Power Quality Analysis and Power System Study in High Voltage Systems

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Abstract
This paper presents is to identify the causes for series reactor failures and to monitor and protect the 11 KV power system components and equipments from the harmonics and transients and other power quality related problems. Power quality is a major concern of our modern industries and other consumers. Poor quality of supply will affect the performance of customer equipment such as computers, microprocessors adjustable speed drives, power electronic devices, etc. and results in heavy financial losses to customers due to loss of production or breakdown in industries or loss of life in a hospital. The two major power quality disturbances are voltage sag and harmonic distortion. In the event of voltage sag, due to insufficient energy, equipments may malfunction or trip. Harmonics introduced by nonlinear loads can pollute the input supply to the sensitive equipments and cause the connected equipments to malfunction. In this paper, a Power Quality Provider is proposed and modeled by simulation with the help of external agencies meters.

Keywords: Capacitor Bank, Harmonics, Phase and Earth Relay, PSCAD/EMTDC Package, Reactors

1. Introduction
The water supply company - Tirupur is operating a booster pumping station located near Perundurai, Erode. The pumping system has three huge size KBL pumps, which are driven by CGL HT motors of 11kV, 1800KW1. For the incoming power supply of 11kV, the pumping station is provided with the separate designated TNEB 110kV sub-station. The TNEB sub-station has been enabled with dual incoming feeders one from 110kV - Erode S/S and another 110kV – feeder from Ingur S/S. The TNEB sub-station has two power transformers (one transformer is normally in service and the other one is stand-by) of 10 MVA, 110kV / 11kV from which they feed supply to the BPS. From TNEB the supply is fed to HT incoming panel through a2-pole structure2. From HT panel, this supply is distributed through vacuum circuit breakers to three numbers of HT motors of rated at 11kV 1800kW, HT power factor correction capacitors of 500 KVAR each for each of these pump motors and 2 numbers of auxiliary transformers (one standby) of 200KVA rating. Auxiliary transformers are servicing the various LT loads. In the usual 24x7 operations, MWUL normally operate one motor continuously and operate the second motor additionally when required. At present, the second motor is being run twice a week. The motor power circuit consists of a

HT motor driving the pump coupled through a speed control device named as fluid coupling, HT capacitor bank with current limiting reactors for power factor correction and FCMA neutral soft starter to regulate the starting current to HT motor. HT panel incomer is provided with Earth fault, over current and under voltage protections and the HT motors are provided with motor protection relays which serve for many protections related to the motor. As per the company, the failure of the current limiting series reactors had taken place repeatedly 3 or 4 times with in 3/4 days. Customer had been changing with the spare reactors or rewound reactors after heating the same in oven3. The failures had taken place only when the 2nd motor is getting connected to the system parallel with the first motor already running. The failures have apparently taken place randomly in any of the phases. The failures were noticed in the incoming motor set capacitor
current limiting reactors and once in the already working motor’s pf capacitor reactor.

Physical inspection of the reactors available at site indicated only inter-turn flashovers. There might have been flashover to earth also as suggested by the photographs of the badly charred reactors (since such a fault will result in large magnitude of current). When the failure had taken place in the last instant, there was transformer tripping with Buchholz relay operation. Subsequently the transformer has been isolated, removed and has been taken to the manufacturer for investigation and repair. The photographs of the opened up transformer at the manufacturer’s site indicates that some of the LT coils have come out of the position along with their clamps and the bolts indicating high current flow through the windings. This paper is very useful in the EHV/HV systems where huge capacity loads are switched ON/OFF intermittently. This project covers the load flow system study and suggests the proposed methods for Power Transformer and other power system elements protection.

The broad areas of the study cover the following areas.
- Load flow analysis
- Short circuit study
- Relay settings review and co-ordination
- Evaluation of earthing and grounding system
- Electromagnetic transient studies and conclusions
- Observations during physical inspection of the reactors

2. Conventional Methods

TWSSP company is operating a Booster Pumping Station (BPS) located near Perundurai – Erode with high power HT motors along with their power factor correction capacitor circuits. These circuits are with current limiting reactors. The pumping operation normally consists of single pump operation with occasional operation with the two pumps. There were series of failures of the current limiting reactors during the starting of the second pump. This had affected the two pump operation. This paper is mainly taken up to find out the root cause for failure as well as protection methods for reactors during the two pump operations. In Conventional Method, 0.2% Reactor, No Monitoring/ Protection for Harmonics and Normal Inverse type relay for load side protection.

