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Elevated Frequency Testing of Ultra High Voltage Shunt Reactors with Advanced Test Setup

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Abstract - **Tests on ultra high voltage shunt reactors are demanding huge reactive power. Earlier, test was performed at 1.7 p.u. applied per phase connection, however, in revised IEC 60076-3, 2013 this test needs to be performed at 1.8 p.u. on symmetrical three phase connection simultaneously. To meet this requirement, advanced test setup is designed to fulfill the requirements of standards. In this test setup, reactive power compensation is provided in between two test transformers to minimize the current drawn by keeping the voltage level moderate in the power system network. Moreover, a HV passive filter is provided in between test transformer and reactor under test for effective filtration of noise emitted from power source and surroundings. The details of the proposed test setup and related simulations are discussed in the paper.**

Keywords – HV shunt reactors, IVPD test, reactive power compensation

I. INTRODUCTION

When long transmission lines are laid, separation between the line and ground forms a capacitor parallel to transmission line, due to which the receiving end voltage rises (compared to sending end voltage) with the increase in distance. To overcome the effect of this capacitance, shunt reactors are installed at the transmission and distribution systems as they are used to reduce the over voltages during light load conditions.

Testing of shunt reactors during manufacturing is imperative to meet the design and performance criteria. Testing on shunt reactors is conducted as per IEC 60076-6 [1], the dielectric testing of shunt reactors is conducted as per IEC 60076-3, 2000. The test was previously known as long duration induced AC voltage test (ACLD) and performed as per IEC 60076-3, 2000 [2]. Recently, this test has been revised and renamed as induced voltage test with partial discharge (IVPD) and is performed as per IEC 60076-3, 2013 [3]. As per this test, all the three phases of the shunt reactor shall be tested at a time and a voltage of 1.58 times the rated voltage is to be applied for 60 min. which is suitable for checking the ability of the insulation to withstand stresses by determining the electrical discharge behavior. The enhanced voltage level, 1.8 times the rated voltage which is applied for duration that depends on the test frequency applied for checking the withstand capability of the insulation.

A new test setup is proposed so that the entire power frequency test on single phase shunt reactor up to 110MVAr, 765/√3 kV and three phase shunt reactor up to 125MVAr, 420kVcan be performed with the same setup [4]. To establish the setup certain calculations are carried out to determine the rating of various equipments connected in the test setup. For this variable frequency generator, higher rated transformers and capacitive compensating network are required to improve the power factor of the system. The test setup parameters should be chosen in such a way so as to avoid catastrophic failure due to overcompensation of the capacitor bank [5].

The main objective of the paper is to design a test setup according to the requirement for testing of various shunt reactors with ease as per revised IEC 60076-3, 2013.IVPD test on shunt reactors with common setup is a challenging task as it requires high level of voltage, elevated frequency and power. The test setup should be such that it must be able to feed the discharge free stable power, which can be achieved by the use of thyristor controlled MG set. The calculations are done both manually and through MATLAB software and graphs are plotted. The validation of the calculation is done through PSCAD software.

I. TEST SETUP

To conduct the test on higher rated shunt reactors a test setup comprising of variable frequency alternators, transformers and reactive power compensation network is required. While conducting the test the active power is fed by the alternators and the reactive power is compensated by the capacitor bank. The design includes the interposing transformer, vacuum circuit breaker and the test transformer for protection and desired voltage respectively. A typical setup for conducting IVPD variable frequency test is shown in Fig.1. The setup comprises of an alternator, step up transformer T1, T2, capacitor bank for compensation of reactive power, HV passive filter for reduction of noise levels and the reactor under test.

II. DESCRIPTION OF THE EQUIPMENTS USED IN THE TEST SETUP

1. MG Set (3 phase, option for single phase in zig zag connection) – To feed active power at elevated frequency in order to meet the losses taking place in the system.

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2. Interposing Transformer(T_1) – The output of the MG set is given to LV side of T_1 for raising the voltage level.

