-	365	1129	35	476
115 kV	-	-	-	-	-	390	213	337
69 kV	-	-	-	-	-	-	109	264

The most frequently-occurring voltage combinations in the transmission network are identified and indicated as red in Table 2 and the top five are highlighted by the dark green shade. These values are consistent with the HV/LV voltage matrix from the FOA [8] and also are the most common in the transmission grid plans for the future (Figure 5). Focusing on these voltage combinations covers both a large range of voltages as per the scope of the project as well as the majority of the transformer installations in the US power grid. Similarly, the variations in short circuit impedance are tabulated and summarized for two-winding and three-winding transformers by UTK.

The summary figures indicate that the average percentage impedance varies generally from around 8% to 32%, and the trend line indicates that the average short circuit impedance is about 15%. If the impedance during the design can be set to a minimum (~10%) value, then the majority of the existing transformer impedance values can be covered by allowing for a variable impedance of up to ~10%. The variations can be addressed through a proprietary process, allowing the total impedance to vary from 10% to 20% with an incremental step of 1%.

For the power range defined in the derived scope, the feasibility of standardized designs have been investigated for five main power transformer voltage combinations, as listed below:

Þ 500/230 kV Þ 345/138 kV Þ 230/115 kV Þ 345/115 kV Þ 230/69 kV

This requires major design changes to bring the working voltage up for many units. Three winding transformers are not considered here, as normally the third winding voltage rating is 13 kV, and this can be achieved by tapping the HV/LV windings.

TASK 3: Design specification requirements and optimization

The recent DHS Recovery Transformer (RecX) gave a 45 ton design for a 200 MVA single phase transformer [9]. While the RecX concept helped to demonstrate the value of modular designs to accelerate recovery (especially emphasizing transportation speed and installation speed), the RecX technology was intended to serve as a short term solution until a permanent replacement can be manufactured and delivered. The expected lifetime for the RecX design was 5-10 years, and the prototype had an efficiency of 99% and a fixed impedance of 14%. Long-term replacements require higher efficiencies, optimized impedances, and longer lifetimes as listed in Table 3, which summarizes the derived targets for the transformer concept being developed in this project.

Table 3 Technical Specifications for Large Power Transformers

Design specification	Initial specification target	Derived specification target
Range of Impedances	5% to 21%	10% to 20%
Design Lifetime	40 years	40 Years
Average Cost	$15/kVA	Modified value proposition
Efficiency	> 99%	Match efficiencies with equivalent three phase transformer designs
Average Max. Operating Temperature	95°C	Matched with existing three phase designs

As also concluded in the DHS RecX program, three separate single-phase units are a logical design option to facilitate transportation. Furthermore, for this flexible solution, the three single-phases are broken down into several interconnected modules to provide voltage flexibility as shown in Figure 6.

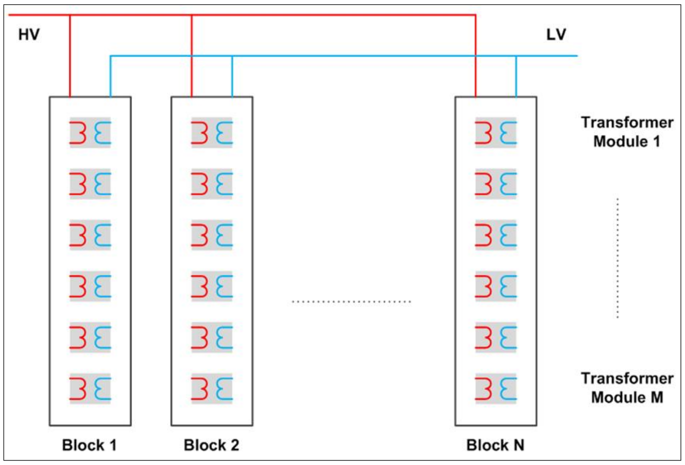


Fig. 6 Proposed concept transformer blocks

IEC and ANSI standards have fixed voltage and current rating specifications for single phase designs with preferred power ratings as listed in Table 4. Many OEM suppliers have inventories and standard parts for these ratings, and cooling assemblies are also available as standardized modules. Utilizing equipment from these standardized levels enables design flexibility at a reduced cost.

Table 4 IEEE preferred MVA Ratings of single-phase power transformers [10]

Preferred MVA ratings for transformers				
	Preferred ratings, MVA			
Single-phase	0.5	5	50	500
	0.67	6.67	66.7	667
	0.83	8.33	83.3	833
	1	10	100	
	1.25	12.5	125	
	1.67	16.7	167	
	2	20	200	
	2.5	25	250	
	3.33	33.3	333	
	4	40	400	

Table 5 Preferred standard MVA ratings of the single phase power transformers

HV side voltage (kV)	LV side voltage (kV)	Units	MVA ranges of three-phase transformers	MVA range of in-scope single-phase transformer units	Design short circuit impedance
500	230	309	368-2228	99-132-165-200	15.00 ± 5%
			3*(200-743)	3*(66-99-132-165-200)	15.00 ± 5%
345	138	729	112-826	33-66-99-132-165-200	15.00 ± 5%
345	115	226	150-813	33-66-99-132-165-200	15.00 ± 5%
230	115	1303	101-643	33-66-99-132-165-200	15.00 ± 5%
230	69	576	102-403	33-66-99-132-165-200	15.00 ± 5%

The single phase power ratings listed in Table 5 are derived assuming three modules per phase to obtain flexibility for the 100 to 600 MVA range to meet the scope of this project. Table 5 summarizes the total thirty test cases with fixed power transformer voltages, and variable power and percentage impedance requirements (blue fonts) as a feasible range of specifications, including the baseline power ranges for single-phase transformers. Four out of the five main LPT voltage combinations have a similar standard power range, except for the combination 500/230kV which needs higher power ratings. In this instance, the decision was to use three transformer installations in parallel, which allows a range of power rating from 40 MVA to 200 MVA, while also limiting the weight per module.

TASK 4: Customer Value Proposition

The objective of this task was to examine different possibilities for weighting and evaluating design tradeoffs. The final result from this task was a well-documented, modified total cost of ownership equation including the impact of factors with tunable weighting such as downtime, lead time, and transportation for comparison between design alternatives.