2.1 Drawbacks
- Not withstanding the high starting current of the circuit.
- Failure of the reactor may lead to major system failure.

3. Proposed Method

The block diagram showing the SLD of 11 KV up to Motor.

3.1 Block Diagram Explanation

To study the Single Line Diagram (SLD) for the system of MWUL as per the data available from the customer. Perform load flow analysis to determine the equipment adequacy of the existing system. Perform the short circuit studies and determine the fault level for three phase and
single line to ground fault and determine the adequacy of
the fault rating of the existing system\textsuperscript{8,9}.

3.1.1 Operation:
To review the present relay settings of MWUL and to give
the observations and Recommendations on the same.
Evaluation of earthing and grounding system in 110 / 11 kV
switch yard. Perform the EMTP related switching
transient studies to determine the over voltages / over The
recordings indicated increase of the Voltage and Current
THD values to a significant level at random intervals. It
was also noted that the most predominant harmonic is
the 13th harmonic. Based on the above finding further
analysis of the electrical system along with the existing
current limiting reactor of value L and power factor
correction capacitor of value C (for both single motor
operation and two motor operation) was undertaken to
find out the possible resonance situation taking place due
to the harmonic frequencies. The analysis indicated series
resonance (resulting into minimum impedance) condition
taking place at harmonic number of 12.92. This is a close
enough frequency to the predominant (13th) harmonic
noticed during the long time parameter measurements\textsuperscript{10}.
Considering the above it is recommended to shift the
occurrence of resonance situation to a higher frequency
to avoid the problem of current amplification under high
harmonic level condition.

3.2 Scope of Work
The above can be achieved by either increasing the
reactor value or by decreasing the capacitor value.
The simple means of achieving the reduction of the value capacitors is by reconnecting the existing power factor
correction capacitors (connected in delta) to star
connection\textsuperscript{11}. It is also found that the above reconnection
results in the reduction of overall operating power factor
from the existing recorded value of 0.98 to 0.92 which is
however still above the minimum value of power factor
to be maintained of 0.9 and hence can be considered
for implementation. To present comprehensively the
conclusions regarding the probable cause(s) of failure of
the reactors and suggest the different remedial measures.

3.2.1 Load Flow Analysis
One of the most common computational procedures used
in power system analysis is the load flow calculation. The
planning, design and operation of power systems require
such calculations to analyse the steady state performance
of power system under various operating conditions and to
study the effects of changes in equipment configuration. The
outcome of Load flow analysis provide information about,
- Component or circuit loading.
- Steady state bus voltages.
- Real and reactive power flows.
- Transformers tap settings.
- System losses.
- Performance under emergency conditions.

The load flow model is also the basis for several
other types of studies such as short circuit, stability,
motor starting, and harmonic studies. The load flow
model supplies the network data and an initial steady
state condition for these studies. Load flow analysis has
been carried out based on the data available from the
customer. The load flow model developed is solved by
Newton Raphson method. The study is conducted to
determine the adequacy of the existing system condition.
During the analysis it is observed that neither of the
bus voltages have crossed their limits nor the system
need any voltage compensation. All the components/
Accessories connected in the system network have proved
its adequacy. No component / accessory to be removed
from the system network.

3.2.2 Short Circuit Study
Short circuit analysis is another important power
system study to be carried out. Short-circuit studies are
conducted to determine the fault currents and fault MVA
levels in the system for various faults at different locations
throughout the system. The proper selection of circuit
breakers depends on the current flowing immediately
after the fault and the interruption current. In addition,
the results of the short circuit studies are used to determine
the settings of relays, which control the circuit breakers.
The model developed for the load flow analysis can also
be used to carry out the short circuit analysis.

4. Relay Settings Review and Co-
ordination
The data of present relay settings have been collected and
subsequently reviewed. Phase to Ground fault and Single
line to Ground fault is created at motor terminal of motor
– 1 i.e., at Bus – 12 (running motor) with minimum fault
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condition. The present settings for Phase current and Earth current of MWUL along with the suggested settings

![Figure 3. (a) Phase relay curves for present settings. (b) Phase relay curves for suggested settings. (c) Phase relay curves for suggested settings with 11 kV fuse. (d) Earth Relay Curves For Present Settings. (e) Earth relay curves for suggested settings.](image)

### 4.1 Observations

#### 4.1.1 Phase Relay Settings

For motor protection relay R12, the short circuit instantaneous time has been reduced to 4 times taking care of the motor starting current. For main incomer Relay R9 is recommended with new relay with Very Inverse Characteristic and settings of the same is provided in Table 1 It is better to provide instantaneous time delay element at R3 relay. Since it is observed from the exhibit 5.1 that the relay is tripping instantaneously at 780 Amps which interrupts the supply to MWUL.

