The HT Capacitor Bank Shunt Compensation

An initiative by State Power Utility to improve the system Power Factor and minimize the Loss

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Abstract:

In Sub-Transmission & Distribution system the significance of HT Capacitor Bank is increasing day-by-day for Shunt compensation. In West Bengal the premier power utility had taken an initiative for installation of HT Shunt Capacitor Banks at 11kV bus of 33/11kV substations. The main motto has been to improve the p.f. under Maximum demand conditions and subsequently improvement of voltage profile by reducing the huge network losses. Thus a part of today's increasing demand can be served, keeping the same Generation & Transmission capacity and consequently, more revenue can be earned. A systematic approach for designing the shunt compensation system along with post commissioning results have been presented herewith as case study basis.

Keywords:

Shunt compensation, compensating kVAR, equipment selection criteria, bank sizing, voltage rise, energy loss.

I. Introduction

Poor power factor results in higher power loss in the power distribution network associated with high transformer load loss and increased voltage drop at the consumer end. Conversely higher power factor leads to energy saving which can be sold, thereby increasing the revenue. Energy saved can also be treated as extra energy generation at the same capital cost. It also saves precious fuel and leads to optimum utilization of power distribution network. Apart from these tangible benefits it increases customer satisfaction by providing proper voltage at the receiving end and reducing frequent interruptions due to system overloading [3] & [10].

Power distribution networks mainly cater load to domestic, commercial, small industries, agricultural, water supply, government and public utility customers where characteristic of load is dynamic and unpredictable. It varies drastically from day to night, from summer to winter, from northern region to southern region of the states, which mainly depends upon socio-economic structures, climatic conditions and demography of different localities throughout the states. Since independence, thrust was given to power development programs through large scale urban & rural electrifications and the rapid expansion of sub-transmission and distribution networks mostly happened without adequate studies to evolve optimum network, size and location of substations, backup transmission systems etc. The problem has been compounded by the rise in industrial & agricultural loads which have increased the reactive power requirements.

With a primary objective to reduce loss & improve system efficiencies, the premier power utility of West Bengal started taking initiative for reactive power compensation at their 33/11kV substations spreading at different locations within the state of West Bengal in India. The utility appointed India's frontline engineering consultant MECON Ltd. for selection of location and design/engineering for installation of shunt capacitor bank at 11kV bus of these substations. Previously, similar initiatives failed in totality due to wrong selection of capacitor banks and the investments in the infrastructure yielded no return.

Under such circumstances, it is not prudent to specify capacitive compensation to a network without undertaking a preliminary investigative study. Before taking up the substations individually for consideration of bank sizing, the initial approach demands a system study, upto the extent possible, to segregate groups of substations having various conditions of p.f. and voltage profile at the recorded maximum demand and/or other load conditions within a stipulated period of measurements. The more the period of observation the accurate would be the inference.

Under practical situations, low power factor does not mean that the sole solution is to put a capacitor bank to improve the power factor and voltage profile. Hence, from the first day, endeavor was made to keep the selection of substations for shunt compensation and the selection of capacitor banks for selected substations through a rational and methodical approach for effective use of capacitor banks in future for minimization of loss and at the same time optimization of project costs.

II. Selection criteria of Substations

An optimum selection of Capacitor Bank is important to avoid over/ under voltages on the bus, which may result in frequent switching of the Capacitor Banks affecting the operation of normal switching device. In this case, endeavor was made to improve the power factor to at least 0.9 at the 11 kV bus under most severe condition and at the same time limiting over voltage on the bus to less than 2% even under lightest load conditions. The motto is to keep the capacitor bank connected to 11kV bus at most of the time throughout the day under all possible loading conditions to reduce the network losses due to drawal of reactive power.

Hence, the **p.f. greater than or equal to 0.9** was considered as **good p.f.** Any normal voltage variation at the bus in consideration, if falls within **permissible variation limits as per standard** (in India it is as per table 2 of BIS: 12360-1988) can be referred to as **good voltage profile**. However, it is pertinent to mention here that utilities can set their own benchmark based on area wise load profile or on bank sizing economics.

