Journal of the Korean Institute of Illuminating and Electrical Installation Engineers (2012) 26(12) : 28~36
http://dx.doi.org/10.5207/JIEIE.2012.26.12.028 ISSN 1229-4691(Print) ISSN 2287-5034(Online)

논문 26-12-4

Selection of Transformer for the Augmentation of an Existing AIS EHV Substation in Hilly Terrain at 3000m+ Altitude

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Abstract

Augmentation of existing EHV substations located in hilly terrain and at high altitude require many different considerations as compared to substations located in plain areas and at lower altitude. Owing to high altitude and steep terrain, meticulous engineering and preparations are required, considering the actual available space at the existing substation. Historical fault events too must be considered to enhance reliability and performance of the substation equipment. This paper proposes ways to augment the existing 2 banks of 20MVA, 220/66kV power transformers (3×6.67MVA, single-phase) to 2×50/63MVA, 220/66kV power transformers to meet continuously increasing demand of the capital city over the next 20 years. Upgrading and augmentation of existing substations, especially the main transformers and associated equipment, require replacement with minimum or no disturbance to the existing power supply system. Considerations should also be made during engineering and design, the operational flexibilities, maintenance aspects, future expandability and value addition, in terms of reliability and space usage of the existing substation.

Key Words : Augmentation of Substations, Transformer, Hilly Terrain, High Altitude, Selection Method

1. Introduction

The substation, referred to in the study is located in hilly terrain 3000m above Mean Sea Level (MSL) at the periphery of Thimphu city, the capital city of the Kingdom of Bhutan. This substation is one of the most important substations in the Western Power Grid, after the generation substations, and was constructed in 1995. Owing to steep terrain, lack of construction equipment with required size and capacity and difficulties in transportation conditions, then, a smaller sizes and lighter equipment were selected. Taking account of the increasing power demand, which surpassed the installed capacity in 2009, and load growth forecast

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Date of submit : 2012. 8. 24
First assessment : 2012. 9. 6
Second assessment : 2012. 9. 26
Completion of assessment : 2012. 11. 9

for the next 30 years, this substation has been considered to upgrade to higher capacities[1]. However, due to existing transportation limitations imposed by the size and capacity of roads, bridges and handling facilities enroute from the port-of-origin to work site, the sizes of new power transformers and equipment are also governed to some extent, while selecting for upgrading. This paper considers how to augment the existing 20MVA with installed capacity (3×6.67MVA, $\frac{220}{\sqrt{3}}/\frac{66}{\sqrt{3}}$kV, ONAN single-phase power transformers) to 50MVA single-phase transformer banks or 3 phase transformers and finally suggest method for choosing an optimal system from two different cases to improve the existing systems in terms of construction time, project cost, and reliability.

2. Different cases for augmentation of existing system

2.1 Existing system

The existing system is briefly discussed presenting the existing single line diagram of the substation in Fig. 1. The 220kV system is installed with a double bus (main & transfer bus system) arrangement providing one-and-a-half breaker configuration, and the 66kV system has two buses each connecting the LV side of each transformer, with a sectionalizing breaker separating 66kV systems in two sections.

The substation is installed with six single-phase 220kV, power transformers connected to form two banks of 20MVA, with a vector group of YNyn0. The single-phase transformers were so chosen, in 1995, owing to limitations imposed by road and bridge capacity, then, between seaport and substation.

The substation supplies power to local neighboring areas at 11kV voltage level through 2×10MVA, 66/11kV power transformers, besides supplying through 66kV feeders to various substations within the capital city and to other Dzongkhags[2].

