Resonance Condition and Resultant Overvoltage Causing 400 kV Circuit Breaker Failure

F. Ghassemi, F. Moore, A Pashaei

Abstract— A 400 kV circuit breaker was opened to disconnect and de-energise a long overhead line circuit and shunt reactor from the transmission system together simultaneously. Immediately after this opening operation, a second circuit breaker within the disconnected network tripped and failed as it opened. This paper presents a summary of the subsequent investigation work to understand the failure, including measured waveforms captured from protection relays alongside analysis and simulations carried out using EMTP ATP. The investigation showed that a resonance condition at 50 Hz was excited during the opening operation to disconnect the overhead line circuit and reactor, which was fed by capacitive coupling to the adjacent overhead line circuit which remained live. This resonance would have resulted in sustained temporary overvoltages on the disconnected network, which was sufficient to cause the second circuit breaker to trip due to overcurrent protection operation and fail due to subsequent excessive overvoltage across its phases. The paper concludes with a discussion of practical mitigation measures to avoid the resonance and circuit breaker failure reoccurring.

***Keyword*: Circuit Breaker, Electromagnetic Transients, EMTP, EMTP-ATP, static overvoltages, stationary overvoltages, temporary overvoltages, reactor, resonance.**

I. BACKGROUND

RESONANCE conditions in power systems are caused by interaction between capacitive and inductive elements. These resonance conditions can occur on the power system at a range of low frequencies. When excited by a disturbance, they can cause temporary overvoltages (TOV) in power systems. Common causes of TOV include system faults and fault clearance, load rejection, line energization and disconnection and transformer energization. Another special case of TOV can be caused by a resonance condition on a disconnected overhead line with shunt inductive compensation that is capacitively coupled to an energised parallel line [1], [2]. It is well known that TOVs can lead to dielectric or thermal failure of equipment [1], [2], [3], [4], [5], [6].

It is well established that the degree of inductive shunt compensation for transmission lines should be carefully selected at the design stage to avoid TOVs due to resonance conditions and excitation of the resonance by a parallel overhead line (OHL) [2], [6].

National Grid Electricity Transmission (NGET) is one of the transmission network owners in the United Kingdom. On the NGET network, a circuit breaker was opened to disconnect and de-energise a long overhead line circuit and shunt reactor from the transmission system together simultaneously. Immediately after this opening operation, a second circuit breaker within the disconnected network tripped and catastrophically failed as it opened. This paper presents a summary of the subsequent investigation work to analyse the failure, which showed that permanent overvoltages (due to resonance) was excited during the switching sequence. The paper presents measured waveforms captured from protection relays together with analysis and simulations carried out using EMTP-ATP. Mitigation was proposed and implemented to ensure that the overvoltage is avoided in future.

II. DESCRIPTION OF THE NETWORK

In the UK, a substation layout known as the Mesh Corner (MC) design is commonly used to reduce the number of circuit breakers in a substation. This design is to some extent a legacy from the early days of the electricity industry where circuit breakers were relatively bulky and expensive. A typical Mesh corner substation has four circuit breakers connected together by a square busbar, with pairs of circuits and transformers banked together at each corner, as shown for Sub A in Fig. 1. This substation design is no longer favoured as the cost and size of circuit breakers have decreased.

Fig. 1. illustrates the network under study. Substation A is a MC design and all other substations, from SUB B to SUB E, use a more modern double-busbar design. The double-busbar substations have been simplified to single nodes in the diagram for simplicity. The wider network was reduced and represented using equivalent sources at Substation A and E. The equivalents used are an ideal voltage source behind a Thévenin impedance. Conventionally, the wider network would be represented at a network node further from the network under study, electrically far away [7] e.g. at least two substations away. However, in this case the investigation focuses on an isolated line where the coupling between the line and the rest of the network is dominated by the stray coupling impedances. As a consequence, the reduced network impedance has minimal influence and a smaller network model could be used. line and cable data for these circuits are given in Appendix A

A double-circuit overhead line connects SUB A and Sub E. Circuit 2 of this double-circuit overhead line connects into several substations (Sub B, Sub C and Sub D) along its route. Circuit 1 on the other hand, directly connects SUB A to SUB E. Circuit 1 is approximately 220 km, making it the longest circuit in the UK. with a length of approximately 219 km of overhead line.