Based upon downloadable multi function meter data analysis, all the 33/11kV substations were categorized as follows:

i) *Substations having **poor p.f.** and **poor/ normal/ good voltage profile** at maximum demand of 11 kV level.*
ii) *Substations having **good p.f.** but **poor voltage profile** at maximum demand of 11 kV level.*
iii) *Substations having **good p.f.** and also **normal/ good voltage profile** at maximum demand of 11 kV level.*

The sub-stations under category iii) can be excluded from the scope as installation of capacitor banks will definitely not give good payback. Moreover, the size of capacitor bank will be small, which will not be sufficient to compensate the reactive power demand after five years due to load growth.

Substations under category ii) can also be excluded from the scope of installation of bank since this situation usually occurs due to several abnormal network conditions like under rated conductors, improper conductoring, long incoming feeders, improper adjustment of taps of EHV/HV transformers or due to low receiving voltage. Putting a capacitor bank in a substation may not cause betterment of voltage profile if poor voltage scenario is attributed to feeder related issues which require load flow studies for correct assessment of the remedy. The rectification of these conditions falls under the scope of different project.

III. Selection criteria of Capacitor Banks

Based upon downloadable multi function meter data analysis for a particular 33/11kV substation, the requirement of shunt compensation will be different, as per different approaches mentioned below:

i) *Max. Demand (in kW) with corresponding p.f.*
ii) *Average demand (in kW) with corresponding p.f.*
iii) *Demand (in kW) with poorest p.f.*
iv) *Max. demand (in kVAR)*

Since maximum demand corresponds to the maximum active power drawal, it doesn't necessarily mean that this condition shall match with maximum VAR drawal. However, at maximum demand condition a substantial VAR drawal does occur, which, though may be less than maximum VAR drawal, still gives a reasonable benchmark for VAR compensation design decision.

This condition is also a predominant factor for selection of substations requiring compensation, since all the equipments in line such as power transformers, current carrying conductors, protective equipments etc. can be saved from overloading by relieving its VAR burden at maximum demand, so that more active power can be extracted without capacity augmentation. However, due importance is also to be given to the VAR drawal at 11 kV during poorest p.f. conditions.

IV. Calculation of Capacitor Banks sizing

The calculation of capacitor bank sizing for individual substations has been done by following steps:

a) From Reactive Power Compensation point of view:

Two different sets of system data at 11kV bus are needed from month wise Meter readings:

- *kW & kVAR Demands corresponding to poorest p.f. condition at 11kV*
- *kW & kVAR Demands corresponding to maximum demand (in kW) condition at 11kV*

Compensating reactive power to be injected into the system to raise the p.f. to a target value of say, 0.9 (in our case) at the same active power demand, are to be calculated for both the above cases as shown below:

$Compensated\ kVAR = [kW \times Sin\ (Cos^{-1}\ 0.9)]/0.9$
$Compensating\ kVAR = Uncompensated\ kVAR - Compensated\ kVAR$

b) From Limiting the Voltage Rise point of view:

Voltage drop in any line section is directly related to line impedance parameters & load conditions. Voltage change can be written as

$\Delta V = I \times (R.\ cos\ \Phi + X.\ sin\ \Phi)$

[$R.\ cos\ \Phi$ reflects the active power contribution to voltage drop per ampere of total current and $X.\ sin\ \Phi$ reflects the reactive power contribution to voltage drop]

Typically X. Sin Φ is many times greater than R. Cos Φ, almost five to ten times greater-because the circuit reactance usually is larger than circuit resistance. Thus, typically, reactive power flow produces a voltage drop magnitude that is several times greater than that produced by actual power flow. Therefore, increasing the p.f. by installation of bank will automatically improve voltage profile.

Hence before finalizing selection of bank based on a) above, it is very much imperative to check that bus voltage at the point of installation of bank (11kV in our case) does not cross the upper limit of allowable system voltage rise at any load condition (refer table 2 of BIS: 12360-1988) and at the same time, limiting over voltage on the bus to less than 2% even under light load/no load condition due to overcompensation. The limiting restriction of overvoltage shall be designer's choice based on particular network.