One of the challenges around this proposed new transformer design strategy is quantifying the impact, both in terms of total system benefits and as well as increased hardware costs. This section describes the approach used to define a modified total cost of ownership equation to better understand and calculate the cost-benefit trade-offs. An existing total cost of ownership equation, combining initial costs together with the costs of load and no load losses over the expected transformer life-span, was used as a starting point. More specifically, the initial total cost of ownership equation [11].

$$TCO = IC + A(P_0 + P_{c0}) + k^2 A(P_L + P_{cL} - P_{c0}) \qquad \dots\dots\dots (4.1)$$

is the sum of the initial cost of the transformer, "*IC*," plus the penalty in lost revenue from the load (P_L), no load (P_0), and cooling losses (P_{c0} and P_{cL}) of the transformer. The *A* factor accounts for the impact of the changing electricity price (assuming 10 cent/kWh initial cost and 1% annual increase) [12] and value of money (assuming a 5% discount rate) over the transformers 30 year lifetime. Generally, "k^2A" is referred to as the "B" factor in TOC calculations. '*k*' is the average loading factor of the transformer over its lifetime, assumed as 0.5 in this case across all US LPTs. Many US regions are seeing peak-to-average electricity demand ratios around 1.8, so using an average factor of two is conservative but reasonable [12].

This baseline equation helps with determining the trade-offs and payback period between low-cost, low efficiency and more expensive, higher efficiency transformers. For this project, additional cost factors have been added to better estimate differences between conventional and the proposed flexible power transformers.

4.1 Initial Cost Calculation

The transformer initial cost comprises a wide range of different factors. The initial cost is defined here as the sum of the costs of transformer materials, assembly, design, engineering, testing, auxiliary components, transportation, and installation. The costs for the grain-oriented electrical steel laminated core, fabricated steel tank, transformer oil, and continuously transposed conductor (CTC) in $/kg are considered based on ABB cost references. An estimated fixed fraction of the total IC is required for assembly of the large power transformers, including labor and passive parts like mechanical supports, cleats, and leads. For both the material and assembly costs, a 10% reduction in cost is applied for the flexible transformer solution to account for the benefit from the standardization in the required materials and assembly process.

An additional fixed amount is added to the initial cost to cover engineering, design, and testing for a traditional transformer. From this amount, the fraction for engineering and design work on each new transformer specification is essentially eliminated with the standardized flexible transformer block designs. The remaining fraction covers factory testing, and this value is reduced to half in the standardized, flexible transformer case, since design and type testing can be eliminated, leaving only routine testing and performance verification. So only a small portion of the fixed amount for the traditional three-phase transformer cost of the design, engineering, and testing is added for the flexible transformer solution.

Continuing with the initial cost, equation (4.2) is used to estimate the cost of auxiliary transformer components as a function of the transformer voltage and power ratings.

$$\text{Component Cost} = f(S, V) \qquad (4.2)$$

In this function, V is the transformer voltage rating in kilovolts, S is the power rating of the transformer in MVA. The transformer bushings, for example, increase in cost as the transformer voltage increases. The cooling system equipment, including the fans and radiators, for the transformer increase in cost as the power rating increases. The fraction of the total initial price due to these additional components varies depending on the power and voltage ratings.

Actual transportation costs vary over a wide range depending on installation location and accessibility of the installation site. Size and mass are important factors, however, most of the variations in transportation costs are independent of the transformer design strategy or details. The simplified total transportation cost estimation for this comparison are defined as $150/ton for individual units' less than 42 tons or $300/ton for cases greater than 42 tons. The 42 tons is based on the lowest tridem axle weight limit across US states for highway transportation. The $150/ton amount is roughly consistent with US domestic highway freight charges, and both values align with commercial examples [13]. Transportation will be easier for the smaller blocks of the flexible transformer solution, but there are also more units to transport. As a result, the calculated transportation costs are not a significant differentiating factor. The additional benefit of ease of transportation on short notice of the flexible transformer blocks is also incorporated in the resiliency calculation.

The final component we are including in the transformer initial cost is the installation and commissioning. This includes the final on-site assembly, interconnection, and oil filling and degassing of the transformer units. Based on the NERC reference, approximately 15% of the total initial cost is attributed to the field installation for a traditional three-phase transformer [14]. For the proposed flexible, transformer solution, we are multiplying this percentage by the cube root of the number of units. This results in roughly doubling the percentage installation cost for a modular solution made up of nine blocks. Keep in mind that actual installation cost depends on the transformer size, rating, and total initial cost, so that the 30% installation cost will more than double since the initial cost for modular, flexible transformers is also higher compared to one traditional three-phase transformer. We believe this increased installation cost is conservative for the flexible solution, and this value can be validated and revised as part of an initial small-scale demonstration. The flexible blocks are smaller, easier to work with, and the installation procedure will be more standardized, but the increased number of units and connections is expected to take more time. The benefits from standardized design, materials, assembly, and testing help to partially offset the increased initial cost of the flexible transformer solution compared to the traditional three-phase baseline. Still, the total initial costs for the flexible transformers are expected to vary high. Additional benefit in terms of lead time and turn-around time is also included in the following resiliency/restoration calculations.

4.2 Additional Total Cost of Ownership Considerations

One of the main objectives of the proposed new transformer technology, reduced downtime, is also one of the most difficult to quantify as a tangible benefit. Our initial calculation accounts for this effect by combining the missed utility revenue during the power outage together with an estimate of the greater economic impact from the power outage. We are defining a hypothetical power outage as lasting just five days for the flexible transformer case, as a combination of two days to locate or build and test plus three days for delivery, installation, and commissioning (as demonstrated from the Recovery Transformer demonstration). The traditional transformer, even in an emergency case, would require more like three weeks, or about twenty-one days, to source the needed components, manufacture, and test a three-phase power transformer. On top of the same three days to deliver and install (likely overoptimistic for the traditional transformer case), this gives at least a 24 day outage in the case of the traditional transformer. These numbers can be debated and adjusted as needed, but we feel this initial calculation provides a reasonable starting-point comparison between the traditional and new cases.

Data from the LBNL report, “Updated Value of Service Reliability Estimates for Electric Utility Customers in the United States,” by Sullivan et al. was used as an initial estimate of the greater economic impact from loss of utility electrical service [15]. This study did not focus on long term power outages. The reported average impact of an eight hour power interruption, averaged across time of year and type of power customer, was conservatively applied to estimate the average economic impact per twenty-four hour day in our transformer cost of downtime calculations. (Lacking extensive data on longer outages, the same eight hour value from the study was used for each twenty four hour day in this calculation, as a realistic minimum value.) This results in an average value of $0.53 per interrupted kWh based on the reported values [15]. The greater economic impact considered in that report includes factors like lost output and wages, spoiled inventory, delayed production, but does not consider additional external factors or societal impact like public health and safety, supply chain disruption and delays, or impact to online traffic and sales.