A 200 MVAr shunt reactor was installed at SUB A in 2016 to manage the voltage on the 400 kV network during periods of light loading. It was installed on the same busbar at the MC substation as both Circuit 1 and the super grid transformer (SGT) as shown in Fig. 1. However, unlike Circuit 1 and the SGT, the shunt reactor was installed with a dedicated circuit breaker CB2. This circuit breaker allowed the shunt reactor to

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be switched in-and-out of service independently of other network plant.

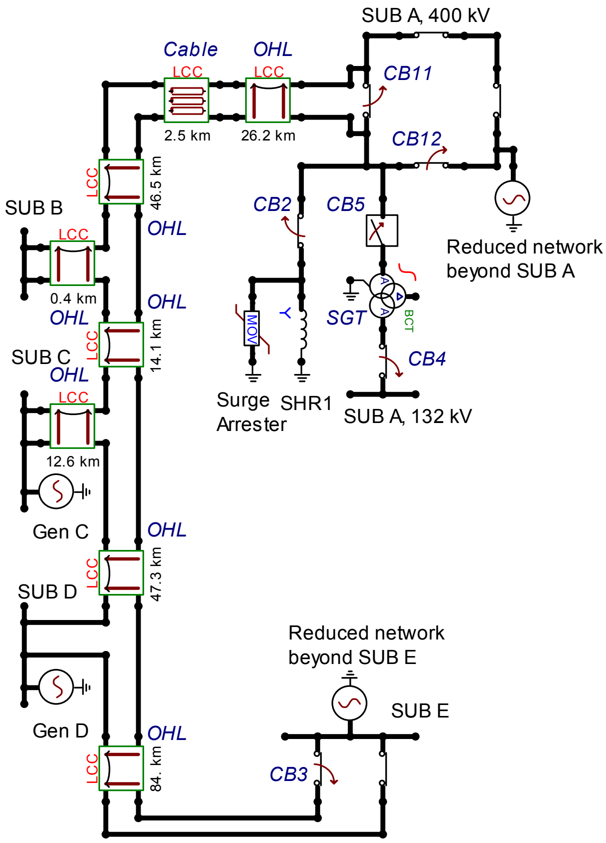

Fig. 1. Network Diagram.

III. DESCRIPTION OF THE EVENT

To bring the shunt reactor into service, it would be routinely switched by opening and closing CB2. However, on this particular occasion, a different switching strategy was used, resulting in the failure of CB2. In this section the sequence of events that led to the circuit breaker (CB2) failure is given.

The sequence of events are as follows:

I. At a light load condition at night, CB2 was commanded by the Transmission National Control Centre (TNCC) to close.

II. After it was closed, TNCC received an alarm signal from CB2 about a fault in the "closing spring mechanism".

III. A shift site engineer was despatched to SUB A, where he confirmed the alarm condition of CB2 locally.

IV. TNCC decided to take CB2 out of service without operating it. This meant that they had to switch the line, SGT, and the reactor out of service.

V. At SUB A, CB4 was opened to off load SGT. The relevant disconnectors associated with CB4 (not shown in Fig. 1) were operated to isolate CB4.

VI. At SUB E, CB3 was opened, disconnecting the line from SUB E. The relevant isolators associated with CB3 (not shown in Fig. 1) were operated to isolate CB3.

VII. At SUB A, CB11 was opened. Subsequently, the relevant isolators (not shown in Fig .1.) were operated to isolate CB11.

VIII. Subsequently the SGT was taken out of service by means of a switched disconnector. A switched disconnector is not a circuit breaker. It can break load current, i.e. magnetising current, but not a fault current.

IX. At SUB A, CB12 was ordered to open. Immediately after CB12 was opened, personnel present on site observed a flashover on Phase A of CB2, which lead to its catastrophic failure.