System impedance corresponding to symmetrical Short Circuit current is to be added with power transformer impedance to get total impedance upto the point of installation of bank. If system impedance to limit short circuit current is not known, symmetrical short circuit analysis may be carried out. For this purpose, support from any latest power system analysis software (in our case ETAP) may be taken or else calculation of total system impedance upto transformer LV bus (point of installation) may be done from design Fault MVA of upstream system.

Voltage rise in transformer bus on installation of capacitor bank can be calculated as follows [3]

% Voltage Rise = [(Capacitive VAR × %Z) / Transformer capacity in VA]

%Z corresponds to total upstream system impedance upto transformer LV bus (point of installation) when referred to transformer VA base. By substituting allowable % voltage rise at transformer LV bus, Capacitive VAR requirement can be found out. This calculated Capacitive VAR will be the maximum compensating VAR that can be put into bus, without permitting the voltage to go beyond permissible limit.

Let "X" be the compensating reactive power calculated with data pertaining to system conditions a) above and "Y" that for b) above. "X" and "Y" are to be compared with this calculated kVAR in b), acting as upper ceiling of compensation. The higher among the two kVARs ("X" & "Y") but within the upper ceiling is to be considered for final bank size for the individual substation.

V. Sample Case

Here is a Sample Calculation for Capacitor Bank Selection in line with cl. no. 3:

Name of substation: M2

PTR configuration: 3x6.3 MVA, 33/11 kV, 50 Hz DYn11.

a) Calculation from reactive power compensation point of view:

Uncompensated system data (total for 3 x 6.3 MVA transformers) with poorest p.f. at maximum load obtained from Meter Data Analysis Report in the month of MAR'07:-

<u>During Peak demand</u>

Load is 10251 kW and 9120 kVAR, i.e. 13720 kVA with p.f. = 0.75

<u>Compensated system data desired</u>

Load is 10251 kW with p.f. = 0.9

Compensated system load would be [10251/0.90] = 11390 kVA and [11390 × sin ($\cos^{-1}$ 0.90)] = 4964 kVAR

Hence, reactive power to be injected [9120 – 4964] = 4155 kVAR

Assuming equal loading for all three PTRs, compensating kVAR required for each PTR = 4155/3 MVAR = 1.38 MVAR at 11kV ≡ *1.87 MVAR at 12.8 kV*

b) Calculation from Limiting the Voltage Rise point of view:

In absence of actual data, minimum fault level at 33kV side of the Power Transformer (PTR) is assumed to be 200 MVA

$Z_{SYS/\,33kV} = \frac{33^2}{200} = 5.45\Omega$

Referring to 11kV side of PTR, this system impedance can be derived as

$Z_{SYS/\,11kV} = \left(\frac{11}{33}\right)^2 \times 5.45 = 0.606\Omega$

In line with the methodology of analysis presented here in connection with the Initial Approach for segregation of substations (cl. no. 2), the results were as shown here:

Data related to PTR:

33/11 kV, 6.3 MVA, percentage impedance considered 7.15 {refer BIS: 2026 (Part –I), 1977}

Hence, actual impedance of PTR w.r.t. 11kV side $Z_{PTR/11kV} = \frac{11^2}{6.3} \times 0.0715 = 1.373\ \Omega$

Considering same p.f., total impedance

$Z_{Total/11kV} = Z_{SYS/11kV} + Z_{PTR/11kV} = 0.606 + 1.373 = 1.979\Omega$

Total percentage impedance, $\% Z_{Total/11kV} = \frac{1.979}{11^2} \times 6.3 \times 100 = 10.3\ \%$

Hence, the maximum Bank size for a no-load voltage rise of 2% is $C_{MVAR} = \frac{\%V \times MVA\ (PTR)}{\%Z\ Total}$

Putting data, $C_{MVAR} = \frac{2 \times 6.3}{10.3}$ = 1.22 MVAR at 11kV = *1.65 MVAR at 12.8kV*

Final Capacitor bank sizing

Since, the compensation required for improving the p.f. to 0.9, 1.38 MVAR at 11kV is higher than the permissible compensation for 2% voltage rise at no-load 1.22 MVAR at 11kV; the lower size is selected as 1.22 MVAR at 11kV. The bank size becomes 1.65 MVAR at 12.8 kV. In order to standardize the banks, the final size selected for M2 Sub-station is therefore, 1.5 MVAR at 12.8 kV for individual control.

