TRV Investigations to Assess the Suitability of 132kV Circuit Breakers for an Offshore Wind Farm Connection

O. Nanka-Bruce[1], S. Nurse[1], M. Jones[1], V. Levi[2]

Abstract **– The current generation of offshore wind farms connect to existing distribution systems onshore. The concern with wind farm connections is the substantial submarine cable system, which results in a large net capacitive charge particularly under low export conditions. It is therefore important for the Distribution Network Operators (DNOs) to ensure that the circuit breakers installed at and near the point of common coupling (PCC) to the DNO's network are fit for purpose with respect to switching operations and fault clearance duty. This paper summarizes the results of transient recovery voltage (TRV) studies carried out to assess the capability of 132kV circuit breakers at the PCC and at neighbouring DNO system locations. The results are compared against the reference TRVs specified in IEC 62271-100:2001 to assess whether the proposed circuit breakers are fit for purpose.**

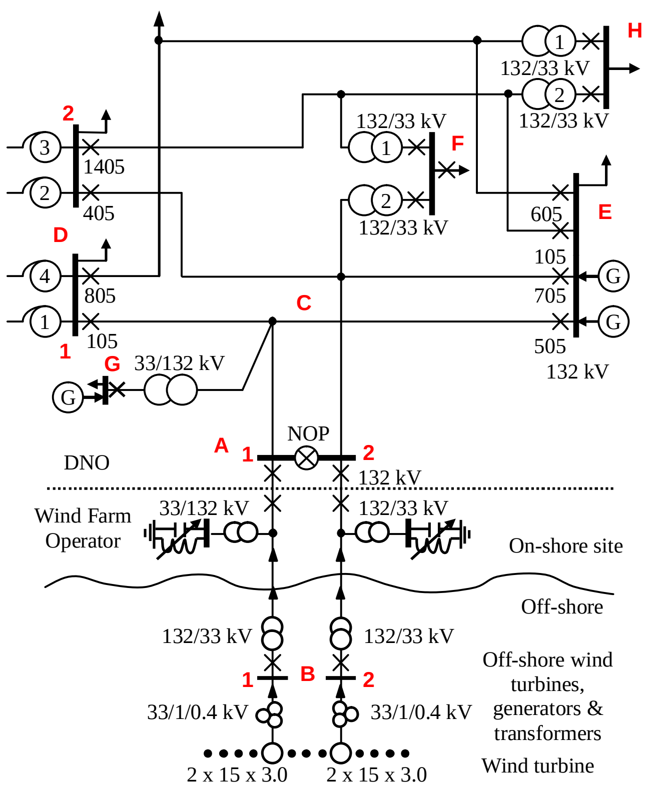
Keywords **– Transient Recovery Voltage, Offshore wind farm, Circuit breakers, ATP/EMTP**

I. INTRODUCTION

Transient recovery voltage (TRV) is the voltage that appears across the circuit breaker contacts upon current interruption. It is important to ensure that the magnitude of the transient and the rate of rise of recovery voltage (RRRV) do not exceed the withstand capabilities of the circuit breaker so that the fault is successfully cleared. The shape of the transient is determined by the inductive and capacitive parameters connected on both sides of the circuit breaker [1]. Other system parameters that can have an impact on the TRV are size of the fault current, type of fault and the assumed model of circuit breakers. Severity of the transient is assessed by determining the first and maximum voltage peaks, corresponding peak times and the RRRV [2].

II. STUDY NETWORK

The network studied is shown in Fig. 1 and comprised a substantial part of the DNOs 132 kV network and the offshore windfarm. The windfarm consists of 2 x (30 x 3 MW) turbines which were connected to the 132 kV level via 2 identical links consisting of 1/33 kV step-up transformers, 33 kV cables, offshore 33/132 kV transformers, 132 kV submarine cable and 132 kV onshore substation with reactive compensation.



Fig, 1: DNO and wind farm system

The studies were conducted using the ATP version of the Electro Magnetic Transient Programme (EMTP) [3]. The main network components were modelled as follows:-

- **Wind turbine generators, Network generators and fault infeeds at 400kV:** The 'voltage behind a reactance' model was used for each generator and fault infeed. Both maximum and minimum fault level conditions were considered. The wind farm generators were not modelled in detail because the focus of the studies was on transient

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voltages on the DNO network, with faults applied at the terminals of the offshore transformer and upstream. The wind farm generators normally operate at unity power factor.