Protection records showed that CB2 at SUB A operated because of a trip signal generated by the backup definite time overcurrent protection associated with shunt reactor SHR1. The overcurrent relay setting was 440 A or 1.5 per unit (pu) of the nominal current at 400 kV. The relay delay setting is 1 s.

IV. MEASUREMENT WAVEFORMS

The phase voltages (obtained from a CVT at the line end) recorded by the circuit protection at SUB A are shown in Fig. 2. when CB2 opened. Fig. 3. shows the zoomed voltages. The sampling rate of the relay is 1 kHz, i.e. 20 samples per cycle.

Fig. 4 and Fig. 5 illustrate the line and reactor currents respectively during the incident. Inspection of these figures shows that the current in the reactor is equal to the line current but in opposite direction. This is due to the connection and convention used for respective current transformers installed in the line and reactor where the positive direction is towards the corresponding equipment being protected. This confirms that the source of the current is in the line which is isolated from the rest of the network and only connected to the parallel line through the capacitive coupling between the two lines.

The following observation can be made:

I. CB2 opened at around 220 ms, although, this is just a reference time on the record and does not mean the fault has been on only for 220 ms.

II. Considering the definite time setting of the overcurrent protection, it can be said that before Phase B and Phase C opened the condition existed at least for 1 s plus the CB2 operating time. Because of the record capability of the relay and its configuration, longer record than 220 ms was not available.

III. Phase B and Phase C successfully open, interrupting currents.

IV. The current in Phase A continues to flow throughout the protection measurement record through the arc across the circuit breaker. The record shows that the current in Phase A eventually ceases to flow, most likely because of arc being extinguished naturally.

V. From Fig. 5., before CB2 opens, the current in Phase A is around 636 A rms (900 A peak) and therefore above the current setting of the backup overcurrent protection associated with the reactor. This protection would have sent a trip signal to open CB2 to open after 1 s..

VI. This high current in the reactor indicates the equivalent high voltage at the terminal of SHR1, pushing current into the reactor.

VII. The currents and voltages before CB2 opened are very unbalanced. The close inspection of the signals revealed that the zero sequence components in voltage and current are small, which may indicate that the zero sequence component coupling from the adjacent line has lesser impact.

VIII. The Phase A voltage is very distorted and seemed to have been clipped at around 450 kV by some form of arcing or non-linear impedance, before and after CB2 opens, which makes it difficult to determine what level actually the voltage increased to.

IX. The distortion in Phase A voltage may be attributed to two possible overvoltage protection:

1. The conduction by the surge arrester across the reactor. Because of the protective margin of the surge arresters used in NGET, which gives a protection level of around 780 kV, it is unlikely that the voltage is clipped at 450 kV by the surge arrester.
2. The overvoltage protection within capacitive voltage transformers (CVT) that the relay was connected to. CVTs overvoltage protection are usually set at 1.3 to 1.4 pu of the rated voltage to protect CVT internal components against ferro-resonance and other overvoltages as well as external equipment connected to the CVT secondary terminals. It was concluded that it was more likely that the voltage captured by the relay was in fact the CVT secondary terminal voltage which did not resemble the CVT primary terminal voltage. In order to determine by how much the voltage increased studies by simulation were considered.

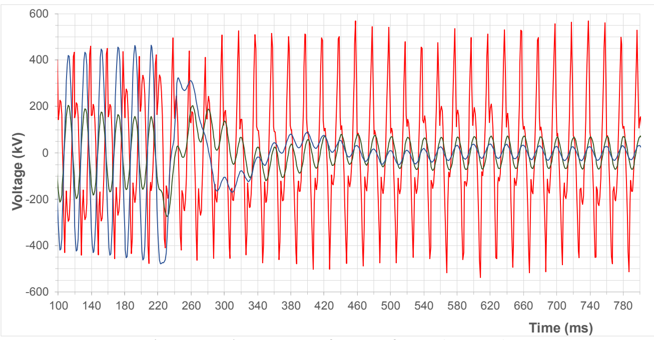

Fig. 2. Voltage Waveforms of MC (reactor).
Phase A: Red, Phase B: Green, Phase C: Blue