VI. Description of the Installations

The single line diagram (SLD) of the arrangement is depicted in fig. 1.

The SLD shows arrangement for two nos. power transformers (PTR) and hence, two nos. of 11 kV buses; the same shall be replicated when number of PTRs are more.

The installation is designed such that there shall be one dedicated bank against the incoming breaker of each transformer corresponding to its capacity. This has been done in order to maximize the use of capacitor bank by limiting the voltage rise at no load condition within the permissible limit against the corresponding transformer.

Re-strike free Capacitive Duty circuit breaker having adequate capacitive current making and interrupting capacity has been employed for the switching purpose. A series reactor of rating 6% of capacitor bank kVAR is used for damping and limiting initial transient inrush current to safe value [1]. This series reactor also acts as a general filter. Two types of capacitor bank arrangements have been proposed – Ungrounded single star (for less than 1000 kVAR installations) and Ungrounded double star (for 1000 kVAR and above). The voltage rating of the bank has been enhanced to 12.8 kV due to induction of overvoltage by the use of series reactor.

Fig. 2 is an actual photograph of site installation showing above components.

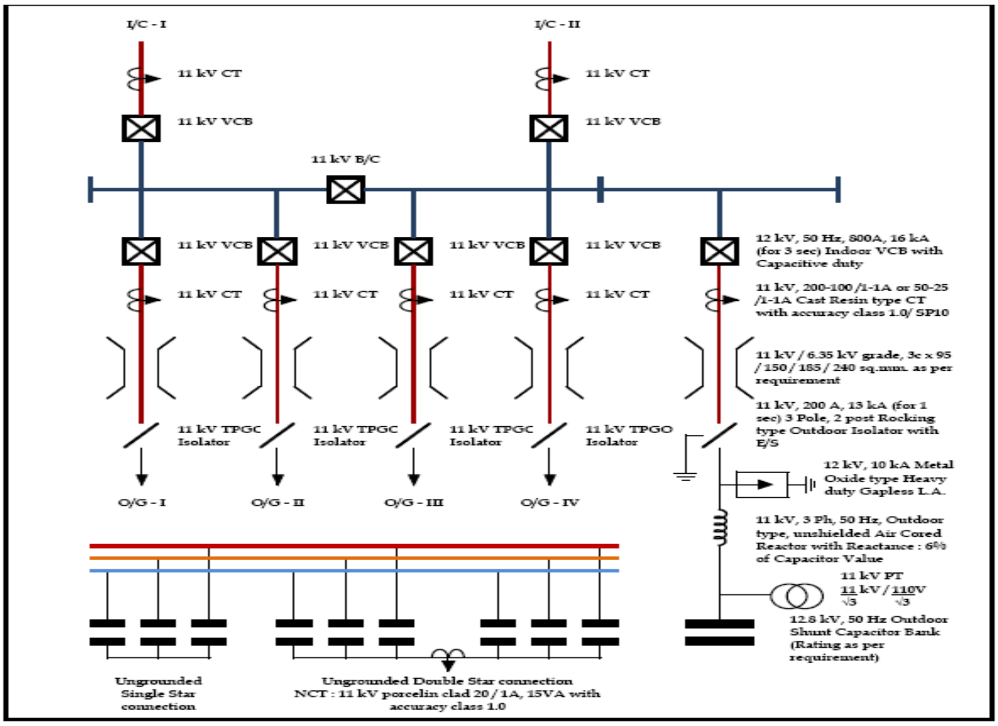

Fig. 1

VII. System Improvement Results (Post Commissioning)

After commissioning of HT capacitor banks in the substations, the actual value of the p.f. and the voltage improvements in the substations throughout the installations were checked ~~after the installation of the capacitor banks~~. Network readings were taken with and without the banks and results were noted to see the improvement in both voltages as well as power factor profile.

The report of **Taldanga 33/11 kV substation** under **Chinsurah division** has been presented herewith as sample basis.