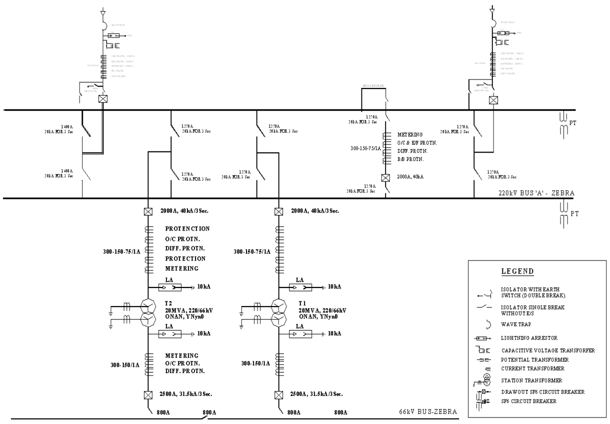
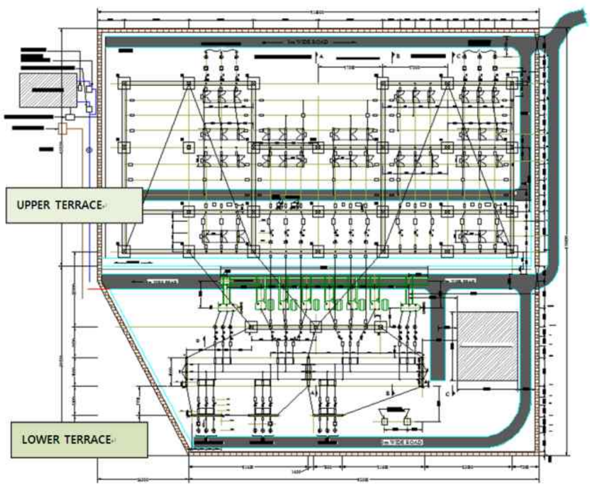


Fig. 1. Existing single line diagram of a 220kV substation

2.2 Switch gear



Substation equipment are arranged in two terraced switchyard with 220kV equipment installed in upper terrace while the lower terrace has six single phase transformers, two 66/11kV transformers, 66kV switchgears and control room.

The layout of the substation is shown Fig. 2.

2.3 Two different cases for augmentation

Table 1 shows the detail facilities of two different cases. They are studied to achieve the most techno-economically feasible substation and meet the present demand and future projected load growth within life span of the transformers. The substation is intended to be able to upgrade to 100MVA of total capacity (the scope of forecast is beyond the scope of this paper).

Table 1. Facilities in different options (Case A & Case B)

Description	Case A	Case B
Existing Transformers	40MVA (2×20MVA)	0 (To be removed)
Added Capacity of Transformer	60MVA (2×30MVA)	100MVA (2×50MVA)
Total installed Capacity	100MVA	

In Case A, 2×30MVA transformers and controlling bays will be added leaving the existing transformers along with its associated system, undisturbed, to let the existing transformers be in service till the end of their economical service life. However, addition of new transformer bays, leaving the existing bays in service, may require additional space, which in this case will make use of the existing land beside the 220kV switchyard.

Assuming physical dimensions of additional single or three phase transformers, which will be added to the existing transformers, the space available will be insufficient to accommodate two new transformers and require extension of switchyard to avoid disturbances to the existing adjacent line bay.

Two additional banks of 30MVA 220/66kV power transformers will be installed and controlled via outdoor circuit breakers, new transformer bays are required. Measures shall be taken to install within the available empty bay space reserved for future line bays. The existing adjacent line bay will not be disturbed in this case except minor modification to connect.

Proposed transformer bays will be connected to existing systems providing similar bus configuration of two buses with an additional bus coupler breaker (one-and-a-half breaker) to maintain the same flexibility for system operations.

In Case B, the existing 2×20MVA 220/66kV power transformers will be replaced with new 2×50MVA, 220/66kV, three-phase power transformers within the same systems with minor modifications. The existing transformers will be removed in turn (one bank at a time) to maintain an uninterrupted power supply to customers and maintain reliability and security of the system/substation.