An expected probability value is also required in addition to the cost and duration of the outage for comparison of traditional versus flexible transformers. The calculation includes a typical estimated failure rate of 0.5% over the 30 year lifespan for large power transformers across the US [6]. This averages the economic impact from downtime per transformer based on the statistical chance of a transformer failure from historical data. The cost of transformer maintenance for our initial calculations is considered to be similar between the traditional and flexible block designs and is not expected to impact the overall cost picture.

4.3 Government Incentive

A final factor potentially impacting the transformer economic calculation is the impact of government incentives. Federal tax exemptions, allowances, deductions, or credits account for nearly half ($479 billion) of all federal energy incentives since 1950 [16]. Examples include incentives for oil and gas exploration and the use of renewable energy. Similar to the federal investment tax credit (ITC) allowing a tax deduction of 30% of the installation costs of a solar energy system, a 30% or other value defined as a tax credit could be used to effectively reduce the total ownership cost of the flexible transformer while encouraging the adoption of this new technology to improve the resiliency of the U.S. power grid. Similar to the solar energy ITC, 30% of the flexible transformer initial cost, IC, is shown in our initial calculations as a representative total cost reduction do a potential government incentive. An alternative example calculation of what would be required to guarantee grid operation using traditional or new, flexible transformer designs is also included below. This calculation is another example of the benefit of this technology but is not easily incorporated into a cost of ownership equation.

TASK 5: Unit Design and Evaluation

Large power transformers (LPTs) having power rating of 100 MVA or greater are critical components. These critical components are vulnerable to aging and damage from extreme weather events like hurricanes or flooding, as well as potential physical attack, electromagnetic pulses, and geomagnetic disturbances. Failure of LPTs from extreme weather events (e.g., hurricanes, flooding), as well as from electromagnetic pulses and geomagnetic disturbances could lead to wide-spread and long-term interruption of electric service. LPTs are typically custom-made and are difficult to replace with procurement lead times of one year or more. Furthermore, their large size and weight make them difficult to transport, often requiring special permitting and equipment, which can add to costs and delays. In the event of an emergency with multiple LPT failures, manufacturers may struggle to meet the demand for replacements in a timely manner. Since LPTs are generally tailored to customer specifications, they are not readily interchangeable, and their high costs prohibit extensive spare inventories. The objective of this task is to define potential design alternatives and estimate tradeoffs between critical criteria including cost, impedance, power rating, voltage level, transportation weight, and foot print. Flexible and adaptable LPTs will increase grid resilience by providing long-term replacements in the event of catastrophic failures and aging replacements.

5.1 Design alternatives

Design alternatives are selected considering the scope of the design specifications listed in Table 6, based on input from the system requirements and design targets.

Table 6 Scope of the design specifications.

Voltage ratings	High voltage ranging from 115 kV to 500 kV and low voltage ranging from 69 kV to 230 kV
Power level	100 MVA to 600 MVA (using three single-phase units, each rated for 33.3 to 200 MVA) as per Table 6
Impedance	Within 10% to 20%
Transportation weight	Blocks with maximum weight < 42 metric tons (US Highway truck limits)

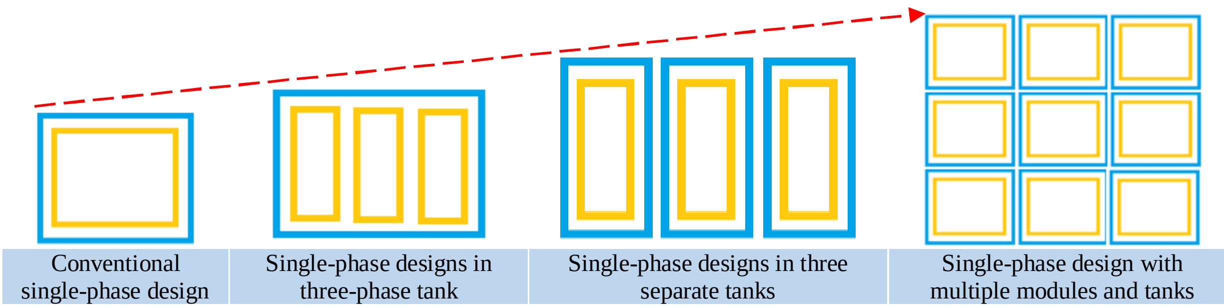


Fig. 7 Design alternatives for the large power transformer

The initial electromagnetic design and sizing examine alternatives including comparison between single or multi-voltage versions of a range of designs to compare alternatives and meet the goals of power, voltage, efficiency, percentage short circuit impedance, material availability, supply chain management, production complexity, transportation, compatibility with other power transformer components and systems, installation, testing, and commissioning. Figure 7 gives various design alternatives.

Table 7 Comparison of design alternatives

Comparison factors	Conventional three-phase design	Single-phase designs in single three-phase tank	Single-phase designs of multiple modules and tanks
Assembly	Moderate (Design and assembly time is very high)	Difficult – (Control of sub assembly is complex)	Unique design, and easy to assemble
Transportation	Very high weight for transportation	Moderate to transport as only active materials without tank (Require on-site assembly)	Easy to transport
Footprint, volume, and weight	Lower footprint and volume on site	Moderate overall footprint, volume, and weight	Higher footprint, volume, and total weight on site
Initial Cost	Cheaper – more conventional designs	Higher (higher core material)	Expensive (higher core material and oil, and additional component cost)
Replacement and restorations	Whole unit replacement required even if one phase fails.	One unit fails – Replacement active parts on site is feasible, but not practical	Quick and easy replacement in case of single unit fails
Sub-components	Efficient, easily handles the forces.	Utilizing common other components like bushings, tank, cooling etc.	More but unique modular sub-component requirement
Testing	All type tests and routine tests are required as all design are different	Testing only one unit is benefit as compare to 3 – separate tanks.	Routine tests for 3 units is time consuming but eliminates some type tests

The first alternative is a conventional transformer with all three-phase active parts placed in one tank. Option two is also a one tank solution where each phase is designed and developed individually and placed inside one tank. The third option is a single-phase, separate tank solution which was considered in the RecX [9] program. The fourth alternative is a modular solution considered for this project, where all the active parts of the modules are placed in separate tanks as shown. There is one more alternative where, not shown, the three modules for each phase can be placed together in one of three tanks. This would give flexibility on the top of RecX solution but transportability and cost will be higher. Therefore this solution also is not considered in the comparison. The three alternatives are compared in Table 7.

Based on above comparison, the “single-phase design with multiple modules” is selected because it provides the following advantages.