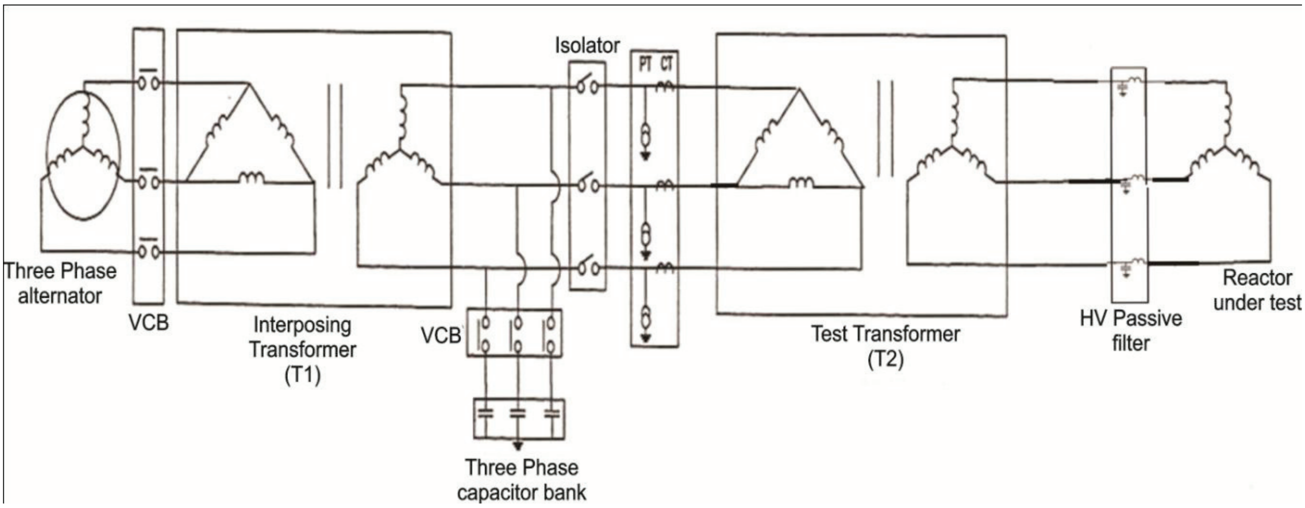

Fig.1. Test setup for conducting IVPD Test

Fig.2. HV passive filter connected between test transformer and the shunt reactor.

3. Test Transformer (T_2) – The output of T_1 i.e from the HV side is given as the input to the test transformer T_2 to step up the voltage as per the desired level for conducting the IVPD test.

Here two transformer T_1 & T_2 are taken to reduce the primary side current.

4. Capacitor Bank – Used for the reactive power compensation on the LV side of the transformer (T_2). The reactive power compensation network comprises of the capacitors which are connected in series and parallel combination depending on the reactor which is to be tested.

5. Measuring Instruments (CT, PT) – These are used for measuring purpose in order to determine the voltage and current flowing in the LV side of the transformerT_2.

6. HV Passive filter – It serves dual purpose i.e. reduction of noise and allows high frequency signal to pass. It also measures the high voltage in terms of peak /$\sqrt{2}$.

III. NECESSITY FOR CONDUCTING TEST ON HIGHER FREQUENCIES

The rated power frequency is 50 Hz. If it is increased above rated frequency for compensation of reactive power than accordingly the voltage will be increased in proportion to the frequency in order to keep the magnetic field constant as:

$$B \ \alpha \ \frac{V}{f} \tag{1}$$

The test level for testing of shunt reactor is 1.8 times the rated voltage to be applied i.e for 420kV class it is 420 × 1.8 = 756kV & for 765kV class the voltage level will be $\frac{765}{\sqrt{3}} \times 1.8 = 795$ kV so in order to achieve higher voltage level for testing, the frequency has to be increased [6].

IV. TEST CONDITIONs

For conducting IVPD test on single and three phase shunt reactor following conditions are considered:

1. Corona discharge free equipment like transformer, capacitor bank, generator, connecting AIS bus link and cables are connected in the test setup to achieve stable power flow in the system.

2. High rating of T_1 & T_2 are considered to minimize the voltage regulation.

3. For measurement of voltage and current highly accurate zero flux CT & voltage divider are used.

4. Earthing resistance of the test lab is less than 0.5 ohm.

5. A hollow Aluminum tubular bus bar consisting of HV passive filter is connected between test transformer T_2 and the reactor under test.

6. This test is conducted in the electromagnetically shielded laboratory.

A. *Case Study 1: IVPD test on three phase shunt reactor*

125 MVAr, 420 kV, 3 phase shunt reactor

Test level:
420 × 1.8 = 756 kV

Power drawn by shunt reactor:

$$Q_1 = Q_2 \times (p.u)^2 \times \left(\frac{f_r}{f_t}\right) \quad (2)$$

where,
Q_1 = reactive power MVAr at 756 kV
Q_2 = reactive power MVAr at 420 kV
Rated frequency (f_r) = 50 Hz
Test frequency (f_t) = 152 Hz
Q_1 = 133.22 MVAr

$$Q_{comp.} = Q_{cap.bank} \times \left(\frac{\text{voltage of LV side of T2}}{\text{capacitor bank voltage}}\right)^2 \times \left(\frac{f_t}{fr}\right) \quad (3)$$

Power compensated by capacitor bank ($Q_{comp.}$) =128.30 MVAr

$$Q_g = Q_1 - Q_{comp.} \quad (4)$$

The power delivered by the generator ($P_{g.}$) = 4.92 MVAr

Table1. Power requirement by different equipment connected in the test setup for different rating of three phase shunt reactor.

