STUDY OF THE TRANSIENT OVERVOLTAGE PROFILES IN THE POWER DISTRIBUTION NETWORK OF DURGAPUR STEEL PLANT (DSP)

P. Mitra, A. De, and A. Chakrabarti

***Abstract*—The recent failures of two medium voltage distribution transformers on the power supply system of Durgapur Steel Plant evoked this study. During laboratory and factory investigations, no design or manufacturing faults could be found on these transformers. The study and the tests conducted attribute the failure to probable part winding resonances inside the transformers. The related system's switching transient profile was analyzed and the transformers' responses to these transients were evaluated on a quantitative basis. This paper reports experimental results from laboratory and on-site measurements and describes typical symptoms, critical factors and throws some ideas for proper system design and appropriate protection. The objective is to make system designers more aware of the fast transient phenomena and to demonstrate that they present larger problems than generally acknowledged.**

***Index Terms*—** *Transformer, fast transient, switching transient, resonance, over-voltage, distribution network.*

I. INTRODUCTION

Switching operations and faults produce various types of transient over-voltages which can result in voltage stresses with above normal operating values in a sections of power distribution system and transformers thereof, a subject which has been investigated and reported by many researchers [1,2,3]. Such transients when travel through transformers, can excite the winding's natural resonate frequencies. The resulting winding resonance leads to severe internal voltage amplification and abnormal stresses on transformer insulation [4]. This paper focuses on and comprehensively analyzes the occurrence and the impact of oscillatory system overvoltages caused by various switching conditions.

II. DESCRIPTION OF THE POWER DISTRIBUTION NETWORK OF THE DURGAPUR STEEL PLANT (DSP)

A number of 33 kV sub-stations: MRS DSP Indoor (I/D) - I, II and III, MRS DSP Outdoor (O/D) - I, II and III, MRS ASP O/D – I, II, Punabad – LHS & RHS, Sajaria – LHS & RHS, New Sajaria – I, II, III & IV and ASP handle a total load of 243.14 MW including export to DVC. Out of this total load, DSP load alone is 143.14 MW, ASP load is 72MW and export to DVC is 28 MW. The power distribution is through 33kV outgoing feeders from these substations. Major equipments installed in the network are as below:

a) 5 Nos. 80 MVA, 220/33KV, YNyn0 transformer with solidly grounded neutral and provided with ±10% OLTC. The transformer MX1 is connected to DSP MRS DSP I/D-3 33kV bus, MX2 is operated on DSP MRS DSP I/D-1 33kVbus,MX3 and MX4 are connected to DSP MRS ASP O/D-LHS 33Kv Bus,MX5 is connected to DSP MRS ASP O/D-RHS 33kV bus and MX6 is operated on DSP MRS DSP-O/D-1 33 kV bus.

b) 7 nos. 1.5 ~ 2.5 MVAR VAR compensating Static Capacitor Banks at various buses

c) 10 nos. 25/40 MVAR Series Reactors and

d) 2 Nos. 11.5 KV, 68 MW, 0.8 p.f. (lag) Synchronous Generators.

A schematic view of the DSP network is presented in Fig.1

III. MODELING OF THE DSP NETWORK

To analyze the possible transient voltage stresses that could develop on the DSP's distribution transformers under different switching events in this distribution network, the relevant portion of the DSP's power distribution network has been modeled using Alternative Transient program (ATP). The developed model helps to prepare the transient overvoltage profiles [5] for the system, particularly at the transformer terminals [6]. Analysis of these transient overvoltage profiles help to identify potentially hazardous switching events [7] which may generate critical voltage stresses [8] inside the 220/33 kV transformers. All substation equipments were modeled by lumped parameter modeling approach.

Transformer Model

The transformers are capacitively modeled [9, 10]. It should be noted that modeling of a transformer by capacitive model

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(which is justified for an interval of time of a few mili-seconds) permits to determine the voltage at the transformer terminals.