However, as peak demand (in winter) is greater than the existing installed capacity, one of the new 50MVA transformers should be installed and put into service before removing the existing transformers. Once the new transformer is commissioned and successfully charged with all existing transformer protection schemes transferred and functioning, one of the existing transformers can then be removed. All necessary modification works designed for new transformer can be carried out for second transformer, including the electrical panels. The second 50MVA transformer can then be installed on the modified/new foundation, incorporating all transformer protection schemes installed/modified. The first 50MVA transformer can then be disconnected and re-installed after removing the remaining (existing) transformer and necessary modifications can be carried out.

Case B is less expensive than Case A as it does not require additional space to install new Transformer control bays and new transformer foundations. If space is not the problem to the owner (Employer), Case A provides leverage for differed investment by utilizing the existing 2x20MVA transformers. Once the new transformers are installed, in Case A, it will provide enough flexibility for maintain the existing transformers, to improve its reliability and extend operational life. Case A will may enhance substation reliability but as the transformer ages, cost of operation and maintenance will increase.

Hence, considering the increasing cost of land and requirement for future expansion of substation, Case B is recommended and considered for augmentation. In this paper, all discussion or arguments, hereafter, is presented considering Case B.

3. Criterion for selection of transformers

Although options for upgrading the substation to provide planned capacity of 100MVA at 220/66kV was selected, it is still necessary to make the best selection of equipment to be installed. A detailed selection of equipment is beyond the scope of this discussion and in this paper, selection of power transformers is discussed in the following sections.

3.1 Power transformer

The main governing factor in selecting power transformers has been the power demand forecast studies carried out through various studies, where the demand by year 2030 is 66.18MW (approx. 82.7MVA at pf=0.8). Selections were also based on the following factors [3] :

☐ Load or demand characteristics

Table 2. Comparison of two cases

Activity	Sub-Activity	Single-Phase		Three-Phase	
		Advantage	Disadvantage	Advantage	Disadvantage
Construction	Construction Period		6~12 months	6~9 months	
	Interruption	Few			More
	Construction Cost	Less Expensive			Expensive
	Construction Management	Difficult			More Difficult
Manufacturing/ Transportation	Time for Manufacturing		6 months		6 months
	Time to on site After manufacturing	2 months			3 months
	Transportation Difficulties	Difficult			More difficult
Space/Land Requirement			Additional Requirement	Use Existing	
Operation/ Maintenance	Operation	Easy		Easy	
	Maintenance		Difficult	Easier	
Result				More Feasible	

□ Transportation facilities and road conditions
□ Handling equipment
□ Space availability
□ Future growth & upcoming plans

Considering the transformer life span of 30 years and the demand forecast projected at 66.8MW by year 2030, MVA rating of the transformer projected should be around 84MW (105MVA at pf=0.8) to service until the year 2040. However, the new (recently completed) industrial substation is expected to cater to an industrial demand of 30MW, leaving an expected demand of 54MW (67.5MVA). A new 220kV substation is in the pipeline to cater loads for a new education city nearby, which will further ease demand on the substation, in the coming years.

However, the limitations poised by road conditions, transportation facilities and inadequate local handling facilities demands lighter & smaller transformers. Hence, considering the reliability factor of n-1, for the substation, and the physical dimensions of the transformers, 2×50MVA power transformers have been selected, to meet demand and ensure reliability in the event of necessary maintenance to one of the transformers.

3.2 Single-phase banks or three-phase power transformers

Once transformer capacity was decided, studies were conducted to choose between the single-phase transformer banks and the three-phase transformers. It was obvious that selecting single-phase transformers would be more suitable to transport, handle and install compared to a three-phase transformer of the same capacity. The space occupied by the 3-single-phase transformers, however, is by far larger than a three-phase transformer and it is felt, with the exponentially rising land prices, that decreasing land use will benefit in the future besides providing opportunity for future growth and necessary expansions.

Brief comparisons on the factors considered to select the transformers are discussed in the following sections.