- **Overhead Lines and Cables:** In general travelling wave models were used for all lines/cables, based on the Bergeron model [3] with the modal transposition matrix frequency set at 500Hz. The wind farm was located 13km from the onshore 132kV substation. The length of the wind farm 33kV cable system connected to each offshore transformer was approximately 20km. The length of the OHL circuits from *D* to *E* was 82km, and 73km from *D* to *H*.
- **DNO and Offshore 132/33kV Transformers:** These were modelled in accordance with the relevant winding arrangement (i.e. auto-transformer or two/three winding). Winding capacitances and transformer magnetising characteristic were also modelled. The magnetising characteristic (ie reactance saturation) is important in dissipating trapped charge during single phase fault conditions.
- **Tripped Circuit Breaker:** An ideal circuit breaker (CB) model was utilised. Initially typical trip times were used for the studies; 100ms for the 132kV CBs, 120ms for the onshore 33kV CBs and 50ms for the offshore 33kV CBs. The actual data [5] as detailed in Table 1 was used in later studies.

TABLE 1: CIRCUIT BREAKER DETAILS

CB Location	Trip time (ms)	CB rating (kA rms)
A (132kV)	70	31.5
B (33kV)	50	25
D (132kV)	150	18.3
E (132kV)	100	31.5
F and *G* (33kV)	120	25

- **Shunt VAR Compensation:** Operation of the reactive compensator ranges between a maximum 18MVAr inductive to 12MVAr capacitive compensation. For the study, the wind farm output was set up to enable the two extreme levels of compensation to be investigated. These were modelled either as pure inductive or pure capacitive elements.
- **Wind farm network**: Each 3MW wind turbine generator, associated 1/33kV generator transformer and 33kV inter-cable connections were modelled in full because of the substantial cable system.

III. STUDY

The study considered the evaluation of transient recovery voltages across the 132kV and 33kV circuit breakers at locations *A*, *B*, *D*, *E* and *G*. The scenarios and operating conditions examined to assess the capability of the DNOs circuit breakers were:

a) Different fault types (ungrounded and grounded three phase faults, single phase to ground faults, ungrounded and grounded two phase faults).

b) Different fault locations involving all relevant protection zones, as follows:-
   1) Terminals of CB at *A1*, on the *A1 – C1* circuit.
   2) Terminals of CB at *A1*, on the *A1 – B1* circuit.
   3) 132kV terminals of offshore transformer at *B1*.
   4) 33kV terminals of offshore transformer at *B1*.
   5) Terminals of CB at *D1*, on *D1 – G – E* circuit
   6) Terminals of CB at *E*, on *D1 – G – E* circuit

c) Different operating conditions (winter maximum, summer minimum, with and without reactive compensation at the PCC).

III. BASE CASE – NO REACTIVE COMPENSATION

The base case studies were conducted for winter maximum conditions with no reactive compensation connected.

A three phase ungrounded symmetrical fault close to the terminals of a circuit breaker will give rise to the most severe TRV across the first pole to open [1]. Thus this type of fault was examined first and the results are tabulated in Table 2. The table shows the symmetrical fault current (as a percentage of the CB rating) through the CB prior to its opening. The test duty as specified in IEC 62271-100:2001 [4] corresponds to the fault current as a percentage of the CB rating. The initial peak value, maximum peak voltage and the initial rate of rise of recovery voltage that the CB would be subjected to are also shown.

TABLE 2: THREE PHASE UNGROUNDED FAULT

Flt No	CBs which operate to clear fault	Fault as % of CB rating	Test duty	Initial peak volt (kV)	Max peak volt (kV)	Initial RRRV (kV/µs)
1	*D1* 105	13%	T10	**245**	**245**	0.610
	E 505	11%	T10	163	234	0.720
	A1 132kV	4%	T10	**238**	**238**	0.120
	G 33kV	7%	T10	16	33.5	0.470
2	*A1* 132kV	19%	T30	140	175	0.350
	B1 33kV	19%	T30	23	**69**	0.960
3	*A1* 132kV	15%	T10	118	163	0.470
	B1 33kV	19%	T30	32.5	**68.2**	**1.550**
4	*A1* 132kV	7%	T10	164	167	0.180
	B1 33kV	27%	T30	**80**	**80**	0.130
5	*D1* 105	52%	T60	209	209	0.360
	E 505	3%	T10	207	207	0.320
	A1 132kV	2%	T10	211	211	0.110
	G 33kV	5%	T10	10.65	42.1	0.360
6	*D1* 105	6%	T10	219	219	0.360
	E 505	27%	T30	153	195	0.300
	A1 132kV	2%	T10	129	185	0.090
	G 33kV	6%	T10	10.3	42.7	0.340

The values were compared against the reference TRVs in IEC 62271-100:2001 [4]. The values that exceeded the reference TRVs presented in Table 3, are shown in bold.