Feeder Model

The Feeders modeled comprised of single section with suitable transpositions. The skin effects on the lines were included in the model. Line Model used in the simulation are high frequency model (J. Marti Model) for over-head transmission lines which takes into consideration the frequency dependence of line resistance and reactance. J. Marti model yields greater accuracy as compared to conventional PI section models.

Circuit Breaker and Isolator Model

Circuit Breakers and Isolators are modeled in the form of voltage and/or time dependent switches along with lumped capacitances (primarily contributed by bushing capacitance) as PI sections. The effect of arc resistance is considered. Shunt capacitive effect is much pronounced in circuit breaker than isolator.

Bus-Bar Model

Bus Bars are modeled by ladder networks with series resistance and inductances and shunt capacitances. Each of the ladder section usually corresponds to a section of 5 or 10 meters of bus length. The inductance and the capacitance of the cells are selected on the basis of the surge impedance of bus-bars.

Static Capacitor Bank Model

It is modeled as set of parallel-grounded capacitors of suitable values connected at the bus bar. Switching of capacitor banks have been modeled by placement of time controlled switches.

Reactor model

Reactors are modeled by their equivalent inductances along with resistances.

Generator model

Model of the generators have been assumed to have the magnitude of constant voltage behind the d-axis transient reactance. Q-axis transient flux linkage has been assumed to be small and has been neglected.