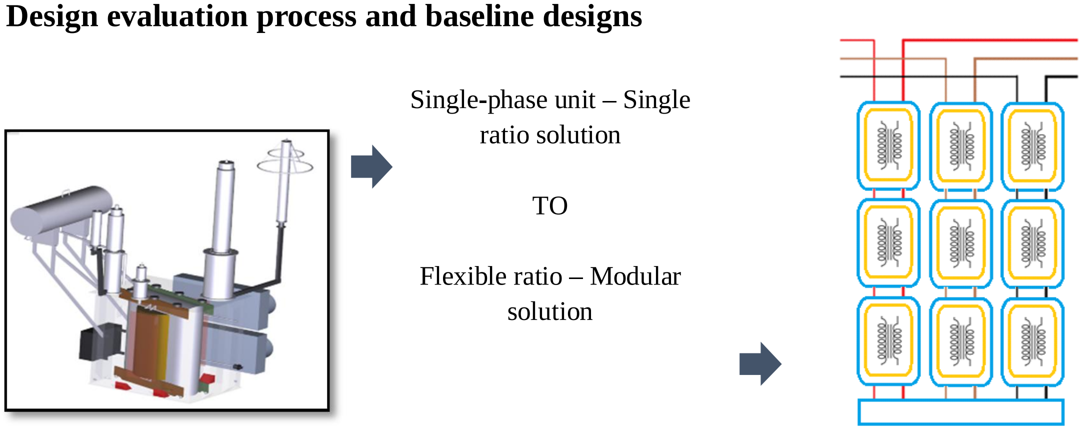
- Easy to transport
- Flexible design by connecting multiple modules in series and parallels
- Increased resiliency from fast restorations with permanent replacement

5.2 Module construction alternatives

Within the selected “single-phase design with multiple modules” solution, three possible modular alternatives were compared for the required single-phase voltage build-ups to provide voltage and power flexibility: to reduce the number of designs and to streamline the design, testing, and assembly.

All three alternatives provide voltage flexibility and meet the transportation criterion for the weight target of <42 tons. Considering cost, ease of installation, involved technical challenges, and simplicity of design options to meet most of the desired voltages, the option referred to here as the “flexible” concept was chosen. The flexible design concept includes two unique construction alternatives for transformer cores wound for two voltage ratios. Connecting multiple, separately housed modules to create each single phase transformer can be accomplished using six different power ratings for each of the two design options to cover most of the voltage combinations appearing in Table 2. Furthermore, since all designs provide similar basic insulation standards (BIL), all designs can utilize similar magnetic core component. Designing for only 2-3 times the operating voltage for the BIL requirements makes this concept feasible for more flexible and cost-effective option as compared to the other two. For this project, the flexible construction alternative is explored for further investigation and design feasibility study focusing on five voltage combinations.

5.3 Design evaluation process and baseline designs



RecX – core form construction   Flex-resilient transformer

Fig. 8 Flexible resilient transformer - Modular and Transportable solution over a RecX solution

Before actually selecting the bases line design, the possible flexible options are evaluated to mitigate technical risks, if any. The RecX solution developed by ABB for the Department of Homeland Security (DHS) successfully demonstrated a resilient single phase transformer solution [9]. Beyond this solution, in order to accommodate flexibility of voltage selections over a wide range from 69 kV to 500 kV and power ranges from 100 MVA to 600 MVA, a further modular solution shown in Figure 8 is necessary using the least number of modules possible to cover the scope of the project study.

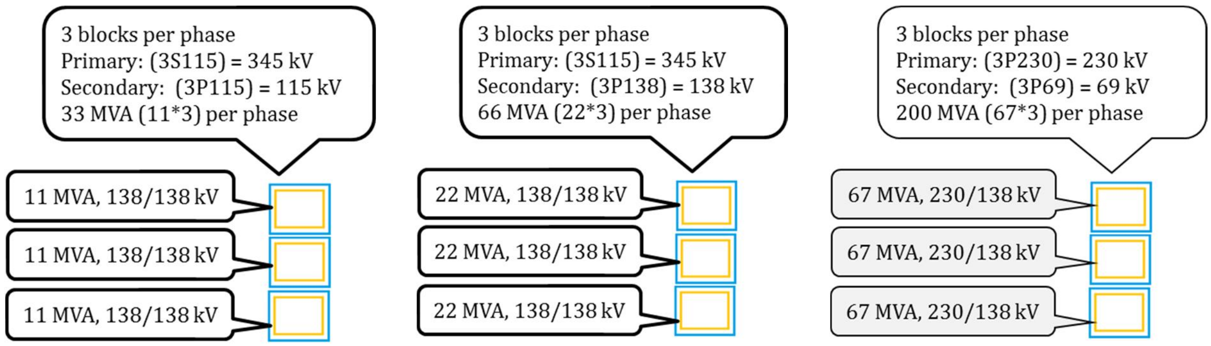


Fig. 9 Flexible voltage and power range demonstration of modular transformer approach

Figure 9 demonstrates the use of different power modules to develop single phase voltages and power. Letter ‘S’ indicates series operations and ‘P’ indicated parallel operations at the corresponding winding.

5.4 Design of modular flexible large power transformer units

The final module concept designs for six module power ratings each (11-22-33-44-55-67 MVA), can deliver the required flexible power and voltage solution. These 12 units are now designed and stored in a database and utilized to build thirty design cases as shown in Table 8 for more detailed investigation. A complete flow chart for the design and evaluation process is shown in Figure 10.

Table 9 Design input parameters

MVA Rating per phase design P_{ph}	11 to 67
LV Line Voltage (kV)	138
HV Line Voltage (kV)	230
Line frequency (Hz)	60

Table 10 Fixed design parameters

Winding temperature
Resistance temp coefficient for copper
Density of laminations (kg/m^3)
Density of CTC conductors (kg/m^3)
Density of oil (kg/m^3)
Density of tank iron (kg/m^3)
Thickness of the tank wall (mm)
Resistivity of CTC conductors (ohm-m)
Stacking factor for the core
Winding space factor

To design the transformer a set of input parameters are defined and fixed before designing the transformer. Such parameters as listed in Table 9 are important to meet industry standards and regulatory standards (i.e. BIL level).

