

The effect of AC System Faults on Inverter Operation of Line- Commutated Converters for HVDC

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1 Introduction

This report describes inverter operation of current-sourced, line-commutated converters (LCC) as commonly used for High Voltage Direct Current (HVDC) power transmission.

Inverter operation of HVDC schemes is of particular interest in the management of AC power systems since all LCC HVDC inverters are susceptible to brief power interruptions following contingency events in the AC network.

These brief interruptions generally follow a commutation failure.

Commutation failures are mainly caused by events in the AC system. Typical causes are a voltage drop or a phase angle change in the AC system resulting from a switching event or system fault. [1]

An actual system event recorded in the Tasmanian power system is provided as a case study.

2 HVDC Inverter Operation Review

In a line-commutated converter, the following three conditions must be satisfied to achieve active power inversion, i.e.: conversion of power from the DC to AC side of the converter station which then supplies power into the connecting AC network (refer Figure 1):

1. Presence of an AC voltage source within the connecting AC network. This provides the commutating voltage waveforms for the inverter. Commutation is the term used to describe the transfer of current from one thyristor "valve" to the next.
2. Provision of firing angle controls that are able to delay valve commutation beyond a firing angle ' α ' of 90° .
3. A DC current source, which is provided by the remote end HVDC converter station operating as a rectifier. The inverter "sinks" current into the connecting AC network.