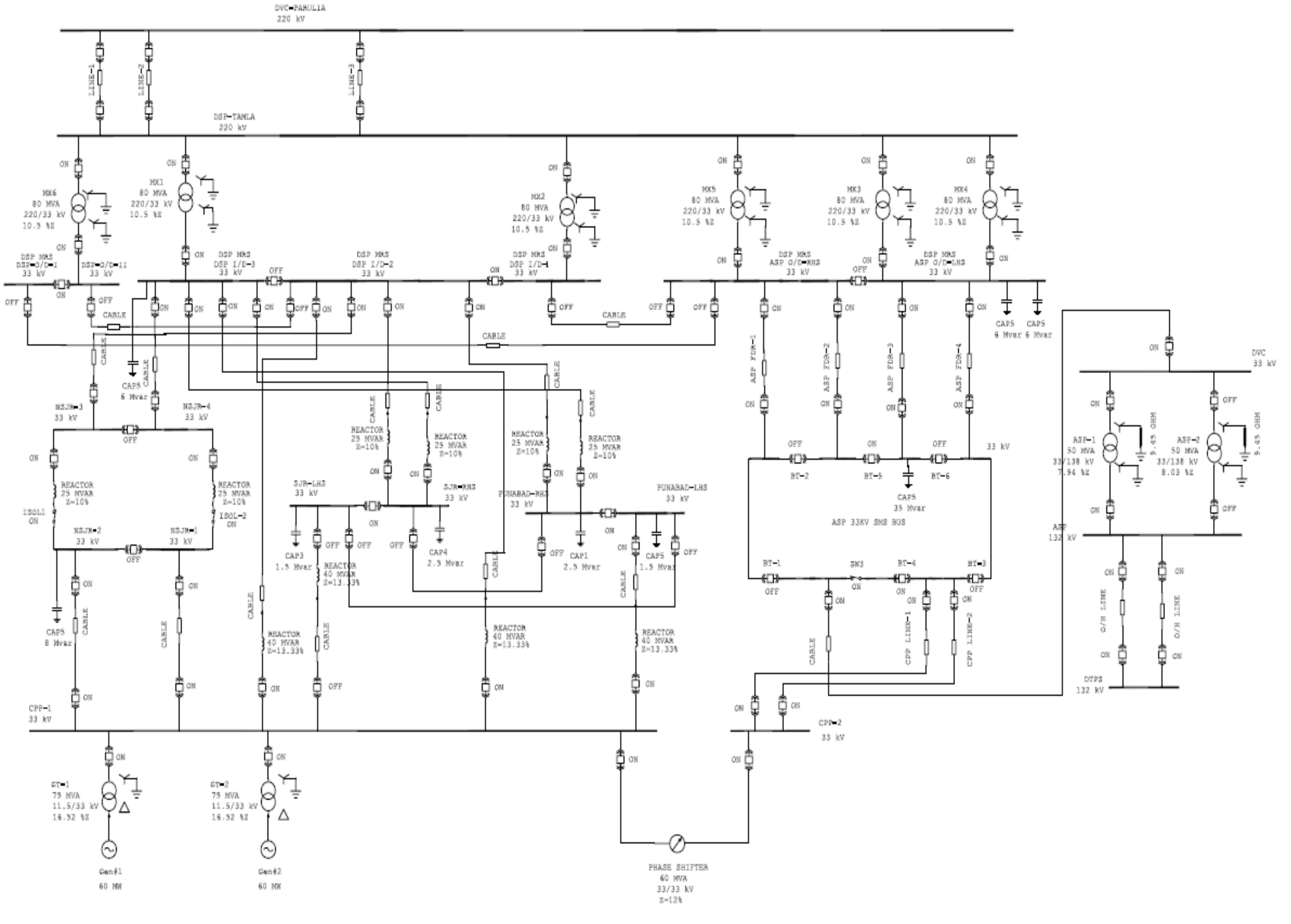

Fig1. Single line diagram of EHV/HV network of Durgapur Steel Plant

IV. ANALYSIS OF DIFFERENT SWITCHING EVENTS IN THE POWER DISTRIBUTION NETWORK OF DSP

Various system switching events [11] were systematically investigated in search for the transient voltages which could be of concern for the substation transformer, and to build a complete system's overvoltage profiles. The studies included the following event categories -

- Transformer energization
- Reactor Switching
- Connection of feeders

As stated earlier, switching events, either deliberate or intentional can result perturbations in electrical networks. The resulting transients can propagate through the transmission systems from the points of origin and may eventually reach the transformer terminal. If the frequency of these external disturbances match closely with any one of the internal resonate frequencies of the transformer winding, severe internal overvoltage may occur due to resonance.

To study the phenomena, the time of event initiation were varied over a range, to determine the worse conditions [12]

Transformer Energization:

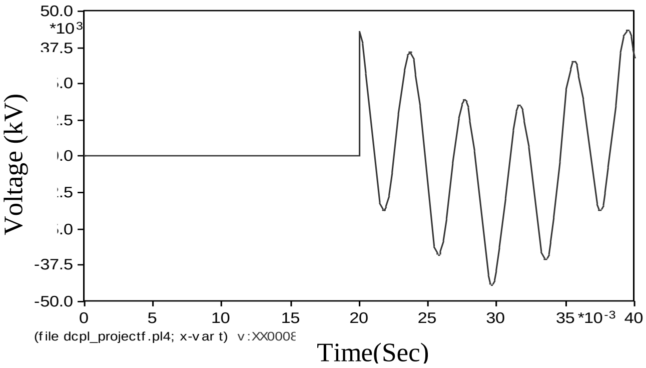

Fig.2: Voltage appearing at MX1 transformer terminal Due to energization of MX1 transformer.
(Peak Value: 43.50 kV)

2. *Reactor Switching:*

(a) Single Operation: Closing of reactor to 33 kV NSJR-3 Bus Bar

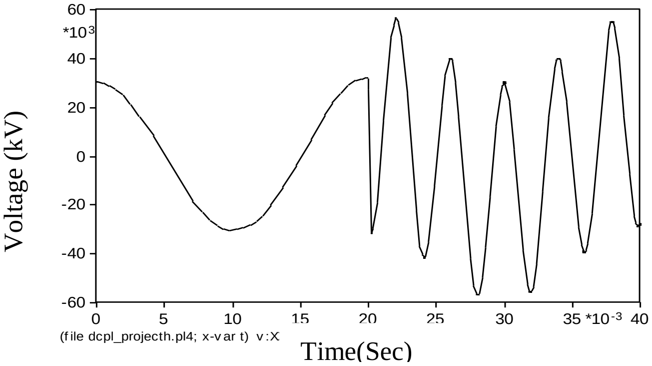

Fig. 3: Oscillatory Voltage appearing at MX1 transformer terminal.
(Peak Value: 56.65 kV)