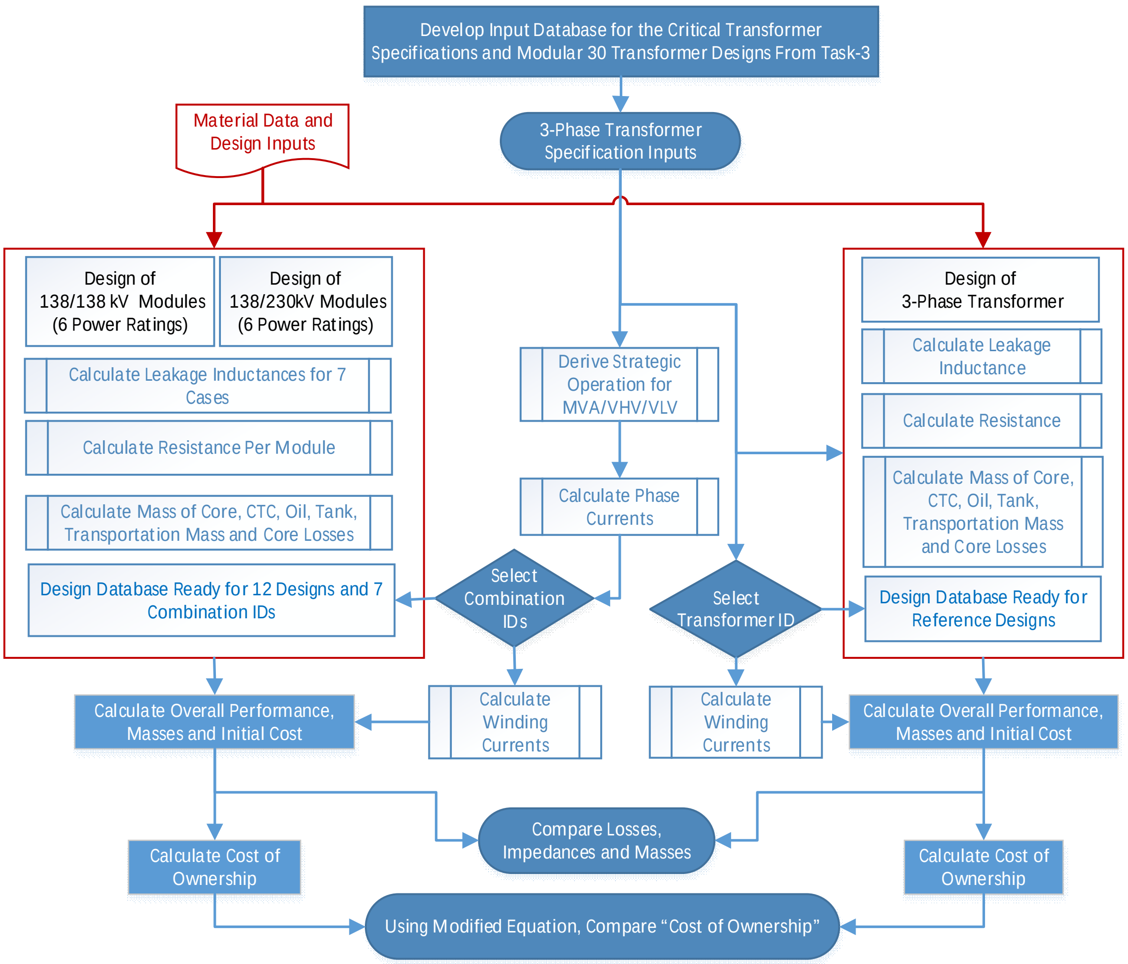


Fig.10 Flow chart for design and evaluation process for 30 test cases

For grain oriented silicon steel, max flux densities are selected based on requirements of transformer weight and efficiency. For light weight designs, higher flux densities are preferable. Normally current density, J, is within 1.5-4.5 A/mm^2. To accommodate short circuit forces, lower values of J should be selected for the design. The window space factor is defined as active conductor area in the window to the total window are. It depends on the voltage ratings of the transformer. For low power and high voltage, the active window height to weight ratio should be higher to address short circuit forces. Axial insulation for top yoke and bottom yoke and all tank clearances depend on BIL requirements, irrespective of the service voltage ratings of the transformers. For this flexible solution, the highest exposure voltage, 500 kV, is selected as an operational voltage for all the module designs. In other words, the IEEE standard rating of 1675 kV BIL (500 kV operational voltage) has been selected for this feasibility study.

Additional design parameters not disclosed in this report are considered based on ABB's standard design tools and requirements. The objective of this process is to create and use the two final module constructions for six power ratings to create thirty example transformer designs over a range of voltage and power ratings. These example designs have been compared to equivalent conventional three-phase designs (30 designs) in terms of the total initial weight, transportation weight, initial cost, losses, short circuit impedance, efficiency, and cost of ownership. Combination of performance and cost from individual modules to the full integrated three-phase assembly is done using an evaluation and integration process discussed in next section.

5.5 Performance evaluation and integrations:

As described earlier in the design flow charts, the performance of the flexible modular transformer concept is calculated based on the specifications of those thirty cases. The specifications of each module for a given coil connection and power rating are called as a function during the design process. Characteristics of individual modules are pulled for calculating performance, mass, and modified cost of ownership for the assembled three-phase unit. The mass of active parts, losses, and percentage impedance of the assembled three-phase transformer as a whole are evaluated at rated power. The transportation mass is also calculated separately for comparison.

The following equations (5.1) and (5.2) calculate per phase high voltage and low voltage side currents.

$$I_{hv} = \frac{P}{\sqrt{3}\, V_{hv}} \qquad \dots\dots\dots (5.1)$$

$$I_{lv} = I_{hv}\, \frac{V_{lv}}{V_{hv}} \qquad \dots\dots\dots (5.2)$$

Copper losses are calculated based on the active winding resistance and current values. Core losses are calculated as a function of the active flux density in the core. Operation temperature and equivalent AC resistances are considered during all the loss calculations.

The total copper loss is calculated from (5.3).

$$P_{cu} = 9\, {I_{hv}}^2\, R_{hv} + 9\, {I_{lv}}^2\, R_{lv} \qquad \dots\dots\dots (5.3)$$

Where, R_{hv} is the primary side resistance and, R_{lv} is the secondary side resistance. There are nine modules for the complete three phase transformer. All the resistances in (5.3) are for the operating frequency and temperature. The core loss depends on the core material and the flux level during operation. The total core loss is calculated from (5.4)

$$P_{core} = 9\, M_{core}\, Loss_{B_m} \qquad \dots\dots\dots (5.4)$$

Where, $Loss_{B_m}$ is the core loss per unit weight in the core for the operation flux level. The operational flux level depends on the design of each individual module. M_{core} is the core mass. The mass of active parts of the transformer ID including the core, continuously transposed conductors, oil, and tank are also calculated, which are used to calculate the total mass of each three-phase unit. For the illustration case, the module mass of the core, CTC, oil, and tank are M_{core}, M_{CTC}, M_{oil}, and M_{tank}, and the total transformer mass of these components is nine times the module mass. This data is used for the initial cost calculation of the thirty base transformers and comparison to baseline, conventional three-phase transformer designs. The percentage overheads and other component costs are verified for available ABB units, and the trends are developed to estimate the overhead and other component costs for all thirty units used for comparison.