S.No.	Rating of shunt reactor (MVAr)	Frequency (Hz)	Power drawn by reactor (MVAr)	Power compensated by capacitor bank (MVAr)	Power delivered by generator (MVAr)
1.	50	96	84.37	81.03	3.34
2.	63	108	96.50	91.66	2.84
3.	80	122	106.22	102.98	3.24
4.	125	152	133.22	128.30	4.92

B. *Case Study 2: IVPD test on single phase shunt reactor*

110 MVAr, 765 kV, 1 phase shunt reactor

Test level:

$$\frac{765}{\sqrt{3}} \times 1.8 = 795 \text{ kV}$$

where,
Q_1 = reactive power MVAr at V = 795 kV
Q_2 = reactive power MVAr at V = 765/√3 kV
Rated frequency (f_r) = 50 Hz
Test frequency (f_t) = 137 Hz

Power drawn by shunt reactor:

Q_1 = 130.07MVAr (refer (eqn. 2))

Power compensated by capacitor bank
$Q_{comp.}$ = 128.02 MVAr (refer (eqn. 3))

The power delivered by the generator
Q_g = 2.05 MVAr (refer (eqn.4))

Table2. Power requirement by different equipment connected in the test setup for different rating of single phase shunt reactor.

S.No.	Rating of shunt reactor (MVAr)	Frequency (Hz)	Power drawn by reactor (MVAr)	Power compensated by capacitor bank (MVAr)	Power delivered by generator (MVAr)
1.	80	116	111.72	108.39	3.33
2.	110	137	130.07	128.02	2.05

From Table 1 & 2 it is inferred that by increasing the frequency, reactive power drawn by the reactor & generator is proportionately reduced and simultaneously the power compensated by the capacitor bank is increased to operate the system near unity power factor (lag) and helps to achieve the economical and stable operation of the system.

V. ANALYSIS THROUGH MATLAB SOFTWARE

For economical and stable operation of the system any of the following can be varied:

1. Frequency of the generator
2. Rating of the capacitor bank

A. *Varying Frequency of the Generator*

The economical and reliable operation of the generator can be achieved by increasing the frequency to meet the required power demand by the reactor. It is seen that if the test is performed at rated frequency then the power required to be delivered by the generator will be more. For such high power installation of the generator, cost will be high and the size of the generator will be large. Fig.3shows the power delivered by the generator on varying the frequency keeping fixed capacitor bank (410MVAr) for different rating of three phase shunt reactor. The program is developed in MATLAB and the graphs are plotted to determine the frequency at which the optimum operation of the generator for different ratings of the shunt reactor can be achieved economically.

From the same setup single phase testing of the shunt reactors can also be possible. This can be achieved by connecting the three phases of the generator in zig zag manner then by increasing the frequency the power delivered by the generator can be minimized.

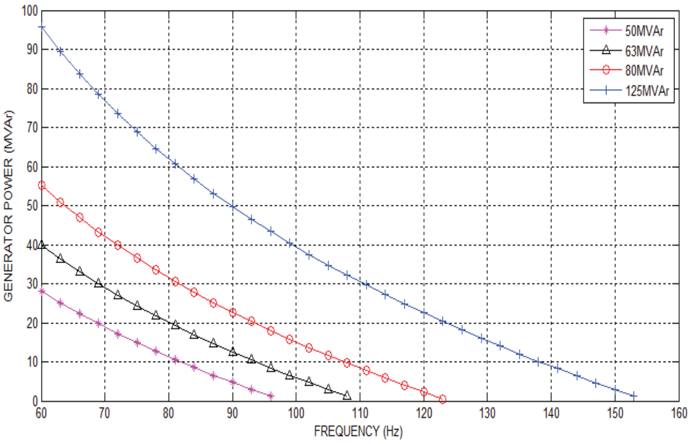

Fig.3. Variation of generator power with frequency for different rating of 420 kV three phase shunt reactor.