#### 4.1.2 Earth Relay Settings

A CBCT is recommended for motor with CT ratio 150/5 to protect from SLG faults since present setting of the motor relay is provided with residual earth fault protection\(^\text{12}\). For main incomer relay R9 is recommended with new relay settings with very inverse characteristic and settings of the same is provided in Table 1

### 5. Simulation Study

Under the present scope of work, to find out reasons for the failure of the current limiting series reactors, a transient switching study has been performed using PSCAD/EMTDC package considered for this simulation study is provided\(^\text{13}\).
5.1 Description
When a capacitor bank is energized, the bank and the network are subjected to transient voltages and currents. The severity of the effect is determined by the size of the capacitor and the network impedance.

The worst case occurs when a capacitor bank is energized close to a bank that is already connected. The inrush current into the newly connected bank is determined by the size of capacitor bank and the inductance between two banks. The frequency of the inrush current is determined by the combination of inductance of energizing circuit and the capacitance of the banks. In installations without the current limiting reactors, the inductance between the banks will be only few micro-henries and a peak current of more than 150 times nominal current, at a frequency of more than 8 kHz can be expected. Capacitor standards such as IEC 60871 state that capacitors should be able to withstand inrush currents up to 100 times nominal. The standards also suggest a lower value for inrush current if capacitor banks are switched frequently.

5.2 Electromagnetic Transient Studies
Based on the sequence of events provided by the client two case studies have been considered for the simulation viz.,

• This case (Case 1) considers starting of one motor. It is assumed that other motor is out of service. The switching instant is so selected such that the one motor is started when the energizing voltage is near its peak value (switch closed at 0.505 sec).

• In the second case (Case 2) it is assumed that one motor is already in service and the other motor is started at time equals to 0.505 sec. The resultant waveforms are shown in Figures 4 to 12 considering existing value (0.2%) of series reactor.

The maximum and minimum phase to ground voltage observed for existing 0.2% series reactor is **16.124 KV and -10.527 KV**.

![Figure 4](image1.png)
**Figure 4.** Phase to Ground Voltage Waveforms at 11 Kv Bus for Case 1 from Table 1 with considering 0.2% Series Reactor.

![Figure 5](image2.png)
**Figure 5.** Current through Transformer LV side for case 1 from Table 1 with considering 0.2% series reactor.

![Figure 6](image3.png)
**Figure 6.** The Inrush current is flowing through the series reactor for case 1 from Table 1 with considering 0.2% series reactor.

![Figure 7](image4.png)
**Figure 7.** The currents drawn by induction motor for case 1 from Table 1 with considering 0.2% series reactor.
From the above results the transient inrush current drawn by capacitor banks are very high as compared to their rated currents and they damp out slowly for back to back switching of capacitor banks (Case 2) as compared to the figure 6 (case 1) Hence it is considered that the existing selected value (0.2%) for series reactor appear to be low. So as to arrive at a more optimum value of the reactor to limit the transient currents, the EMT studies were conducted for 5% reactor value. The selection procedure for the L and C are as described as follows for both 0.02% and 0.5 %. The capacitor units of 500 KVAR, 11 kV delta connected are used in electrical system of plant under study.

The voltage across the capacitor is system voltage plus other voltages as follows,

- Induced voltage occurred by reactor when electric current is flowing it.
- Voltage occurred by harmonic current flowing to capacitor unit.

**Calculation to choose capacitor units suitable for detuned filter is described in following two steps.**

**Step 1: Induced Voltage Calculation**

We assign $U_n$, $U_c$ and $p$ to be system voltage, the voltage across the capacitor after series reactor installation and ratio between impedance of reactor and impedance of capacitor respectively. When the current is passing through reactor, $U_c = U_n / (1 - \%p)$. When the voltage ($U_c$) is higher, reactive power of capacitor ($Q_c$) = $N_c / (1 - \%p)$ which $N_c$ is reactive power of capacitor at system voltage or nominal voltage.

**Step 2: Calculation Harmonic Current flowing to Capacitor**
Due to the presence of the harmonics, the RMS value of the currents through the reactor and the capacitor increases from the rated 100% value to a marginally higher value. The actual calculations require some more details. Presently a 10% rise may be assumed.