The leakage inductance calculation for the proposed transformer design is an important challenge as it must provide a fast and sufficiently accurate analytical method to predict the inductances. Also, there are multiple coil sections within each module as described in coil construction alternatives. A MATLAB script based on Rabins' method was developed and incorporated directly into the overall design routine. The results of the leakage inductance calculations were verified by comparing the stored magnetic energy produced by the script, and observed in corresponding finite element analyses. The leakage inductances of single-phase blocks are subsequently combined, determining the overall leakage inductance of the transformer. If the result is not satisfactory in meeting the impedance target for all thirty cases, the modular design can be modified and repeated as needed.

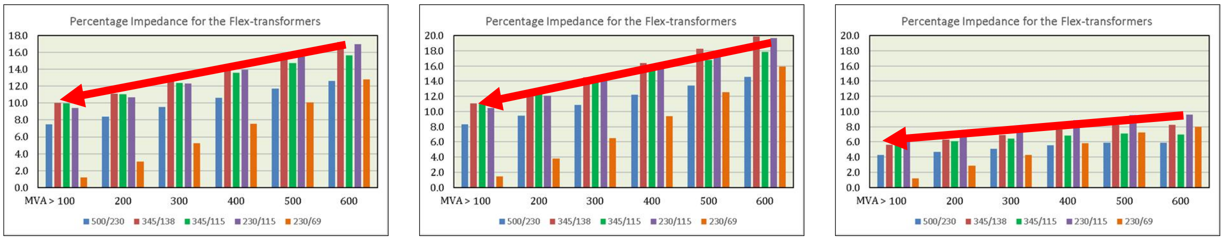
TASK 6: Impedance Variations and Impact of Variable and Mismatched Impedance

One of the important parameters of the transformer design is the short circuit impedance which is set for short circuit currents, forces and system load flows. Higher short circuit impedance is preferable from design aspects and lower short circuit impedance is preferable for the load flow aspects. A complete study is carried out by the University of Tennessee Knoxville (UTK) to first find the range of impedance in the power system and impact on load flow study during the mismatch of the impedance calculated for the flexible solution. The power flow models of Eastern Interconnection, Western Interconnection, and Texas Interconnection are used as base cases for the transformer parameter analysis. The range of high voltage winding of the transformers is between 11 kV and 765 kV. In this project we focus on the transformers which high voltage side between 115 kV and 500 kV, and rating equal to or larger than 100MVA. The transformers are categorized according to the voltage level of the windings. The number of transformers, mean value of the impedance, and rating of each category are calculated and summarized.

The sensitivity analysis of the impedance change is explored for every single transformer in the model of all three interconnections. For every single transformer, the impedance is changed from the original value Z0 to a new value Z1. The power flow analysis is checked under the new impedance Z1. The general impedance Z1 is selected within a range from 10% to 20%, in 1% steps. The solution is checked according to the convergent performance. Meanwhile, the overloading branches are found to check the local impact of the power flow on the transmission line or neighboring transformers. The study did not consider three winding transformers due to the smaller numbers involved. Voltage problems from impedance changes are not studied but are expected to have only limited impact.

For the economical design of the flexible transformers, the general range of the large transformer impedance within 10% to 20% based on the nameplate rating is selected as the impedance change range. The load flow sensitivity analysis shows the impedance of transformers can be in a reasonably wide range without causing system stability issues. Manufacturers could take advantage of this result and design a small number of transformers to economically meet the backup requirement economically.

Initially all the twelve base modules were designed using the similar design rules and assumptions. Later the design is modified to see the impact of modification to the short circuit impedances.



(a) (b) (c)

Fig. 11. Short circuit impedances for the 30 test cases with (a) Initial design (b) Modified design and (c) design for minimized impedances

It is observed from Figure 11 (a) that impedances are within the limit of <20% for all 30 test cases using the modular design concept. Figure 11 (b) represents how changes in those twelve module designs can impact the total impedance when used to create 30 test cases. Also, effort can be made to minimize the short circuit impedance and equalize their values as shown in Figure 11 (c), where impedances are mostly within 6 to 8% and required additional impedance can be provided through a proprietary process, to provide the short circuit limiting and load flow requirements. In conclusion, the short circuit impedance values can be altered to any value required for the system need by redesigning those twelve modules.

Task 7: Final Design Selection

After understanding the feasibility of the proposed flexible concept, as illustrated in Figure 12, the final design is selected based on the combined results from all previous tasks, by identifying and refining the best candidate designs. As the single-phase block requirements are combined with electromagnetic design rules, all required parameters are varied differently for the final twelve module designs.

- Twelve designs with power ratings of 11, 22, 33, 44, 55, and 67 MVA are developed
- Losses, weight of active parts, and initial cost are evaluated for the assembled units.

The 30 test cases are compared with the equivalent, conventional three-phase transformer designs having similar performance and design standards. Five voltage cases for the range of MVA ratings, 100 MVA to 600 MVA, are evaluated.