The results shown in Table 2 indicate that:

- For fault No. 1, transients on 132kV CBs at points *D*, *E* and *A* were within the RRRV limits specified in [4]. The peak TRV values obtained for CBs at points *A* and *D* marginally exceeded the peak value of 235kV as specified in Table 3. However the voltage waveforms drop below the limit in less than 100µs (Fig. 2). This study was repeated with the wind farm circuits disconnected and the results showed that the transients on circuit breaker at point *D* still exceeded the TRV limits. The implication is that in this case the windfarm connection was not the cause of the excessive peak TRV values.
- For the faults (Nos. 2, 3 and 4) on the circuit between *A* and *B*, the TRV across the 132kV circuit breaker at point *A* was within limits. However the TRV across the 33kV offshore transformer circuit breaker marginally exceeded the peak TRV value [4] for the postulated 132kV faults. A higher TRV peak value (92kV) is applicable in the Out-of-Phase test, albeit with a lower rate of rise of 0.43kV/us. As can be seen from Figs. 3 and 4 the TRVs from the studies fall between these two envelopes.
- For the faults Nos. 5 and 6, the TRVs obtained across the 132kV CBs at points *A*, *D* and *E* were within the limits specified in [4] for both the peak TRV value and the RRRV.

TABLE 3: TRV AS SPECIFIED IN IEC 62271-100:2001 FOR 36KV AND 145KV CIRCUIT BREAKERS

Voltage (kV)	Test duty	TRV peak (kV)	Time (us)	Rate of Rise (kV/us)
36	T10	66	23	2.88
	T30	66	23	2.88
	T60	66	46	1.44
	Out-of phase	92	214	0.43
145	T10	235	34	7
	T30	237	47	5
	T60	231	228	3
	OP1 - OP2	296	232-464	1.54

In summary, **fault No. 1** produced the worst TRV for the on-shore 132kV CBs, **fault No. 4** the worst case TRV for the 33kV offshore transformers CBs and **fault No. 3** the worst case initial RRRV. Sample plots for the worst case faults are shown in Figs. 2 to 4. The figures show (a) the fault currents and corresponding TRVs for the circuit breakers that open to clear the fault and (b) the comparison of the worst case TRV against the relevant reference TRVs from Table 3.

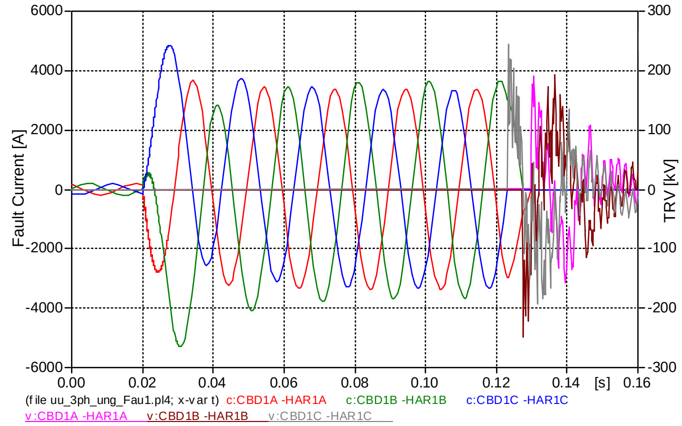

Fig. 2a: **Fault No.1, D1 CB 105 -** TRVs and fault currents for a 3-phase ungrounded fault.