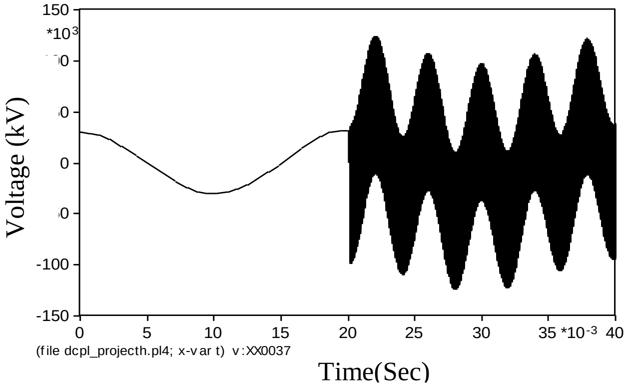

Fig.4: Oscillatory Voltage appearing at 33 KV NSJR-3 Bus Bar.
(Peak Value: 122.84 kV)

(b) Multiple operations:- (i) Closing of *four reactors to 33 KV NSJR-3, NSJR-4 ,DSP MRS DSP I/D-1 & DSP MRS DSP I/D-3 Bus Bars*

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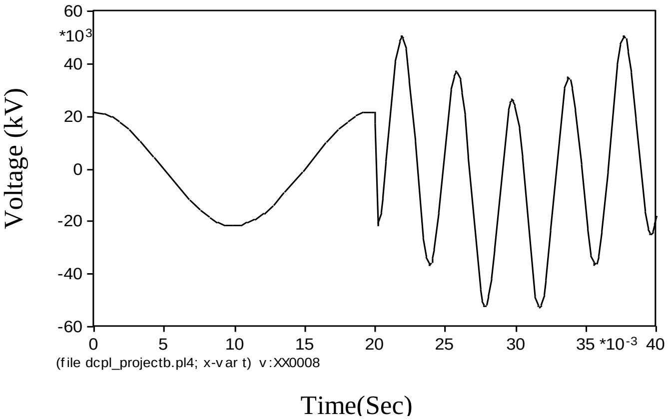

Fig.5: Oscillatory Voltage appearing at MX1 transformer terminal
(Peak Value: 50.57 kV)

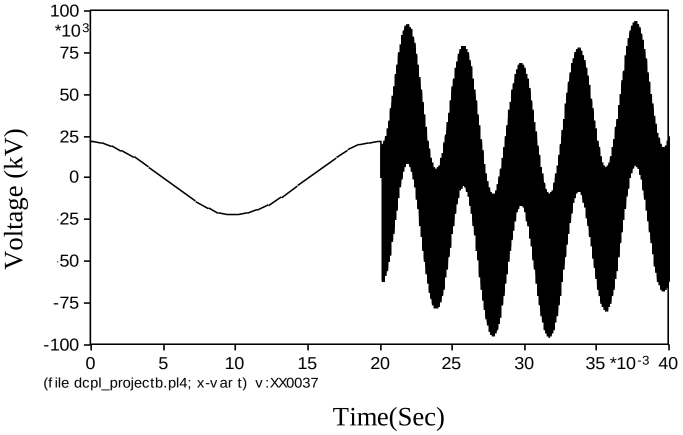

Fig.6: Oscillatory Voltage appearing at 33 kV NSJR-3 Bus Bar.
(Peak Value: 88.98 kV)