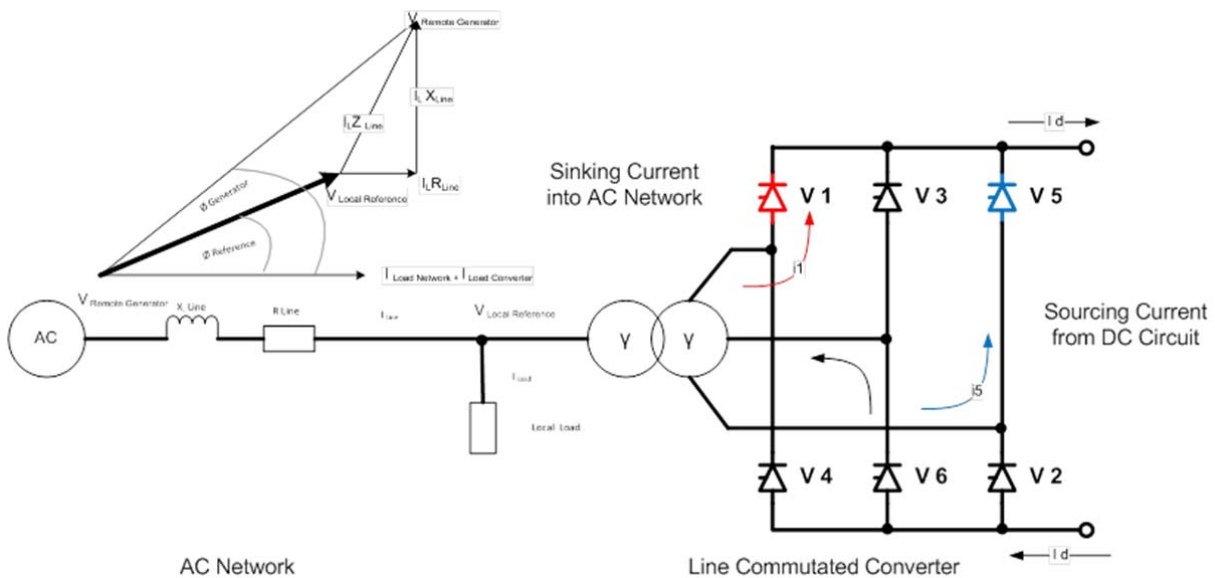


Figure 1: HVDC connected to an AC network with remote generation

3 Inverter Commutation Process

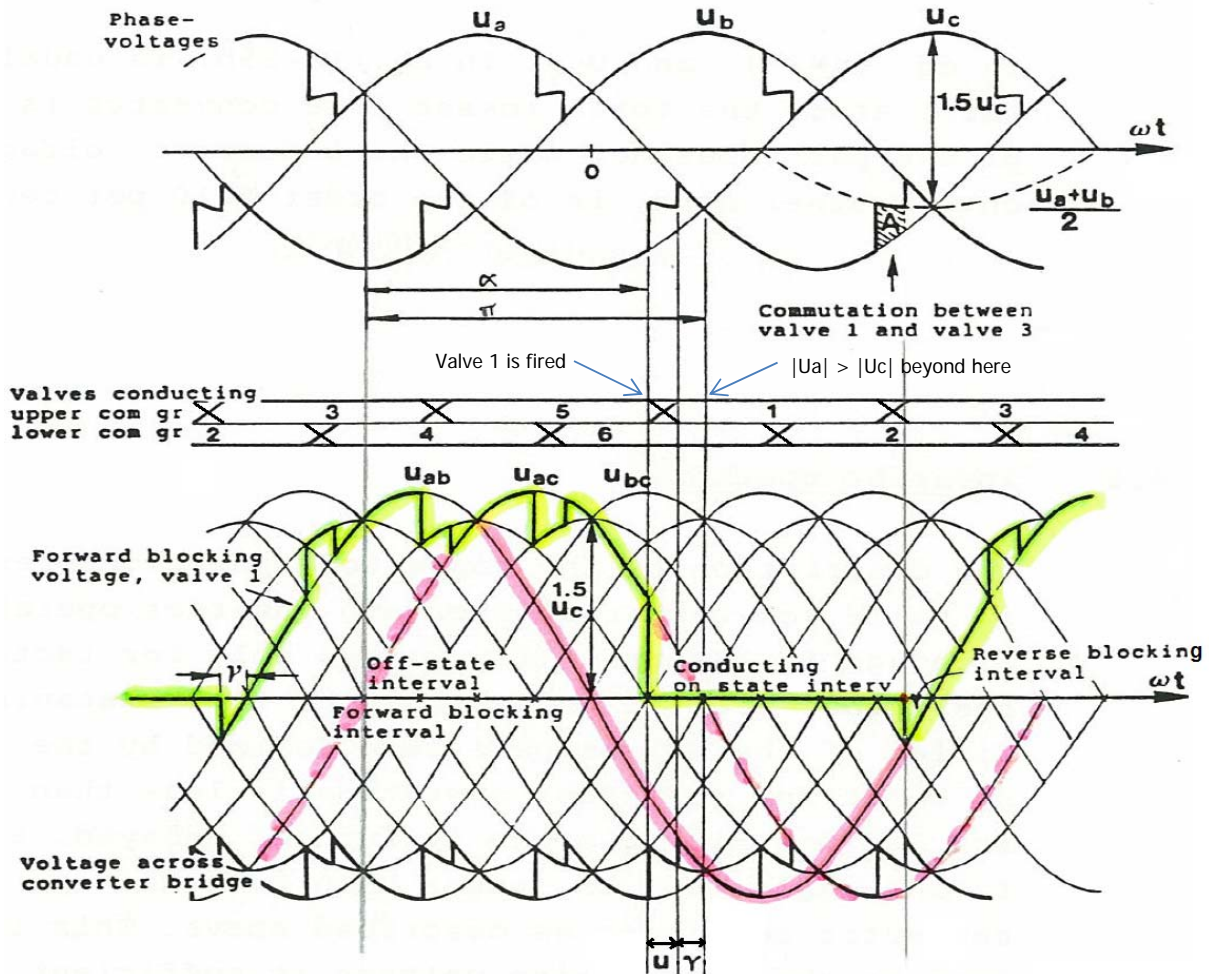
Figure 2, which is taken from [2], illustrates how the commutation process occurs during inverter operation. Commutation of current from Valve 5 to Valve 1 in the upper half of a six-pulse bridge is demonstrated.