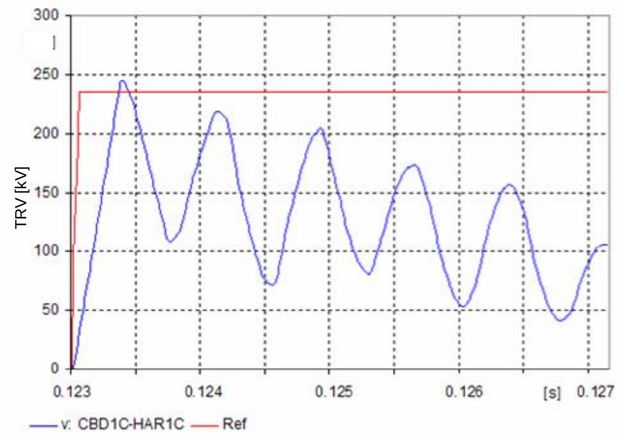

Fig 2b: Time expansion of Fig. 2a showing first pole to clear TRV for D1 CB 105. Also shown is the T10 test duty, a 2 parameter TRV curve for 145kV CBs.

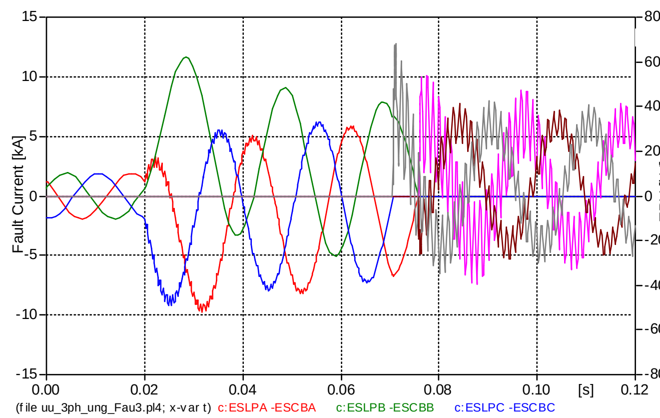

Fig. 3a: **Fault No. 3, Offshore Transformer 33kV CB -** TRVs and fault currents for a 3-phase ungrounded fault

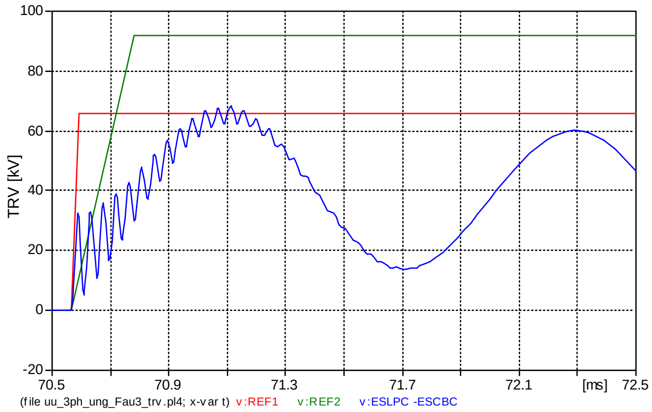

Fig. 3b: Time expansion of Fig. 3a showing first pole to clear TRV. Also shown are the test duties, namely 2 parameter TRV curves for 36kV CBs based on (i) T30 test duty (ii) Out-of phase test duty

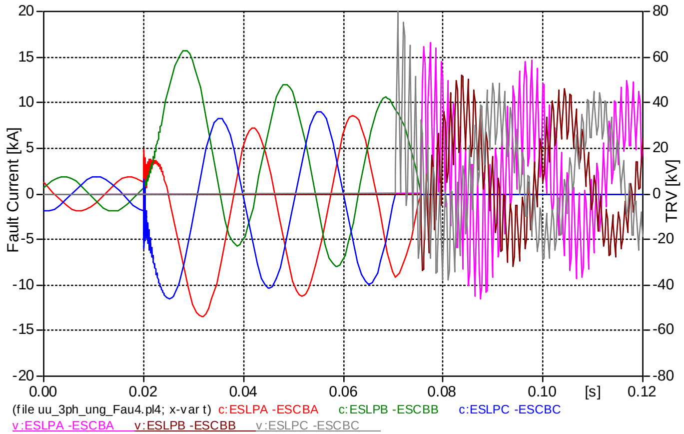

Fig. 4a: **Fault No. 4, Offshore Transformer 33kV CB -** TRVs and fault currents for a 3-phase ungrounded fault