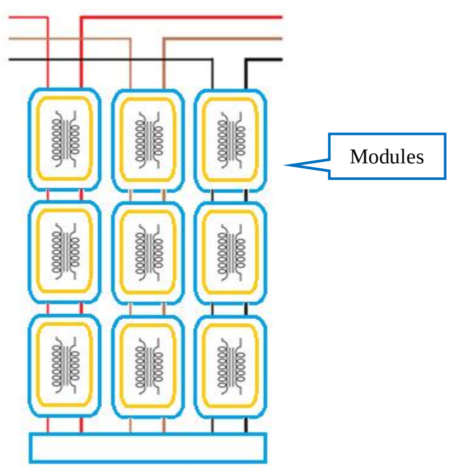
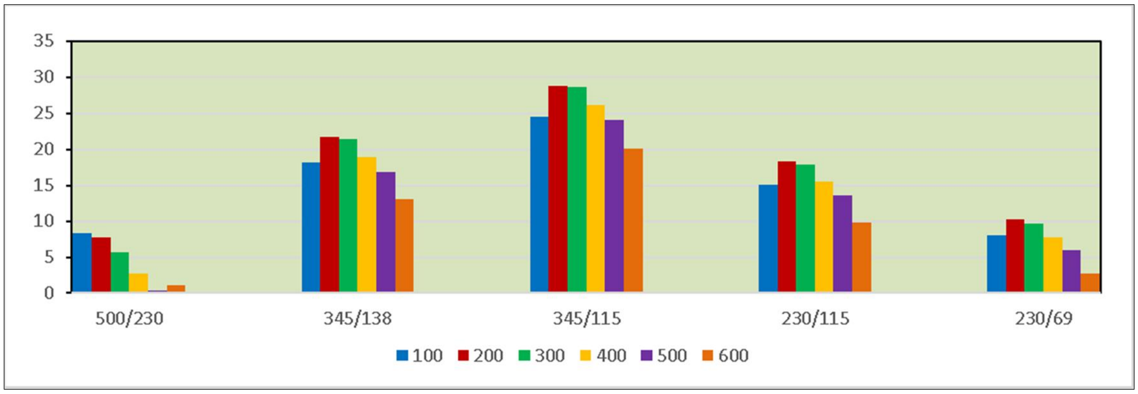
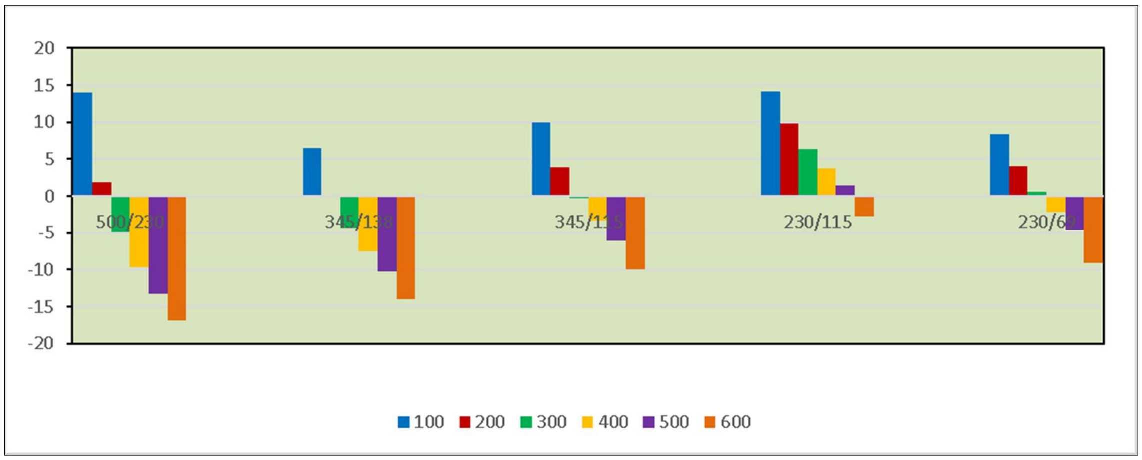


Fig. 12 Flexible modular power transformer solution



(a) Initial flexible transformer designs



(b) Modified flexible transformer designs

Fig.13 Comparison of losses for full-load operating conditions at various power and voltage levels

The losses for the flex-transformer solution are higher for the initial flex designs as shown in Figure 13 (a). Replacing the core material to a higher commercially available grade, the losses are still higher, but by less than 25% as indicated in Figure 13 (b). For certain voltage combinations as shown in the initial design, losses are higher as those units are overloaded by about 20%. Design modifications, over designing modules, and utilizing higher grade core material will bring all losses within +15% range as compared to equivalent three-phase transformers.

Usually, the transportation mass of the large power transformer is calculated by excluding the components and oil in the transformers. At the site, during the installation and commissioning, all components including the cooling system, bushings, etc. are assembled. Transportation mass for all 12 module in the flex-transformer case are less than US state highway transportation limits [13].

For the mass comparison, core mass of each of the three-phase transformer is considered as reference and all other masses are calculated for the comparison. The total mass is about 3 to5 times higher as compared to one single three-phase unit. However, it is easier, faster, and more economical to transport modules to the site for rapid system recovery and restoration.