Commutation starts when Valve 1 is initially **turned-on** (fired) with a firing angle delay of ' α '. Given that conduction now begins in Valve 1 *while* Valve 5 is still in a conducting state, this places an effective short-circuit across the converter transformers A and C phases (on the valve winding side). This short circuit causes a very high di/dt current (limited by transformer leakage inductance), which ramps up current in Valve 1 and ramps down current in Valve 5. Note: the phase voltages drive the di/dt current backward through Valve 5 from cathode to anode. The time period when commutation is occurring between two adjacent valves is referred to as the overlap angle ' u '.

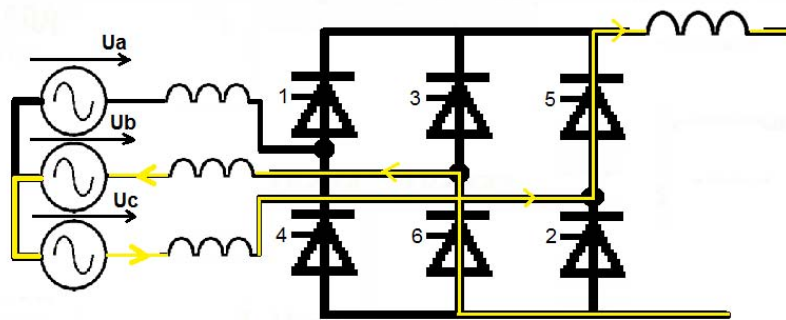
When the current through Valve 5 transiently passes through zero, the valve will experience a brief negative current before finally turning off. During this time the stored charge is removed from each thyristor's p-n junction and the valve begins to support reverse voltage. A short period of reverse "recovery" voltage is needed to prevent unintentional re-firing should thyristor voltage becomes positive again. After this recovery period (denoted as ' γ ', the extinction angle), the thyristor can safely support the full forward blocking voltage imposed from the next AC cycle.

Critically, commutation from Valve 1 to Valve 5 is only possible while U_c is more negative than U_a , i.e.: the current changeover must be completed before the point on the waveform highlighted in Figure 2, with sufficient margin to allow for valve extinction.

In steady-state commutation is a regular sequential process. The next commutation process shown occurs 60° later between Valves 6 and 2 on the bottom half of the six pulse bridge. Since the nominal conduction period for each valve is 120° it is the turn of Valve 1 to be commutated off 60° later and this commences with the firing of Valve 3.



Inverter operation. Phase-voltages, voltage across valve bridge and voltage across valve 1 at $\gamma=15^\circ$ and $u=15^\circ$.



Current paths just prior to firing of Valve 1. During the shown overlap period, i , current will commute out of Valve 5 into Valve 1.

Figure 2: Converter Waveforms during HVDC Inverter Operation

There are several important characteristics of inverter commutation that make it susceptible to disturbances in the commutating voltage waveforms provided by the AC system:

1. The firing pulse sent at angle ' α ', occurs near to the negative going voltage zero crossing of the valve needing to be turned-on.

As seen in Figure 2, the voltage across Valve 1 just prior to firing, follows the trajectory of U_{ac} which is only about $30^\circ (u + \gamma)$ before its next zero crossing.

2. The just extinguished valve (Valve 5 in Figure 2) has only a short period (γ) of reverse "recovery" voltage before it must support forward voltage again. Maintaining an adequate extinction angle ' γ ' is therefore critical for the thyristors and decreases the available time to complete commutation.
3. The commutating voltages for both the turning on and turning off valves are naturally decreasing, whereas the converse applies for rectifier operation.

The impact is that the time available to achieve commutation is very limited and becomes more difficult as voltage decreases towards the end of the γ window.

These are the three main factors that make HVDC inverter terminals much more at risk of suffering commutation failures compared to rectifier terminals.

Since AC network disturbances cannot be avoided, the inverter is designed to operate with a ' γ ' margin that is sufficient to allow uninterrupted HVDC scheme operation for events in the system that are not associated with faults, e.g.: switching events, load changes etc. Typically a γ margin of 15° to 17° is chosen, which makes the HVDC scheme tolerant to dips in commutating voltage in the range 10-15 %.

It is assumed that HVDC inverters will experience commutation failures for larger voltage dips associated with AC network fault events. It is normal for AC system operators to apply constraints to network operation that allow the power system to cope with transient interruptions in HVDC power transfer lasting for up to approximately 500 ms.