(ii)Closing of Two Reactors to 33 kV NSJR-3 & NSJR-4 Bus Bar simultaneously

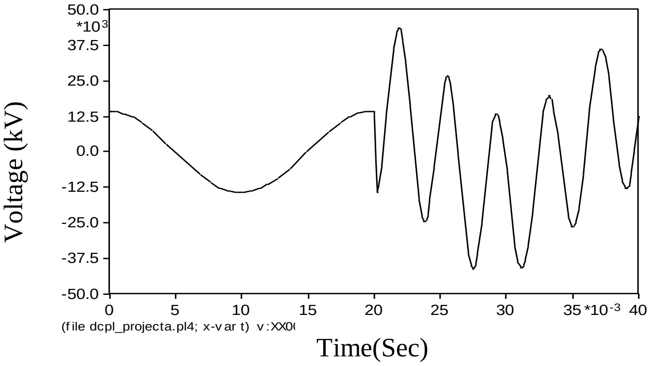

Fig.7: Oscillatory Voltage appearing at MX1 transformer terminal
(Peak Value: 43.26 kV)

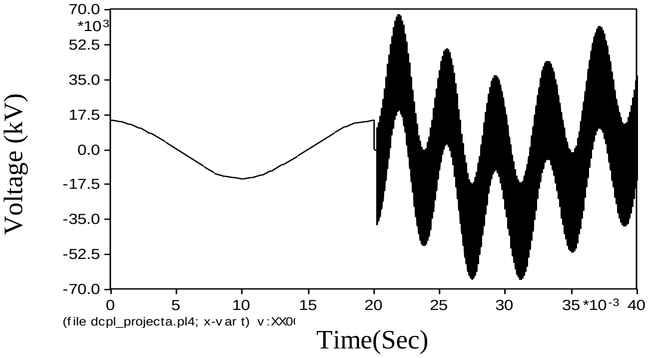

Fig.8: Oscillatory Voltage appearing at 33 kV NSJR-3 Bus Bar.
(Peak Value: 63.42 kV)

3. Connection of feeders

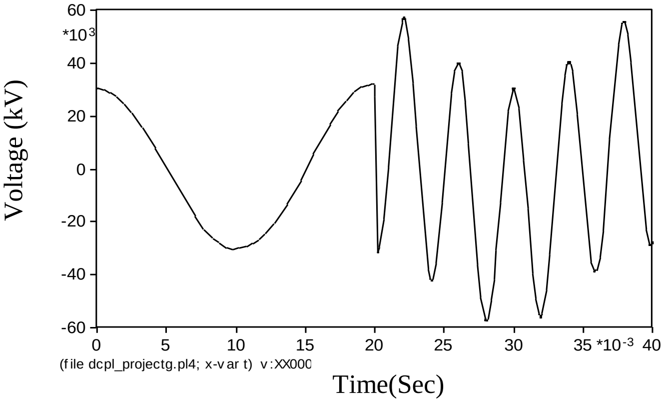

Fig.9: Oscillatory Voltage appearing at MX1 transformer terminal connected to DSP-Tamla 220 KV Bus Bar when four feeders (ASP FDR-1, ASP FDR-2, ASP FDR-3 & ASP FDR-4 are switched to 33 kV DSP MRS ASP O/D – RHS & LHS Bus Bars simultaneously.
(Peak Value: 56.97 kV)

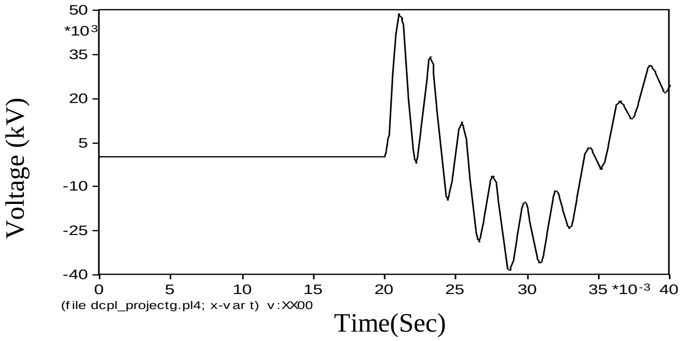

Fig.10: Oscillatory Voltage appearing at MX5 transformer terminal when four feeders (ASP FDR-1, ASP FDR-2, ASP FDR-3 & ASP FDR-4 are switched to 33 kV DSP MRS ASP O/D – RHS & LHS Bus Bar simultaneously
(Peak Value: 48.66 kV)