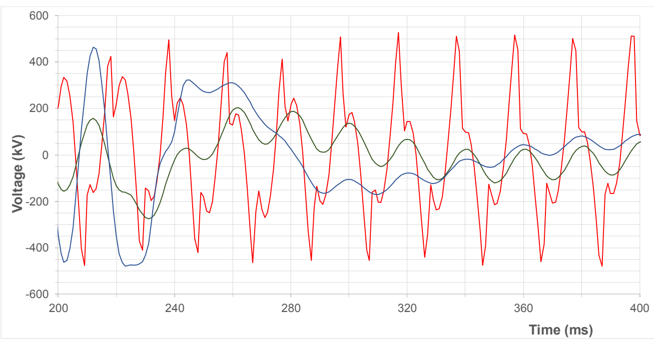

Fig. 3. Zoomed Voltage Waveforms of MC (reactor).
Phase A: Red, Phase B: Green, Phase C: Blue

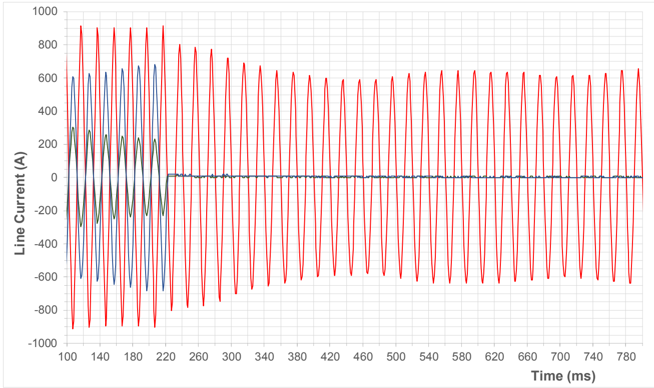

Fig. 4. Line Current Flowing toward SHR1.
Phase A: Red, Phase B: Green, Phase C: Blue

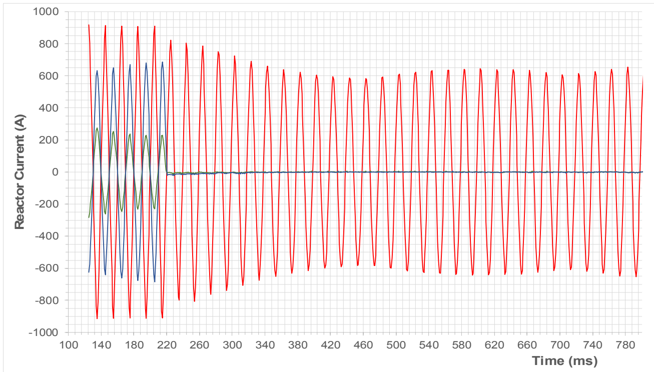

Fig. 5. Reactor Current.

V. EMTP MODEL AND RESULTS

NGET has the whole UK transmission network modelled for standard design works such as load flow, short circuit (fault level) and stability studies. This model was used to examine the overvoltage on the MC at terminal of SHR1 when the line and the reactor are disconnected from the system. This was a steady state analysis and determined the voltage attained by MC in the situation considered. It was shown that even using a simple 50 Hz load flow simulation the high overvoltage established at MC could be determined.

The network was modelled in EMTP-ATP (ATP). The overhead lines were modelled using multi-section PI model and the short cable sections as balanced distributed parameter model based on 50 Hz parameters (Type LINEZT_3). Because the phenomenon under consideration is a 50 Hz effect only distributed nature of the components are important and the frequency dependency of parameters with frequency is of lesser interest. Therefore, Bergeron or multi-section PI model set at 50 Hz can be used. A few tests were carried out with Bergeron model but no significant difference with the PI model was observed. In addition, some large shunt resistances were connected Phase-to-Earth at the end of each overhead line section, to represent the leakage current across the insulator strings. The resistances were calculated assuming a leakage current of 5 mA per tower insulator, with each tower located 300m apart. The details of line and cables are given in Appendix A. The loads were modelled as static parallel resistance and reactance according to the loads' MW and MVAr.