The capacitance value \( C \) is calculated from step 1 by use of \( U_c \) and \( Q_c \). \( C \) is computed as 4.38\( \mu \)F for the case of 0.2\% reactor and 4.17 \( \mu \)F for the case of 5\% (this matches within -5\% tolerance of the selected capacitor bank, (please refer Annexure-A4) and inductance of series reactor is also computed as 4.62 mH for the case of 0.2\% reactor and 0.122 H(considering 5\% of \( X_c \) instead of the 0.2\% used in the existing system). With these calculated new values of \( L \) and \( C \) considering 5\% reactor, the simulation of two case studies described earlier have been carried out and corresponding resultant waveforms are shown in Figures 13 to 21.

**Figure 13.** Phase to Ground Voltage Waveforms at 11 Kv bus for case 1 from Table 1 with considering 5\% Series Reactor.

**Figure 14.** Current through Transformer LV side for case 1 from Table 1 with considering 5\% series reactor.

**Figure 15.** The Inrush current is flowing through the series reactor for case 1 from Table 1 with considering 5\% Series Reactor.

**Figure 16.** The currents drawn by induction motor for case 1 from Table 1 with considering 5\% Series Reactor.

**Figure 17.** kV bus for case 2 from Table 1 with considering 5\% Series Reactor.

**Figure 18.** Current waveforms through Transformer LV side for case 2 from Table 1 with considering 5\% Series Reactor.
5.3 Study of System Harmonics and Calculation of Maximum and Minimum Impedances at Harmonic Frequencies

Subsequent to the preliminary report submission and discussion with customer on 28th July and 19 August 2010, it was decided to have continuous recording of the power system over a long-time (24 hrs or more). The recording given below under Figure 7 indicates the random occurrence of high level of harmonics with predominant number being 13. Considering the occurrence of large harmonics in the supply system further studies were conducted of the electrical system to check the possibility of the resonance condition setting in.

The result of the study indicated that at the harmonic number of 12.92 (646 Hz) the existing electrical power system with connected power factor capacitor and reactor experiences the series resonance condition providing a minimum impedance path of less than 0.2 Ohm (for one motor operation) and less than 0.1Ohm (for two motor operations). The above analysis was repeated for several of X / R ratio of the reactor considering additional cable resistance. From the above it is clear that the existing system has the tendency to get into resonance condition when the predominant harmonics (13th) exceeds a certain level. The direct solution to this problem is to provide appropriate de-tuning filter circuit of appropriate harmonic number or rating. However considering the randomness of the occurrence of the harmonic voltage it is recommended to go for shifting the resonance condition – occurrence of minimum impedance by modifying the values of the Reactor (L) and Capacitor (C).

A simple and the most inexpensive method is to connect the power factor correction capacitors in star connection instead of the existing delta connection by which the capacitor value ineffectively is reduced by a factor of 3. With this condition the resonant frequency is shifted to a value more than 22 in Exhibits 5.11 which is a safe value. Customer may consider going in for this option and overcoming the problem of current amplification.

| Case | Description | With 0.2% series reactor | With 5% series reactor |
|------|-------------|--------------------------|------------------------|
| 1    | Only one motor switching on at time of 0.5 sec, along with its terminal capacitor bank | 347 (Refer Fig 5.3) | 134 (Refer Fig 5.12) |
| 2    | Second motor switching on at time of 0.5 sec, along with its terminal capacitor bank when the first motor in operation | 374 (Refer Fig 5.7 and 5.8) | 128 (Refer Fig 5.16 and 5.17) |
experienced due to resonance. The other option is to use higher values of the reactor; Calculations have been done for 0.5 %, 1%, 5% reactors; It is seen that with 5% reactor, there is hardly any resonance condition and with 1% and 0.5 % reactors, the series resonance conditions shift 5.6th and 8.2th harmonic number respectively. Hence it is seen that by having larger value of reactor, the resonance condition effectively shifts to lower frequencies and since the actual harmonic voltages noted at 5th, 7th and 9th harmonics are comparatively lower we can operate without changing the existing capacitor connection from delta to star.

Figure 21. Voltage and Current Harmonics recorded showing Increased harmonic voltages and currents (THD).

Figure 22. Voltage and current harmonic spectrum of the recordings done showing high level of 13th harmonic voltages and currents.

Figure 23. Voltage and Current Harmonics recorded on 7/8 October 2010 showing increased harmonic voltages and currents (13th Harmonic) between 12 noon to 5:45 PM and 9 AM to 12 noon.

Figure 24. Active and Reactive Power w.r.t. power factor.