<table>
<tr><th rowspan="2">Installed Capacity
Installed kVAr
&
Mode of compensation</th><th rowspan="2">Transformer No.</th><th rowspan="2">I/c No.</th><th colspan="3">Without Capacitor Bank</th><th colspan="3">With Capacitor Bank</th><th rowspan="2">% Loss Reduction</th><th rowspan="2">% Capacity Addition</th></tr>
<tr><th>P-P Voltage (kV)</th><th>Line Current (A)</th><th>p.f.</th><th>P-P Voltage (kV)</th><th>Line Current (A)</th><th>p.f.</th></tr>
<tr><td rowspan="4">4 x 6.3 MVA with 4 x 1250 kVAr

Individual Compensation</td><td rowspan="2">6.3 MVA</td><td rowspan="2">1</td><td>10.57</td><td>128.0</td><td rowspan="2">0.873</td><td>10.88</td><td>110.8</td><td rowspan="2">0.992</td><td>25.07%</td><td>10.90%</td></tr>
<tr><td>10.70</td><td>134.4</td><td>11.00</td><td>119.2</td><td>21.34%</td><td>08.82%</td></tr>
<tr><td rowspan="2">6.3 MVA</td><td rowspan="2">5</td><td>10.58</td><td>576.0</td><td rowspan="2">0.772</td><td>10.90</td><td>476.0</td><td rowspan="2">0.968</td><td>31.71%</td><td>14.86%</td></tr>
<tr><td>10.52</td><td>580.0</td><td>10.76</td><td>480.0</td><td>31.51%</td><td>15.35%</td></tr>
</table>

	6.3 MVA	2	10.77	134.4	0.844	10.98	115.2	0.986	26.53%	12.61%
			10.69	131.2		10.82	110.0		29.71%	15.14%
	6.3 MVA	3	10.68	378.0	0.782	10.86	306.8	0.987	34.12%	17.47%
			10.54	344.0		10.78	283.6		32.03%	15.68%

Results have been derived and tabulated from above similar tables for all the substations (78 nos in totality), where HT capacitor banks were installed and commissioned. The summarized results are presented here in tabular form:

Improvement in power factor at 11 kV bus

Range of p.f.	**0.85 to 0.90**	**0.90 to 0.95**	**0.95 to 1.0**
% of Installations	14.71%	37.25%	47.06%

Improvement in voltage profile at 11 kV bus

Range of voltage	**(-7.5% to -5.0%) of 11kV**	**(-5.0% to -2.5%) of 11kV**	**(-2.5% to 0.0%) of 11kV**	**(0.0% to +2.5%) of 11kV**	**(+2.5% to +5.0%) of 11kV**
% of Installations	12.26%	23.58%	30.19%	16.04%	17.92%

It is evident from the above table that the voltages at all the buses have been maintained within the allowable limits of +6% to -9%.

Improvement in voltage profile due to switching of capacitor banks at 11 kV bus

% Improvement in voltage	**0 to 2%**	**2 to 5%**
% of Installations	77.78%	21.21%

Equivalent capacity addition

% Capacity addition	**0% to 5%**	**5% to 10%**	**10% to 15%**	**Above 15%**
% of Installations	41.31%	37.09%	17.37%	4.23%

Reduction of loss

% Reduction in loss	**0% to 5%**	**5% to 10%**	**10% to 15%**	**15% to 20%**	**20% to 25%**	**25% to 30%**
% of Installations	13.49%	21.40%	18.14%	19.53%	13.95%	13.49%

It is evident that there is considerable reduction in system loss after installation of capacitor banks.

VIII. Conclusion

In line with earlier elaboration, kW & kVAR Demands corresponding to poorest p.f. condition at 11 kV shall be consulted for more accurate analysis. This has not been done in our case due to non-availability of field data. Moreover stepless capacitor banks were considered in our project to optimize the project cost. A stepped bank can address the problem of varying compensation in line with load fluctuation in a better way [6]. In absence of system harmonic data, a general filter was proposed. It is always recommended to carry out proper harmonic analysis to specify correct filter [4].

Fig. 2

IX. Disclaimer

The views expressed here are strictly the personal belonging to the authors only and any organization does not necessarily subscribe to them in any way.

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