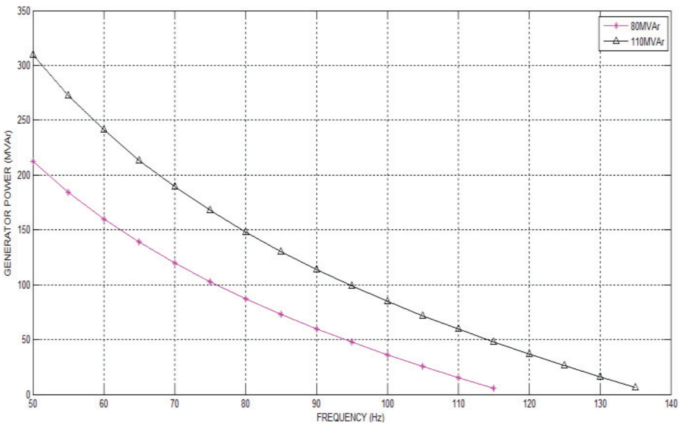

Fig.4. Variation of generator power with frequency for different ratings of single phase, 765/√3 kV shunt reactor.

B. *VARYING RATING OF THE CAPACITOR BANK*

The other way to achieve the economical operation of the generator is by varying the rating of the capacitor bank. In the fig.5 it is seen that the power delivered by the generator for different rating of three phase shunt reactor is minimized by increasing the power rating of the capacitor bank keeping fixed frequency (150Hz). If the rating of the capacitor bank is low then more amount of power has to be delivered by the generator which is not economical so the program is developed in MATLAB and the graphs are plotted accordingly to determine the rating of the capacitor bank at fixed frequency for optimal operation of the generator.

For the single phase shunt reactors the power delivered by the capacitor bank keeping fixed frequency (150 Hz) and varying the rating of the capacitor bank is shown in the fig.6.

Both the methods i.e, varying the frequency of the generator and varying the rating of the capacitor bank can be used for economical operation and minimum loading of the generator.

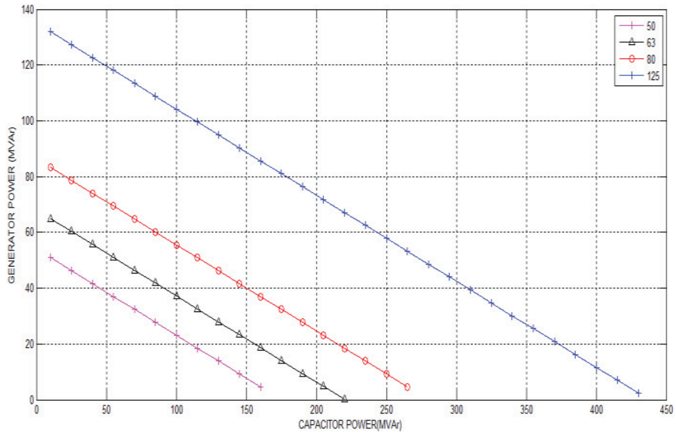

Fig.5. Variation of generator power with capacitor power for different ratings of three phase, 420 kV shunt reactor.

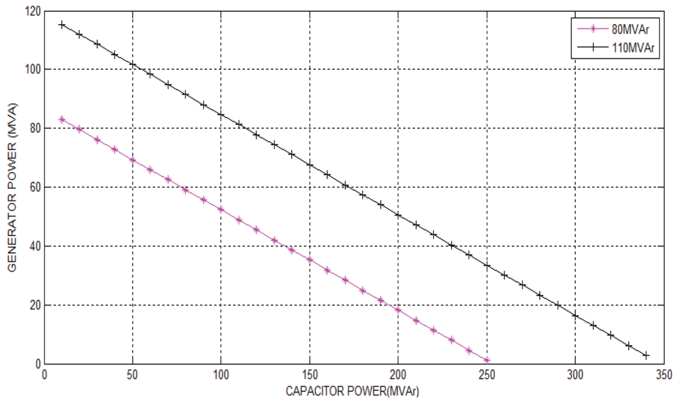

Fig.6. Variation of generator power with capacitor power for different ratings of three phase, 420 kV shunt reactor.

Both the methods i.e, varying the frequency of the generator and varying the rating of the capacitor bank can be used for economical operation and minimum loading of the generator.

VI. VALIDATION OF THE MATLAB RESULT USING PSCAD SOFTWARE

The simulation for the IVPD test on 125 MVAr, 420 kV three phase shunt reactor is done using PSCAD/EMTDC software.

Simulated test setup can check the conditions of over, under and ideal capacitive compensation at any frequency. The simulation is performed on the test setup for determining the active power, reactive power, voltage, frequency and current at every node.