A frequency sweep was carried out on the EMTP-ATP model to examine the behaviour of the network in the frequency domain. The network model was set up with circuit breakers CB11, CB12, CB3 and CB4 in the open position, with CB2 in the closed position. All network equivalent voltage sources were replaced with short circuits, and a three phase positive and negative sequence currents of one Ampere were injected into the main busbar section at Substation A. During the frequency sweep, two voltages at the Substation A were recorded; one was busbar section where the current source and the rest of the network were connected and the other was the busbar section where the Circuit 1 line and SHR1 were connected. The ratio of the latter voltage to former gives the voltage gain between the rest of the network and the isolated section, i.e. the reactor/line terminal. Note that these voltages represent the self impedance of the main busbar and the transfer impedance to the isolated section of the network formed by the line and shunt reactor. The frequency scan was performed within the band of 20 to 80 Hz. Note that non-linear components in the model, such as shunt reactor and surge arrester would not exhibit their non-linear behaviour in the frequency scan.

Fig. 6. Illustrates the positive sequence self impedance and transfer impedance for the default line and cable data as they were in the database. As can be seen there is a strong resonance in the transfer impedance at 49.6 Hz. At 50 Hz the self impedances of the main busbar are 11.6, 11.5 and 11.7 Ω respectively for Phases A, B and C. The transfer impedances are 44.7, 12.3 and 39.5 Ω respectively for Phases A, B and C. Using the transfer impedances and self impedances for each phase, the transfer gains can be calculated, which are 3.85, 1.06 and 3.37 respectively for Phases A, B and C.

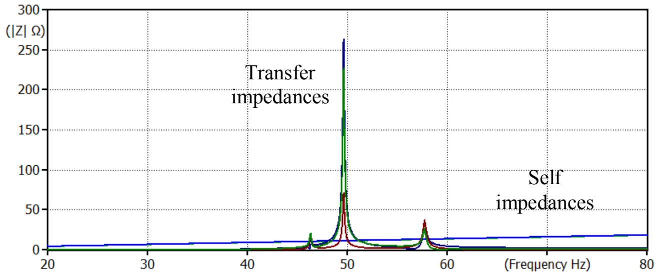

Fig. 6. Positive Phase Sequence of Self and Transfer Impedances between Main and Isolated Busbar Sections.

Fig. 7. Illustrates the zero sequence self and transfer impedances. The main resonance has moved away from 50 Hz, however a minor resonance is occurring close to the system frequency. At 50 Hz, the self impedances are 11.8, 11.9 and 11.7 Ω respectively for Phases A, B and C. The corresponding transfer impedances are 30.8, 10.7 and 11.9 Ω, which lead to the transfer gain of 2.61, 0.9 and 1.0 respectively for Phases A, B and C.

Fig. 8. Illustrates the voltage gain at the isolated MC when the system voltage is 1 V peak. It can be seen that if the main busbar voltage, which is connected to the rest of the network, is 1 V (pu) the voltage at MC will be more than 3 pu, if the non-linearity of surge arrester and shunt reactor are ignored.

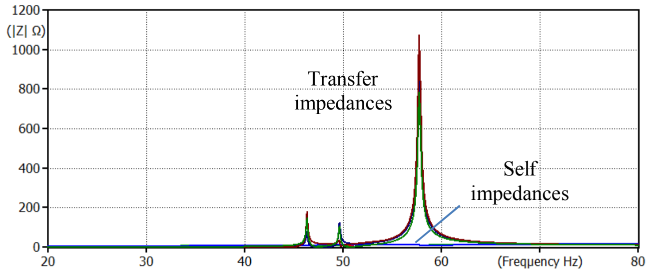

Fig. 7. Zero Phase Sequence of Self and Transfer Impedances between Main and Isolated Busbar Sections.