6. Calculation of the Power Factor of Operation with the Suggested Reconnection of Power Factor Capacitors

This section provides the calculations for the power factor of operation when the pf compensation capacitors are
reconnected in star as recommended in the earlier section to overcome the problem of 13th harmonic resonance when operating with 2% reactor. The following recording shows the maximum Active power, Reactive power and the corresponding power factor recorded at the maximum load condition (80 amperes load).

7. Conclusion

The conclusions have been arrived at after extensive deliberation of all the direct possibilities which might result in over voltage flash-over failure listed as follows:

• Large capacitor banks which might have got included into the upstream supply system in the recent past which could induce larger switching over voltages; from the information received from MWUL no such supply system changes had taken place.

• Possibility of deterioration of the earthing integrity of the power line or the substation. Extensive earthing integrity measurements were carried out as detailed in section 6 and the results of the measurements indicated a healthy earthing system.

• Possibility of discrepancy of the closing contacts of a particular breaker which can result into over voltage possibilities during switching. This possibility is also unlikely and excluded as the switching breakers involved were different for the different switching instants when the failure had been reported.

• In the EMTP studies conducted and as elaborated under section # 7, no major over voltage situations have been identified under the conditions of both single motor and two motor switching conditions. Since the above direct over voltage possibilities are ruled out, the other possible indirect reasons are enumerated as follows;

• Based on EMTP studies conducted for MWUL system described under section 7 it is seen that with the existing series reactor (0.2%), the magnitude of inrush current is significantly high especially for the case of 2nd motor switching on when first motor is in operation. This operation which is repeated couple of times a week can result in the deterioration of the insulation levels of the reactors and over a period of time results into their failures unless the same is designed to take up the very high transient currents. The wet atmospheric condition of December 2009 could have been the immediate specific reason for the inter-turn flashover. Hence the solution for this situation is to provide the reactor which is designed to take the large transient conditions with the proper design of the conductors, core and insulation. The desired specification of the reactor is 5% based on the visual observation of the existing failed reactors.

• Based on the recording of the long time electrical parameter measurements the presence of significant values of 13th harmonic voltages / currents have been identified at random intervals - maximum value of 4.2 % 13th harmonic voltage has been recorded at one instant. The resonance condition study has indicated that with 0.2% reactor, the electrical system provides minimum impedance at 12.92th harmonic. Hence the other strong reason for the failure of the reactor is the possible occurrence of the current getting amplified during the 2 motor starting when the minimum impedance presented is 50 % of the case with one motor operation.

• With the alternate value of reactor (5%), the EMTP studies indicate maximum inrush current value of around 128A (about 5 times to nominal current of capacitor). This is much less than the maximum inrush current of 374A (about 15 times). The figure of 5% is a recommended value in the literature of similar systems to limit the inrush currents experienced by the capacitor and the reactor itself and hence the EMTP studies have been conducted for this value of reactor as detailed under section # 7.

• It is also seen that with 5% reactor, the chances of resonance is also not there; this is also elaborated. This is technically the correct solution.

• However considering the large size of the 5% reactor, as compared to the panel mounted 0.2 % reactor, an intermediate value can be selected; e.g. 0.5% and 1.0%. In terms of the transient currents which are likely to flow, the transient currents will be lesser with larger inductor value. In addition, it has been calculated, that with 0.5 % reactor, the tuning frequency for minimum impedance is 8.2th harmonic and for the value for 1% reactor, it is 5.6. These are much safer than the existing situation of having harmonic number of 12.92 as the tuning frequency. The practicality of providing either 0.5% or 1% or any other appropriate value of reactor can be considered as a compromise solution.

• In case, providing higher values of the reactor is totally not practical due to space problems, the existing value of 0.2% reactor should be replaced by a reactor manufactured taking into consideration the various transient conditions it is likely to experience. The specification given under Annexure A6 has to be followed thoroughly for the manufacture of the reactor.
• Under this condition – i.e. retaining the existing value of reactor appropriately manufactured as per the specification - it is however necessary to shift the tuning frequency for minimum impedance, to higher value by reducing the capacitor value (instead of increasing the inductor value as suggested above) to overcome the possible current amplification. This can be achieved by connecting them in star instead of the existing delta connection. This is quite practical and safe at MWUL site except that the total reactive power compensation supplied will be only one third of the existing KVAR provided. The Company may consider going for this option as a practical solution with the understanding that technically this is a least preferred option.

This proposed method is very useful in the high voltage systems to maintain the power factor and protect the sophisticated equipments from the power quality issues. Normally large capacity pumping stations, steel industries etc., where huge capacity induction loads are present and to improve the power factor as per electricity board guidelines.

8. References

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