To mitigate the risks to the valves imposed by commutation failures, HVDC converter stations utilise valve based protection systems.

The protection must be able to discriminate between external power system events and transient and genuine internal faults, so that undue disruption or disturbance to DC transmission can be avoided. A typical example is the requirement to avoid tripping on inverter commutation failure caused by AC network faults. The DC link in this case is designed to recover from commutation failures. [3]

There are two main "types" of commutation failure:

1. The failure of the valve attempting to turn off actually being successful. This is usually due to the valve's commutating voltage suffering a dip (in magnitude), or having its zero crossing advanced (in time).
2. The failure of the valve attempting to turn on actually being successful. This is usually due its firing signal occurring too late in time, i.e. after the commutating voltage has already become negative.

It must be remembered that AC network faults impact both the magnitude **and** phase angle of the voltages upon which the inverter relies for commutation.

Once a commutation failure has occurred, there will be a time period where two valves in each six-pulse group will undergo uncontrolled, continuous conduction. Typically, these two valves will short-circuit the valve winding terminals of the converter transformer and thereby draw a heavy inductive current from the AC network. However, it is also possible for these continuous

conduction currents to flow via the DC side with negligible interaction with the AC network. Whether this occurs or not is largely dependent on what conduction states the valves were in at fault inception and the nature of the fault itself.

Normally the period of continuous conduction ceases quickly (during the network fault) either by natural decay of the "trapped" DC current, or by successful "re-commutation" of the trapped current into one of the non-conducting valves. The latter cannot occur for bolted 3-phase AC faults since there is no commutating voltage. Re-commutation can occur during faults at quite low voltage levels if the non-conducting valves are fired during periods with sufficient **positive** voltage-time integral.

Refer to Figure 3 for a simulation of a valve experiencing a period of continuous current during a 120 ms duration remote AC network fault which started at $T = 0.05$ s.

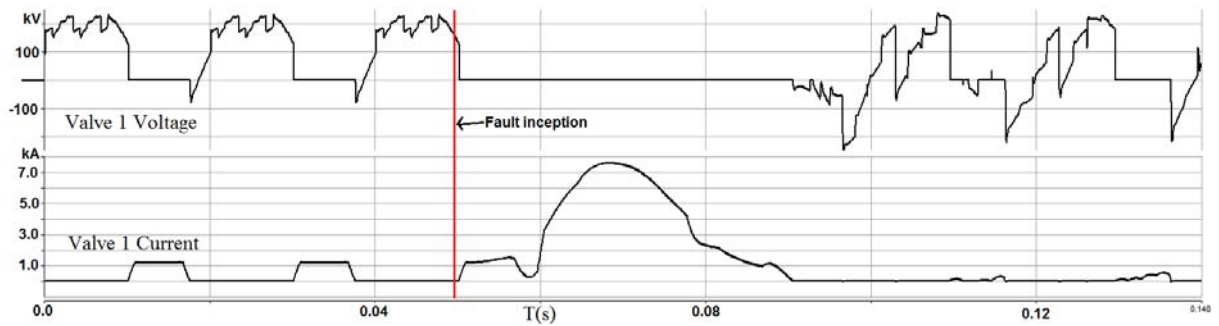


Figure 3: AC fault with "trapped" DC current and long absence of valve voltage

4 Types of AC Network Events

This section describes the impacts of different fault types on the commutating waveforms. It should be noted that for a given fault location and impedance a line-line fault will cause a greater shift in phase angle than a line-ground fault although the likelihood of line-line faults is significantly less.

4.1 Type A

An AC network event of type A (brown dashed trace on Figure 4) represents a *balanced* AC network event that has caused a magnitude dip in the commutating waveform presented to the converter.