3.2.1 Handling & transportation facilities

In hilly terrain, routes are narrow and more than 90% of roadway is either uphill or downhill with narrow turns almost every 100m or so, which demands transporting vehicles to have sufficiently high horsepower and the right length to navigate turns without breaking the speed of the vehicle.

Besides transportation problems, loading and unloading is a major problem as such consignments are rare in hilly project sites. Hiring cranes/lifting equipment would require long term scheduling and planning. Most of the time this is not economical as the equipment may remain more idle than the actual working hours. Using a high capacity crane will require a large space to move around and position to lift, which, just as in most of the upgrade projects & work sites, is inadequate.

The single-phase transformers are the best choice considering the transport weight and sizes compared to three-phase transformers of an equivalent rating.

3.2.2 Installation and switchyard

Considering the existing switchyard area and system configuration of the existing transformers and possibilities for expansion, it is difficult to install three single-phase transformers within the available space due to standard requirement of minimum electrical clearance and fire protection walls between the transformers. The minimum space required to install the single-phase transformer bank will be more than 21m×7.8m per transformer bank with a stringent maintenance space, while a three-phase transformer will require a maximum space of 12.6m×5.9m.

Hence, considering the space requirement, three-phase transformer is more compact and easier to install.

3.2.3 Construction

It is obvious that due to individual foundation requirement for each single-phase transformer, civil works required for installation is more than double that of three-phase transformer. In single-phase transformers, accessories like Bucholtz relays, pressure release devices, tap changers, local panels, cabling, neutral bushing, NCT, etc. are required on individual transformers which otherwise are required only one per one set (for three phase transformer).

Such additional requirement demand longer construction period (mandays), which increases the construction costs besides the additional cost of accessories. Further, with the increase in civil foundation works, all associated earth grid work will increase. Testing and commissioning activities, too, will increase by 2/3 of that required for a three-phase transformer.

Considering the increasing cost of construction and time required, it is advantageous to select three-phase transformers, at least, for the 50MVA rating selected in this study. With the increasing MVA rating, the three-phase transformer's transportation and handling, onsite and during transit, will be more difficult with an increasing single-piece transport weight. It has been found that as the transformer rating increases the corresponding weight of single-piece detachable component (main tank in most cases) increases the difficulty and cost of transportation in hilly terrains. Beyond certain capacity rating of transformer, the road bents becomes difficult to navigate for the transporting vehicles, unaccommodating through the roads cutting through the cliffs and bridges not able to bare loads. However, new techniques allow transporting transformers in smaller components and assemble at site. The technique and process, however, will be expensive (more than 5 times) compared to conventional installation process, due to requirement of controlled site environment (shade) and full transformer testing to confirm successful commissioning.

Hence, for higher MVA ratings, single-phase transformers will be more economical compared to three-phase transformers.

3.2.4 Operation, maintenance and reliability

Like any other system, increasing number of equipment increases its maintenance and an exponential increase in transformer downtime. Three single-phase transformers in each bank require more than 3 times the maintenance required for one three-phase transformer. As experienced, the three single-phase transformers operating as one bank will increase in transformer downtime, as any one of the transformers in the bank would mean the shutdown of the other two. Generally, the downtime of a single-phase transformer bank is 32 times longer than that of a three-phase transformer.

Increasing downtime for maintenance (planned or unplanned) will mean low reliability (SAIDI, SAIFI) for the transformer and, at times, may cause power interruptions. Hence, with the aim to decrease the amount of equipment in an operational group, a three-phase transformer is more advantageous than three single-phase transformers.

3.2.5 Construction time line

With increasing activities to replace existing transformers with a bank of single-phase transformers, it is obvious that the time required to construct transformer foundation is longer than that of a Single-phase transformer of same capacity. It is important to note that the construction time of many of the activities can be adjusted with proper management of resources but the time required for concrete work is defined by concrete setting time and the technology used. In a projects sites at high altitude, where ambient temperature in winter is between -10 to -15 ℃ and humidity is less than 26%, the time required for concrete setting is longer and generally, a great deal of concrete work in Bhutan (at higher altitudes) are suspended due to poor concrete strength during cold winter months.