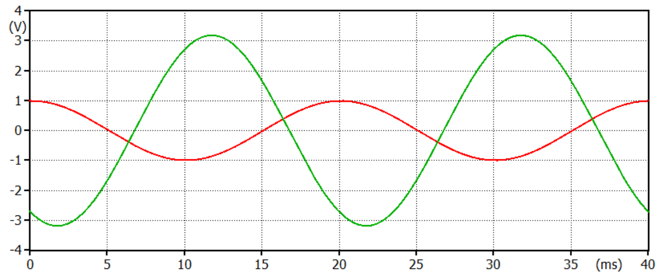

Fig. 8. Time Domain Voltage Gain for 1 pu voltage.

VI. SIMULATED WAVEFORMS

The focus of the EMT study was the instant at which CB12 was ordered to open using the EMTP-ATP model, as this step corresponds to the switching immediately prior to the flashover at circuit breaker CB2. It is worth emphasising that the measured waveforms described previously in section IV correspond to the instant that CB2 tripped, as they were captured by the protection systems associated with the tripping event. The simulations presented here correspond to a slightly earlier time period, as the focus of the simulations presented here is to show how the event was initiated by the opening operation of CB12. In the simulation, Circuit breaker CB11 and CB12 were opened to de-energise the circuit towards Substation E and shunt reactor SHR1 simultaneously with CB2 in the closed position & CB3 in the open position. The simulated voltage waveforms at SUB A end of this circuit are shown in Fig. 9. These results show that resonant overvoltages would have occurred on the circuit and shunt reactor. These overvoltages are composed of a 50 Hz component that is induced and fed by the system voltage source through the capacitive coupling to the circuits that share the same double-circuit towers, and a lower frequency oscillation which is decaying with time, as there is no driving voltage source for these transient oscillatory components. The maximum voltage of 497 kV occurs on Phase C at around 0.36 seconds. After around 2 seconds, when the low frequency oscillations have died away, the highest voltages occur on Phase A which consistently peaks at around 447 kV.

The corresponding current waveforms into the terminal of shunt reactor for the same simulation are shown in Fig. 10. They show that the resonant overvoltage condition results in high currents in the reactor phases, with an instantaneous peak of around 871A in Phase C occurring at 0.36 seconds. Fig. 10. (b). shows that after the low-frequency oscillation has started to settle down at around 1.5 seconds, the Phase A current is peaking at around 750 A exceeding the overcurrent relay setting. Analysing this Phase A waveform between 1.55 and 1.57 seconds reveals the 50 Hz RMS current is 490 A.

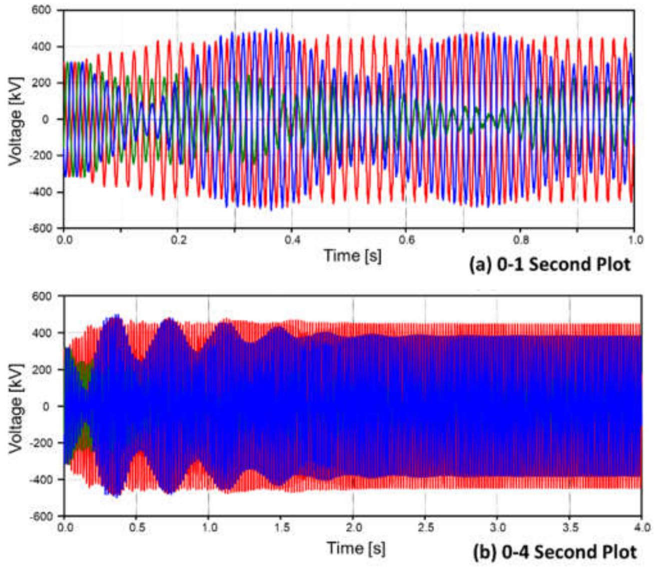

Fig. 9. Simulated Phase Voltages at SUB A of MC during and after the Opening of CB12 with CB2 in the closed position and CB3 and CB4 in the open position.
Phase A: Red, Phase B: Green, Phase C: Blue

The exact magnitude and frequency content of these resonant overvoltages (Fig. 9.) and phase currents (Fig. 10.) are very sensitive to model types and data parameters used. However, a resonance condition around 50 Hz between the energised part of the network and isolated circuit and reactor clearly exists, resulting in overvoltages on the circuit and reactor that have been disconnected from the transmission system.