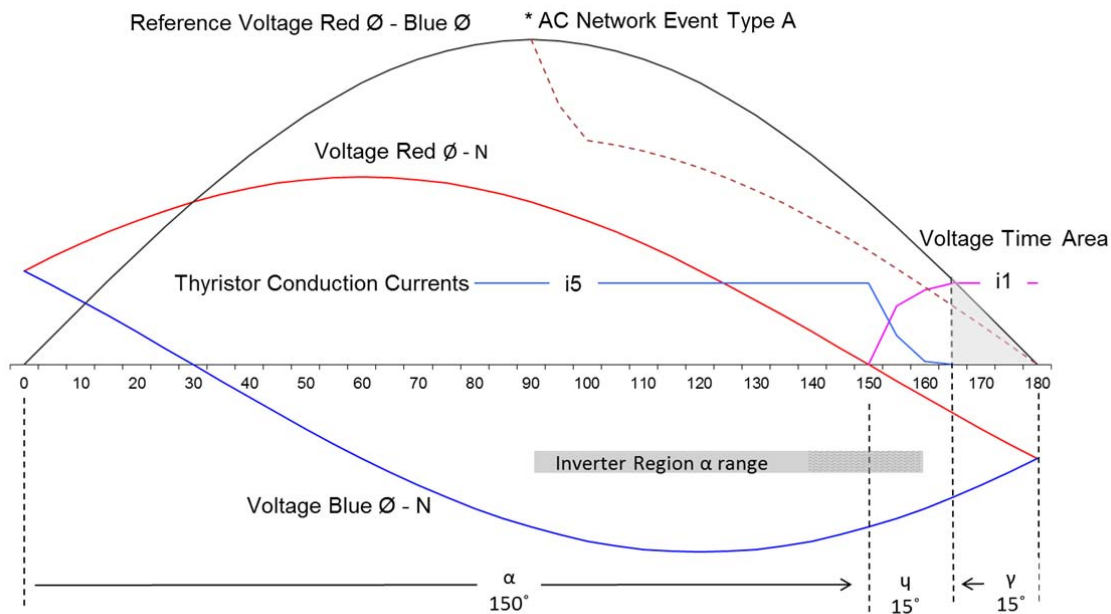


Figure 4: HVDC Commutation Overview with Event Type A

This type of event presents a phase to phase commutating voltage (shown as Red-Blue) at the converter transformer primary that is at a reduced magnitude from the original reference voltage but with no phase shift at the point of zero crossing.

The following results occur:

1. Voltage time area reduced resulting in a commutation failure.
2. This results in a temporary bypass of the converter group.
3. The commutation failure results in the DC current increasing, due to the temporary DC voltage collapse at the inverter.
4. When the AC voltage recovers sufficiently commutation is restored.
5. The standard control system response is for the rectifier to limit DC current while the inverter increases extinction angle (gamma control) and restores power flow in an attempt to minimise the disturbance to the AC network.

4.2 Type B

An AC network event of type B (grey dashed trace on Figure 5) represents an *unbalanced* AC network event that has caused a phase advance in the commutating waveform presented to the converter. In Figure 5, note the position of the zero crossing of the phase to phase voltage (Red-Blue) relative to the reference voltage.