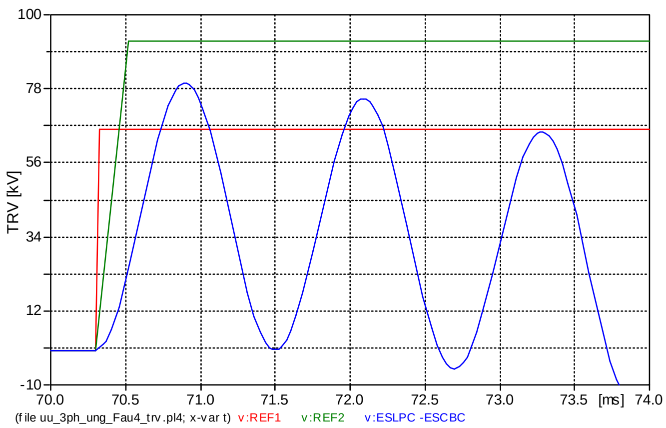

Fig. 4b: Time expansion of Fig. 4a showing first pole to clear TRV for East side Offshore transformer 33kV CB. Also shown are the test duties, namely 2 parameter TRV curves for 36kV CBs based on (i) T30 test duty (ii) Out-of phase test duty.

Examination of other fault types focused on faults at locations 1, 3 and 4. The results for the other fault types are shown in Tables 4 to 7.

TABLE 4: THREE PHASE TO GROUND FAULT

Flt No	CBs which operate to clear fault	Fault as % of CB rating	Test duty	Initial Peak volt (kV)	Max peak volt (kV)	Initial RRRV (kV/us)
1	*D1* 105	14%	T10	206	206	0.56
	E 505	10%	T10	152.7	160.8	0.66
	A1 132kV	4%	T10	161.5	185.6	0.083
	G 33kV	7%	T10	18.8	33.3	0.47
3	*A1* 132kV	15%	T10	108	135.8	0.63
	B1 33kV	19%	T30	32.55	68.03	1.36
4	*A1* 132kV	7%	T10	166	166	0.17
	B1 33kV	27%	T30	74.5	74.5	0.1

TABLE 5: SINGLE PHASE TO GROUND FAULT

Flt No	CBs which operate to clear fault	Fault as % of CB rating	Test duty	Initial Peak volt (kV)	Max peak volt (kV)	Initial RRRV (kV/us)
1	*D1* 105	13%	T10	203	203	0.137
	E 505	9%	T10	141	141	0.613
	A1 132kV	6%	T10	209	209	0.122
	G 33kV	5%	T10	11	19.6	0.184
3	*A1* 132kV	9%	T10	101	123	0.289
	B1 33kV	10%	T10	9.2	33.89	0.383
4	*A1* 132kV	1%	T10	32.8	204	0.032
	B1 33kV	5%	T10	37.8	48.4	0.045

TABLE 6: TWO PHASE UNGROUNDED FAULT

Flt No	CBs which operate to clear fault	Fault as % of CB rating	Test duty	Initial Peak volt (kV)	Max peak volt (kV)	Initial RRRV (kV/us)
1	*D1* 105	8%	T10	169	169	0.469
	E 505	6%	T10	120	126	0.500
	A1 132kV	2%	T10	191	191	0.096
	G 33kV	4%	T10	12.9	20.1	0.323
3	*A1* 132kV	9%	T10	83.4	117	0.327
	B1 33kV	13%	T10	13.5	45	0.75
4	*A1* 132kV	5%	T10	164	164	0.168
	B1 33kV	17%	T30	37.6	55.5	0.122

TABLE 7: TWO PHASE TO GROUND FAULT

Flt No	CBs which operate to clear fault	Fault as % of CB rating	Test duty	Initial Peak volt (kV)	Max peak volt (kV)	Initial RRRV (kV/us)
1	*D1* 105	9%	T10	192	192	0.519
	E 505	6%	T10	152	152	0.661
	A1 132kV	2%	T10	175	195	0.660
	G 33kV	4%	T10	10.3	31.4	0.343
3	*A1* 132kV	10%	T10	185	185	0.090
	B1 33kV	14%	T30	13.8	46	0.767
4	*A1* 132kV	5%	T10	165	165	0.121
	B1 33kV	17%	T30	65.6	65.6	0.083

The results indicate that for the other fault types (three phase to ground, single phase to ground and two phase ungrounded/grounded faults) the TRV for the circuit breakers under investigation were within the limits specified in IEC 62271 – 100:2001. The results confirmed that the three phase ungrounded fault scenario produced the worst case TRV values.