3.2.6 Interconnection of existing & new systems

For this substation upgrading, interconnecting and matching control & protection systems with the existing system will be one of the most difficult activities as the substation has already undergone relay retrofitting and bay additions, at least for 3 times. Some changes have been incorporated during every retrofit or modification has been carried out. The major problem will be in matching standards, as the initial substation construction followed IS (Indian Standard) and all later retrofitting and upgrading that tried to match it followed IEC standards.

This mix of standards makes the maintenance of the substation as difficult as initial construction, if not more. Hence, it is important to try matching the existing standards with every possibility to make it easier to construct and traceable during operation and maintenance.

3.2.7 Future Growth and Expandability

Besides techno-economically chosen transformer ratings and type of equipment, augmentation, like any other shall never be final. With the continuously-increasing load demands and advancing technologies, need for future upgrade/expansion cannot be avoided. Hence, it is mandatory to plan and consider adaptability to future requirements when choosing type of equipment to be installed.

Luckily in this case, as the proposed substation is AIS, equipment adaptability will not be of major concern but planning, engineering and proper usage of space will allow future expansion without the need for many changes to the already-installed system.

4. Comparison between single-phase & three-phase transformers

As discussed under Sub-clause 3.2 above and compared in Table 3, when compared to a bank of single-phase transformers, a three-phase transformer is more advantageous for the selected size and the terrain.

In this case, as the capacity of the transformer is optimally selected for the terrain and facilities available or possible to access, techno-economically, for the selected project size, providing three-phase transformers is advantageous. To reiterate: selecting three-phase transformers reduces the total owning cost (TOC) as the three-phase transformer banks require additional accessories like LV bushing, Bucholtz relays, PRD relay, Conservator tank, OLTC, extra cables, an NCTs, etc. The three-phase transformer bank also requires additional civil works (separate foundation for each single-phase transformer, soak pit, grating, set back area, safety clearances for O&M, etc.). Most significantly, the space requirement for a three phase transformer is less than that for the

Table 3. Activity/Cost comparison of single-phase to three-phase power transformer

Activity	Sub-Activity	Single-Phase		Three-Phase	
		Advantage	Disadvantage	Advantage	Disadvantage
Construction	Construction Period		7 months	6 months	
	Interruption		More Difficult	Difficult	
	Construction Cost		Expensive	Less Expensive	
	Construction Management		More Difficult	Difficult	
Manufacturing/ Transportation	Time for Manufacturing	6 months			6 months
	Time to on site After manufacturing	2 months			3 months
	Transportation Difficulties	Difficult			More difficult
Space/Land Requirement			Larger Area	Smaller Area	
Environmental	Noise and Volume of Insulation Oil		Higher/Larger	Lower/Smaller	
Operation/ Maintenance	Operation		Difficult	Easier	
	Maintenance		More	Less	
Result				More Feasible	

three single-phase transformer bank.

5. Conclusion

Studies for proposing an optimal selection of transformers along with associated equipment and visits are recommended, especially in developing countries, due the amount of development and ad-hoc planning.

The appointment of agents to clear the goods while crossing international borders (Korea-India-Bhutan) for construction and logistic activities has been performed to the best of the information available. Where written information was not available, information from field visits and discussions with locals were considered in decision-making. Interestingly, some decisive factors discussed in this paper are the results of actual field activities.

The selection & decision-making methods discussed will be very useful for similar decision making processes. Data for this study were collected at great effort, difficulty and, at times, cost as there is no written documentation regarding transportation in hilly terrains. Theoretical analysis for transportation in many cases does not hold true in fact due to varying physical conditions as the road passes through many different terrains. Specific studies at actual sites will be interesting chapters for future study as every country has their own system and interpretations are sometimes dependent on local offices.

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