The nonlinearity of the shunt reactor above 1.3 pu voltage would have slowed down and limited the rise in voltage. Strong harmonic content in the reactor Phase A and Phase C currents indicates that the reactor was in the saturation region.

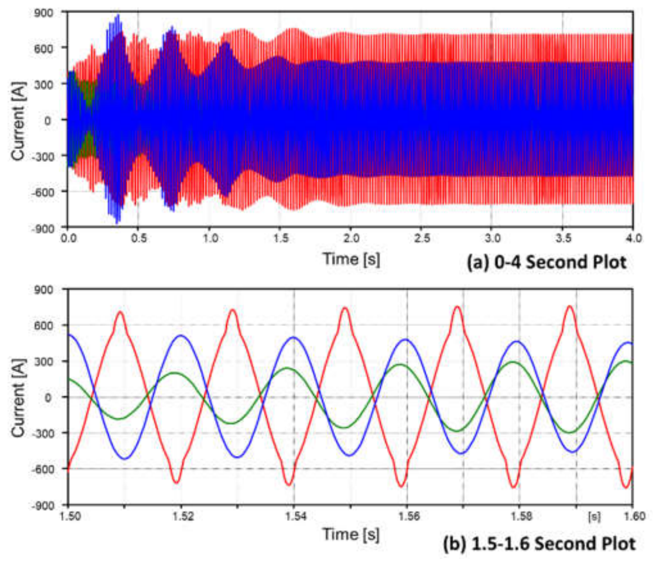

Fig. 10. Shunt Reactor Phase Currents at SUB A During and after the Opening of CB12 with CB2 in the closed position and CB3 and CB4 in the open position.
Phase A: Red, Phase B: Green, Phase C: Blue

VII. PROPOSED SOLUTION

As a company design requirement, no single failure should jeopardise the safety and security of supply. In the case under study the failure of the shunt reactor circuit breaker to open would have led to high voltage on the isolated section.

In order to eliminate the resonance condition between the shunt reactor and the line capacitance, it has to be ensured that the two cannot be isolated from the rest of the network while connected together. Therefore, it was recommended that a line circuit breaker is installed between the busbar section and the line. In this way failure of one equipment e.g. CB2 will not lead to possible excitation of the resonance condition.

Fig. 11 illustrates the location of the new circuit breaker, which has already been installed and commissioned.

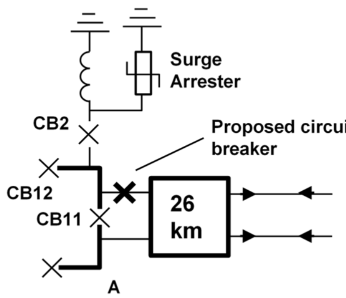

Fig. 11. - Position of the New Circuit Breaker

A Technical Guidance Note, TGN 288 [8], have since been prepared and enforced that sets the limits for overvoltages in the National Grid network. All designs should adhere to the requirements within TGN 288. The risk of this type of resonance condition happening again is reduced through implementation of this guidance document.

VIII. CONCLUSIONS

It is thought that when CB12 was opened at SUB A (400kV) to de-energise the SUB A-SUB E circuit and SHR1 together, it resulted in resonance on the SHR1/line terminal, due to the capacitive coupling with the adjacent overhead circuits, which fed the resonant circuit at the system frequency.

The resonance would have resulted in overvoltages on the line and SHR1. These overvoltages could have caused higher than rated current in the reactor. These currents would have been sufficient to operate the overcurrent protection.