V. KEY FINDINGS

Occurrence point	Switching Event	Time Interval (sec)	Peak Value (kV)	% Over Voltage
MX1 80 MVA 220/33 kV Transformer	Closing of Mx1 Transformer	0.02	43.50	31.81
	Closing of reactor to33 KV NSJR-3 Bus Bar	0.02	56.65	71.66
	Closing of four reactors to 33 KV NSJR-3 &4 and DSP MRS DSP I/D 1&3 bus bar at a time	0.02	50.57	53.06
	Closing of two reactors to 33 KV NSJR-3 &4 bus bar at a time	0.02	43.26	31.09
	Closing of ASP FDR-1 to 4 to DSP MRS ASP O/D at a time	0.02	56.97	72.63
MX5 80 MVA 220/33 KV Transformer	Closing of ASP FDR-1 to 4 to DSP MRS ASP O/D-LHS & RHS bus bar at a time	0.02	48.66	47.45

VI. ANALYSIS OF TRANSIENT PHENOMENON

Terminal disturbance of two 220/33 KV distribution transformer (MX1 &MX5) have been investigated under the various switching operation including transformer energization, circuit breakers and reactor switching and switching of feeders connected to the different bus bars. Some of the switching operations created considerable overvoltage at transformer terminals and bus-bars but the voltage levels were below the Basic Insulation Level (BIL). For 33kV transformer and bus-bar BIL are 200kV and 310 kV respectively. As the terminal voltage of the transformer remains well below the BIL in all switching cases, these low amplitude oscillatory transients may easily pass on to the transformer windings, without being attenuated by surge arrestors. If oscillation frequencies of these transients match with any one of the natural frequencies of the transformer windings, local voltage amplification may occur inside the transformer, resulting in severe stress on insulation.

VII. PROTECTIVE MEASURES

The questions that obviously concerns the transformer manufacturer is how to design a transformer winding to minimize the effect of resonance and how to determine the degree of insulation needed to safeguard the windings against possible resonant over voltage? The results show that arrestor protection is not effective for all types of voltage wave-shapes. Safeguard of winding insulation against oscillatory over voltages cannot be ensured by conventional dielectric tests on transformers, nor can the inherent internal damping within the transformer be significantly increased to minimize the impact of such oscillatory transients. However some actions can be taken at the design level to improve winding's response to oscillatory system waves. Some suggested measures are enumerated below.

(a) Non- linear metal oxide resistive elements can be placed across those portions of the windings which exhibit close proximity to resonance, such as the tap changer winding. This is equivalent to the internal application of a surge arrestor across the section of winding susceptible to damage.

(b) Placement of resonance filters in series with the windings and tuned with major resonant frequencies of the transformer windings and provided with proper damping arrangement.

(c) By adding a capacitor bank to the tertiary winding which increases the damping characteristics.

(d) R-C suppression branches connected as close as possible to the capacitor terminal to locally arrest the oscillations.

VIII. CONCLUSION

Switching events produced oscillatory transient overvoltages in the frequency range 251 Hz – 166 kHz. If these frequencies match the resonate frequency of the 220/33 kV MX1 or MX5 distribution transformer, large voltage stresses are likely to be produced across the winding disk coils and cause breakdown of insulation. The findings of the present investigation reveal that many of the switching events can generate high frequency oscillatory transients in the system which could be of concern. The reported failures of several transformers in the DSP distribution system could be attributed to these high frequency switching transients and transformer resonance there off. Some measures have been suggested to prevent future failures.

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