IV. Studies with Reactive Compensation

The reactive power exchange with the DNO at the PCC is limited to a control band of +/- 4MVAr. Two operating modes of reactive compensation were investigated: (a) maximum capacitive compensation where the wind farm was operating close to full active power; (b) maximum inductive compensation where the wind farm was operating at approximately 20% active power.

From the base case studies the worst case TRV and RRRV results were obtained for the three phase ungrounded fault scenario. Therefore this fault scenario was repeated for the network with the reactive compensation connected on each cable circuit at substation *A*.

The results are shown in Table 8 for the configuration with maximum capacitive compensation and in Table 9 for maximum inductive compensation.

TABLE 8: Maximum Capacitive Compensation Configuration - Three Phase Ungrounded Fault

Flt No	CBs which operate to clear fault	Fault as % of CB rating	Test duty	Initial Peak volt (kV)	Max peak volt (kV)	Initial RRRV (kV/us)
1	*D1* 105	9%	T10	208	208	0.562
	E 505	7%	T10	155	171	0.646
	A1 132kV	2%	T10	135	135	0.090
	G 33kV	4%	T10	18.87	33.5	0.472
3	*A1* 132kV	10%	T10	120	160	0.320
	B1 33kV	14%	T10	26.7	75.8	1.110
4	*A1* 132kV	5%	T10	141	149	0.146
	B1 33kV	20%	T30	80	80	0.131

TABLE 9: Maximum Inductive Compensation Configuration - Three Phase Ungrounded Fault

Flt No	CBs which operate to clear fault	Fault as % of CB rating	Test duty	Initial Peak volt (kV)	Max peak volt (kV)	Initial RRRV (kV/us)
1	*D1* 105	9%	T10	178	220	0.481
	E 505	7%	T10	156	175	0.650
	A1 132kV	2%	T10	162	187	0.095
	G 33kV	4%	T10	18.8	33.4	0.47
3	*A1* 132kV	10%	T10	119	163	0.315
	B1 33kV	15%	T10	28.4	76.4	1.350
4	*A1* 132kV	5%	T10	167	167	0.169
	B1 33kV	21%	T30	83	83	0.136

The results indicate that when reactive compensation is connected, the TRV and RRRV values for the 132kV circuit breakers at points *A* and *D* were within limits specified in [4]. For the 33kV circuit breakers, there was no significant difference in the TRV and RRRV values obtained with and without reactive compensation.

Studies were also conducted with the network operating under summer conditions (i.e. minimum fault level) with the reactive compensation connected. The results were similar to those shown in Tables 8 and 9.

Sample plots are shown in Fig. 5 for *D1* 105 CB in the case of fault No. 1 when the maximum inductive compensation is connected.

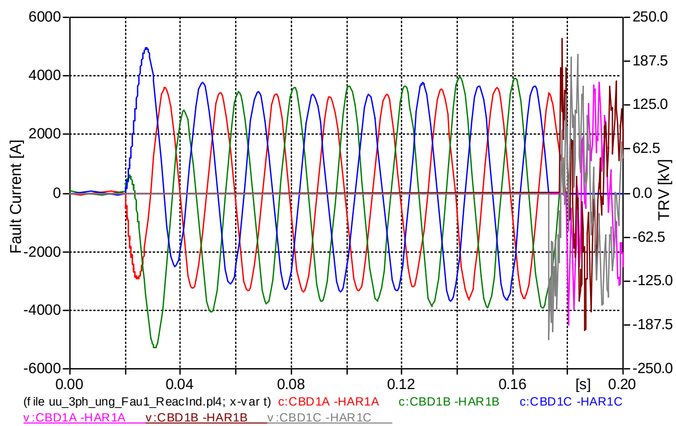

Fig. 5a: **Fault No. 1, D1 CB 105 -** TRVs and fault currents for a 3 phase ungrounded fault. Reactive compensation connected.