Circuit breaker CB2 appeared to have a mechanical fault prior to operation. Based on the alarm, it was decided not to operate the circuit breaker, but instead isolate CB2 by operating other circuit breakers in the vicinity. However, by switching the overhead line circuit and shunt reactor off together, an induced resonance overvoltage condition would have occurred. This overvoltage condition would have caused overcurrents in the shunt reactor causing protection to trip and open CB2. When CB2 tried to open during the overvoltage condition it would have likely failed as a result. It is thought that the failure was directly caused by a flashover across the phase A of circuit breaker CB2, which would have caused a crack in the circuit breaker chamber due thermal stress. As a result of the crack, the circuit breaker chamber would have failed due to internal gas pressure.

Although this study has shown that a resonance condition exists around 50 Hz, the exact magnitude and frequency content of the simulated resonant overvoltages and phase currents are very sensitive to certain modelling assumptions and data parameters. These parameters include but not limited to; the insulator string losses, the geometry of the line, the cable data, and system configuration at the time of the incident. The model used standard tower geometry to model the overhead line, and 50Hz data for the length of cable. The model could be improved most significantly by modelling the cable explicitly using the conductor geometry and the route records. However, using a combination of simulated and measured event data, it is estimated that the voltage in red phase was well above the limits in TGN 288.

It is thought that protective devices within the CVT at SUB A may have operated to limit the internal and secondary voltages, as a result distorted voltage waveforms recorded from the CVT. The distortion apparent in the measured waveforms could be better understood by looking at the CVT and its inbuilt overvoltage protection in more detail.

IX. ACKNOWLEDGEMENTS

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X. APPENDICES

A. *Appendix A*

The line conductor and tower geometry data are given in TABLE A. 1 and TABLE A. 2 respectively. The length of each section of the line is given in Fig. 1.

The 50 Hz cable data is given in TABLE A. 3.

TABLE A. 4 shows provides the equivalent networks data considered at the boundary points in the model. Each boundary point equivalent is identified by the three phase fault infeed, positive phase sequence X to R ratio and zero to positive phase sequence impedance ratio.

TABLE A. 1- TYPICAL 400 kV OVERHEAD LINE DATA

Internal Radius (cm)	External Radius (cm)	DC Resistance (Ω/km)	Separation (cm)	Bundle No
0	1.431	0.0674	30	4

TABLE A. 2- TYPICAL 400 KV TOWER DATA

Phase number	Horizontal Position (m)	Vertical Position (m)
1	-10.16	21.79
2	-6.93	32.26
3	-8.33	12.95
4	6.93	32.26
5	10.16	21.79
6	8.33	12.95
7	0	43.09

TABLE A. 3- 400 KV CABLE DATA FOR THE TOTAL LENGTH OF 2.5 km

Impedances (50 Hz)	L (mH)	R (Ω)	C (μF)
PPS	1.767	0.0423	1.098
ZPS	0.740	0.560	1.098

TABLE A. 4- SHORT CIRCUIT POWER FOR REDUCED NETWORKS

Short circuit Power Contribution	3 Phase (GVA)	X1/R1	Z0/Z1
Equivalent source at SUB A	9.7	14.7	0.83
Equivalent source at SUB A	20.4	18.4	1.7
Equivalent source at SUB D	3.0	10.6	1.6
Equivalent source at SUB C	9.1	41.3	0.76

B. *Appendix B*

The shunt reactor data is given in TABLE B. 1. The data was obtained from [9], which was published by the same manufacturer as SHR1. As the phenomena under consideration is a 50 Hz effect, the shunt reactor interwinding and winding to ground capacitances were ignored as they play a minimal role in the high voltage under study.

The characteristic data for the surge arrester used across the shunt reactor is given in TABLE B. 2.

TABLE B. 1- 400 kV SHUNT REACTOR CHARACTERISTIC

Shunt Reactor Properties	
Rating	200 MVAr
Copper Losses	200 kW
Iron Losses	100 kW
Knee Point	1.3 p.u.
Saturated Inductance (Final Slope)	25% of linear inductance

TABLE B. 2- REACTOR SURGE ARRESTER CHARACTERISTIC

Voltage [kV]	773	800	820	856	901	987	1086
Current [kA]	1	2	3	5	10	20	40

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