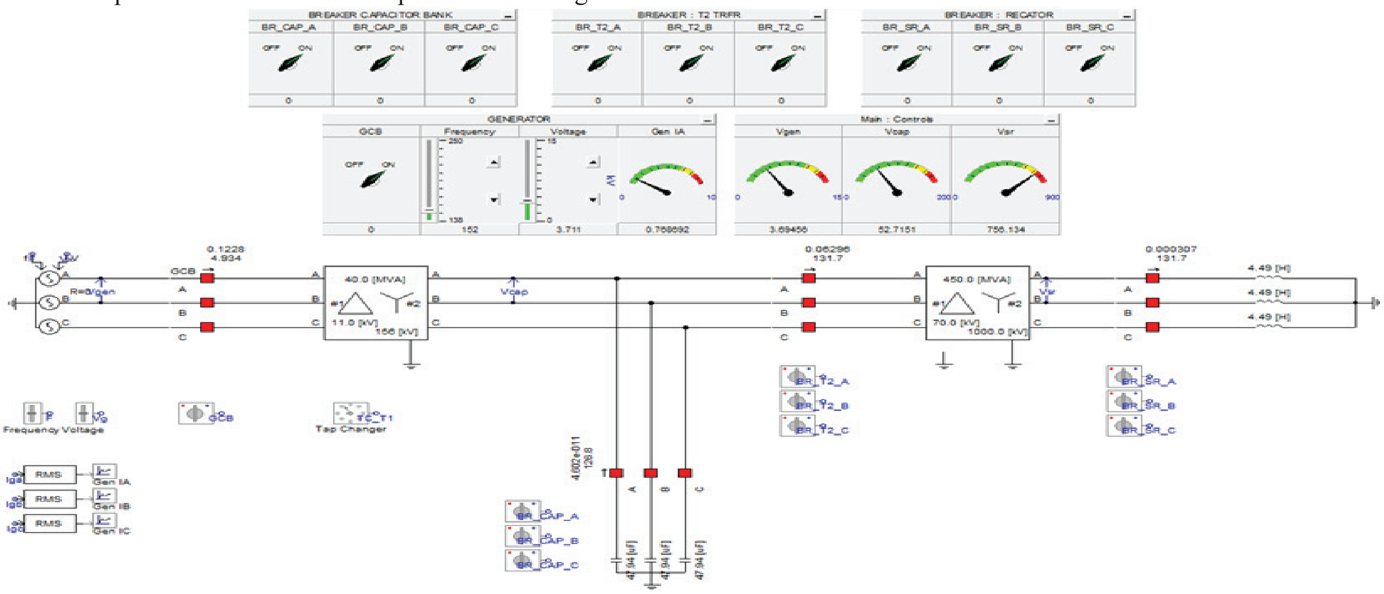

Fig.7. Power flow analysis through PSCAD/EMTDC software

Table3. Comparison of the results obtained using MATLAB and PSCAD software considering 125 MVAr, 420 kV three phase shunt reactor.

Software	Frequency (Hz)	Test level (kV)	Power drawn by reactor	Power compensated by capacitor bank (MVAr)	Power drawn by generator (MVAr)
MATLAB	152	756.00	133.22	128.70	4.92
PSCAD	152	756.13	131.70	126.80	4.93

From the Table 3, it is concluded that the results obtained by MATLAB have been validated by using PSCAD software hence the test setup can be used for performing IVPD test on both single and three phase shunt reactor.

VII. HIGH FREQUENCY REACTIVE POWER COMPENSATION

It is necessary that the capacitive power should be close to the power drawn by the reactor to operate the system near unity power factor, reduce the voltage drops, improve the efficiency, reduce the electric utility bills, hence losses will be reduced as less heating of cables occurs.

A. Over Compensation

If it occurs then bursting of capacitor units and fire may take place. A slight increase in the voltage, harmonic magnification, resonance and overheating may be seen due to overcompensation. To avoid such failures reactive power relay is installed, this senses flow of reverse reactive power in alternators and trip the breaker.

B. Under Compensation

If small rating of the capacitor bank is chosen then more power is drawn by the generator which will be costly and huge maintenance is required.

VIII. CONCLUSION

The test setup is proposed for performing IVPD test on single and three phase ultrahigh voltage shunt reactors. The calculations show the suitable selection of test frequency for small but optimal rating alternator. The approach is validated by varying the frequency and rating of capacitor bank to obtain the economical operation for different rating of shunt reactors. The results obtained by MATLAB software have been validated by PSCAD software.

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