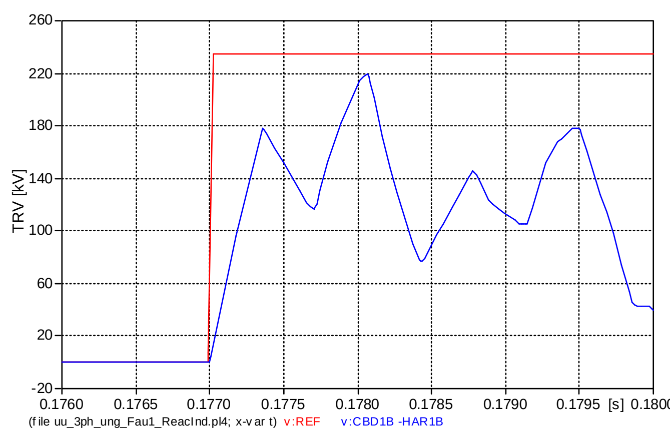

Fig. 5b: Time expansion of Fig. 5a showing worst case TRV. Also shown is the T10 test duty, a 2 parameter TRV curve for 145kV CBs

V. Conclusion

With the increase in wind farm connections, it is important for the DNO to ensure that its circuit breakers in the vicinity of the wind farm are fit for purpose. Transient recovery voltage studies were conducted to investigate the capability of 132kV circuit breakers connecting an offshore windfarm to a DNO's network.

The studies examined different fault types, fault locations and operating conditions. The results were assessed against the reference TRVs specified in the IEC standard [4].

The results of the studies indicated that three phase ungrounded fault scenario produced the worst case transient recovery voltages. With reactive compensation connected, the TRV peak values obtained for the 132kV circuit breakers at points *A*, *D* and *E* were within the limit specified in [4] for 145kV circuit breakers. Without reactive compensation, the 132kV circuit breakers at *A* and *E* experienced TRVs that marginally exceeded the peak limit specified in the standard. Studies conducted without the windfarm connected confirmed that the windfarm was not the cause of the TRV peak limit being exceeded.

The TRVs obtained for the 33kV offshore circuit breakers were within the RRRV limits specified in the standard [4]. However the TRV peak values exceeded the value of 66kV for the T30 duty.

In summary, the studies indicated that the DNO 132kV circuit breakers were fit for purpose when the system was operating with reactive compensation. The standard provides TRV limits against which circuit breakers are tested in order to achieve type test approval. These are minimum requirements that the circuit breakers must fulfil. As these studies have shown, there are circuit conditions that give rise to TRVs that marginally exceed the specified limits. In such situations it is important that the circuit breaker manufacturer is consulted to confirm that the proposed circuit breakers can safely accommodate the values calculated.

VI. Acknowledgement

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VII. References

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VII. Biographies

Oona Nanka-Bruce is a Principal Power Systems Engineer with Parsons Brinckerhoff with experience in the analysis of transmission and distribution systems ranging from 500kV down to distribution voltages. She received her BSc (1985) in Electronic Engineering and DPhil (1989) in Control Engineering from University of Sussex, UK. Her responsibilities include SPAR, insulation co-ordination, loadflow, reactive compensation and transient stability studies using EMTP, PSS/E and ERACS software. Her particular areas of specialisation are fast transient studies and transmission planning.

Steve Nurse is a Principal Power Systems Engineer with Parsons Brinkerhoff whom he joined 4 years ago. He was previously employed in a similar role by the switchgear manufacturer, A. Reyrolle and Co. and its various subsequent trading names over a period of 26 years. He has extensive experience in power systems analysis of both transmission and distribution systems ranging from 500kV down to 415V. He specialises in Electro-Magnetic Transient Analysis and has over 27 years experience in performing studies using the EMTP program. Typical transient studies include insulation co-ordination in relation to both lightning and switching phenomena, SPAR, TRVs, TOVs and ferroresonance in transformers. He personally produced the electrical design for the 275 kV and 400 kV MSCDNs for VATECH Reyrolle Projects Ltd that are currently in use on the EHV transmission network in the UK. His responsibilities also include loadflow, fault, transient stability, harmonic and protection co-ordination studies primarily using ERACS and IPSA software.

Martin Jones is a Power Systems Engineer with Parsons Brinckerhoff with experience in power system analysis and transient studies. He received his MEng (2007) in Electronic & Electrical Engineering from the University of Bath, UK. He is responsible for performing analysis on electrical transmission, distribution and industrial power systems.

Victor Levi was the Professor of Power Systems at the University of Novi Sad, Yugoslavia and Research Fellow at the University of Manchester, UK. He joined ENW (formerly United Utilities) in 2003 and is currently holding position of Strategic Planning Manager. His responsibilities include development of new methodologies for planning and pricing of distribution systems, analysis of regulatory framework, introduction of system studies into the everyday business, etc.