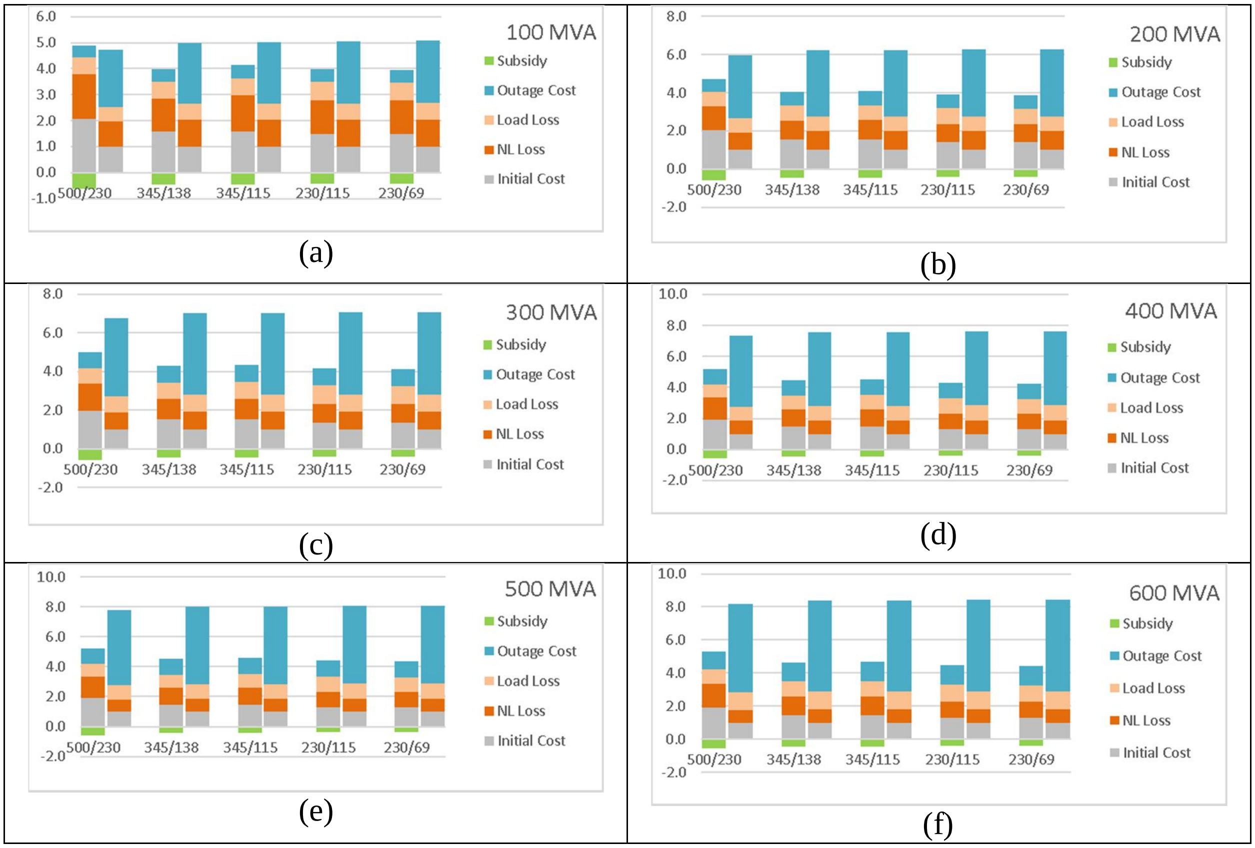


Fig. 14 Comparison of modified cost of ownership of conventional three-phase transformer and flexible transformer solutions

The critical performance in terms of losses, transportation mass and impedances are compared and found acceptable for the flexible transformer. The concept transformer provides additional resiliency and flexibility to operate at different voltage ratios as demonstrated in this report. However, the total initial cost of the flexible solution is higher. This increase in the initial cost is justified through the modified cost of ownership equation described in task-4. The equivalent three-phase designs for all 30 test cases are developed and compared for the modified cost of ownership as shown in Figure 14.

CONCLUSIONS

Many transformers in the transmission grid are more than 50 years of age. To address the future resiliency requirements and reducing the downtime, lead time and economic losses, a feasibility study was conducted for the proposed modular, flexible and resilient solution for the US power grid. A detailed study of the US power grid was first completed to find the voltages and impedance value required for the feasibility study of the proposed solution.

There are several voltage categories in the US power grid system, but it is clear that the majority of transmission networks and substations adopt only a few voltage categories. Also, the assumed impedance range from 10% to 20% allows designers to set a minimum impedance, and variation of impedance required from the grid location is adjusted through a proprietary process. The highest BIL level for the design is considered to accommodate all voltage categories.

Load flow sensitivity analysis shows that the line impedance is the dominant component as compared to the transformer short circuit impedance. The transformer impedance can vary over a reasonably wide range without causing system stability issues, which allows flexibility for system operators to decide an impedance requirement for specification preparation.

As seen from the system study all transformers are built as a custom design which necessitates spare transformers for each of the designs deployed in the field. Creating the least number of common designs allows grid operators to use spare transformers with more flexibility in terms of voltage and impedance needs. This study shows it is feasible to develop twelve common designs which can be adopted at variable voltage as needed and having fixed standard impulse voltage requirements. Using these twelve base designs, the range of voltage combination between 69 kV to 500 kV can be achieved at 100 MVA to 600 MVA power levels.

Smaller and lighter modular designs proposed in this study are more suitable for transportation and installation, improving resiliency and flexibility of the system as they allow faster restoration and an economically viable total cost of ownership.

Initial cost of the flex transformer solution is higher, however considering economic losses due to the downtime, lead time and restoration time, the flexible solution has lower overall cost of ownership over a 30 year life cycle. The modular solution proposed in this study should be pursued by the grid operators, from a set of design specifications to begin with. This would reduce LPT lead time and downtime and also enable minimum spare transformers needed for fast restorations.

As a next step, the proposed modular concept should be validated, using a small scale pilot installation of a design selected from this feasibility study. As an example, such a pilot installation could be designed, developed, and installed as a replacement for at least one phase of an aged transformer needing replacement. The goal would be to demonstrate the manufacturing and resiliency benefits using the modular concept in collaboration with an identified utility partner.

REFERENCES

[1] Report from DoE – Transmission and sub transmission network overview, 2015

[2] UTK/DOE study report for power ratings of GTU and non-GTUs

[3] Fischlein M., et al., States of transmission: Moving towards large-scale wind power. Energy Policy (2013)

[4] United states transmission grid - FEMA Source: https://commons.wikimedia.org/wiki/File:UnitedStatesPowerGrid.jpg

[5] 2016 Fact Book – American Electric Power (AEP), 51st EEI Financial Conference, Phoenix, AZ, November 6-9, 2016

[6] Large Power Transformers and the US Electric Grid," Infrastructure Security and Energy Restoration, Office of Electricity Delivery and Energy Reliability, U.S. Department of Energy, June 2012.

[7] ABB Report - Resiliency planning for the transmission grid – 2013

[8] Funding Opportunity Number: DE-FOA-0001579, U. S. Department of Energy, Office of Electricity Delivery and Energy Reliability, August 2016

[9] DHS RecX Summary report [Recovery Transformer, DHS Science and Technology Directorate, 2012]

[10] IEEE Standard for Large Power transformers - C57.12.00

[11] Total Cost of Ownership Method Basics of Transformer TCO calculation, presentation, ABB Transformers, 2016https://library.e.abb.com/public/2ba5a58c5dcc4aa6a6f9ec471fb95860/TCO-Method-Basics.pdf

[12] Timothy Shear, “Peak-to-average electricity demand ration rising in New England and many other U.S. regions.” February 18, 2014 ttps://www.eia.gov/todayinenergy/detail.php?id=15051#tabs_SpotPriceSlider-1EIA reference for cost of ownerships

[13] Guide for Uniform Laws and Regulations Governing Truck Size and Weight Among the WASHTO States, March 2009

[14] North American Electric Reliability Corporation (NERC), “Special Report: Spare Equipment Database System,” October 2011. http://www.nerc.com/comm/PC/Spare%20Equipment%20Database%20Task%20Force%20SEDTF%20DL/SEDTF_Report_Draft_PC_Meeting_2.pdf

[15] Michael J. Sullivan, Josh Schellenberg, and Marshall Blundell, Nexant, Inc. “Updated Value of Service Reliability Estimates for Electric Utility Customers in the United States,” Lawrence Berkeley National Laboratory LBNL-6941E, January 2015. https://emp.lbl.gov/sites/all/files/lbnl-6941e.pdf

[16] “Two Thirds of a Century and $1 Trillion+ U.S. Energy Incentives - Analysis of Federal Expenditures for Energy Development, 1950-2016.” Report prepared for the Nuclear Energy Institute by Management Information Services, Inc., May 2017, 63 pages. http://www.misi-net.com/publications/EnergyIncentives-0517.pdf