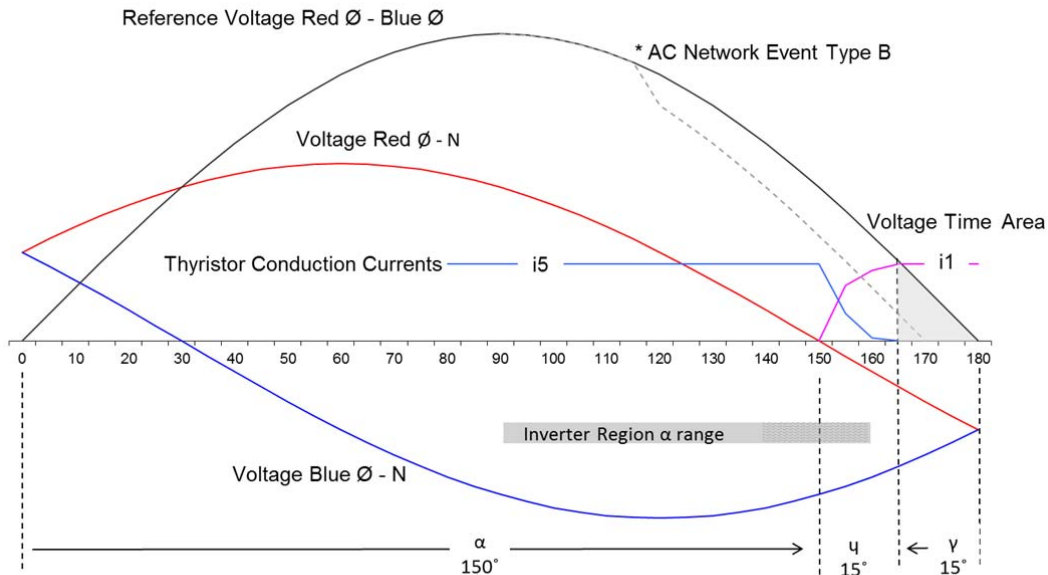


Figure 5 – HVDC Commutation Overview with Event Type B

This type of event can present a phase to phase commutating voltage at the converter transformer primary with a phase shift that leads the original reference voltage.

The following results occur:

1. γ (extinction angle) is decreased as it is now measured from $\approx 170^\circ$.
2. The voltage time area is reduced resulting in a commutation failure.
3. This results in a temporary bypass of the converter group.
4. The commutation failure results in the DC current increasing, due to the temporary DC voltage collapse at the inverter.
5. With fixed equidistant firing, the triggering signal to the thyristors will occur at the same time for the next valves that are required to conduct. With asymmetric commutating waveforms, this may result in sustained or extended commutation failures. This will continue until corrected by the control system.
6. Sustained or extended commutation failures may result in the operation of valve protection.

5 Case Study

This case outlines an actual network event that caused the commutating waveforms presented to the HVDC converter at George Town to contain the distortions described in section 4.

On 23 February 2015 at 00:54 hrs, there was a line-line fault on TasNetworks' 220 kV Gordon – Chapel Street (GO-CS) #2 transmission circuit about 20 km from Gordon Power Station. This is about 340 km distant from George Town (GT) substation and was therefore seen as a remote fault on the GT 220 kV busbars. In electrical terms a remote fault will have much higher network impedance between it and the point of measurement when compared to a local fault.

The three traces presented in Figure 6 show the three measured line-ground voltages at GT (indicated by blue lines), as well as three line-ground reference voltages (shown by red lines) which are the pre-fault voltages simply extended in time.

Prior to the fault, the Basslink HVDC converter was importing 458 MW into Tasmania. The fault occurred at sample number 500 and triggered a commutation fault at the George Town converter station. Basslink tripped about 30 ms after fault clearance. The impact of this additional event can be observed near sample number 1200.

The reference waveforms clearly illustrate the level of disturbance due to the fault event with annotations provided in Table 1. The initial voltage dip of 18 % in white and blue phases is sufficient to trigger a commutation failure.

Phase name	Pre-fault voltage	Pre-fault phase \angle	Voltage 20 ms into fault	Phase \angle 20 ms into fault	Phase \angle shift relative to R-phase
Red	1.030 pu	0°	1.000 pu	-15.24°	0°
White	1.032 pu	-120.09°	0.842 pu	-148.13°	-12.89°
Blue	1.034 pu	-240.17°	0.843 pu	-243.40°	+11.84°

Table 1: Voltage and phase measurements at GT 220 kV substation (23/02/15 00:55 hrs)

Since this fault was of the line-line type, the change in phase angles during the fault follows the expected asymmetric pattern, i.e. white phase lags red phase by an extra 13° whereas blue phase is 12° advanced compared to its un-faulted position. Note the actual vectors of all three phases are lagged compared to their pre-fault positions. This is predominantly due to the phase angle shift and reduction in rotational frequency following the loss of HVDC import.

Referring back to Figure 2, it can be seen that additional lag in the actual commutating waveforms will improve the inverter's operating margin (white phase), but an advance of the actual waveforms (blue phase) will have the opposite effect.

As a result of the phase shifts imposed on the individual phase voltages, a HVDC inverter using a fixed method of equidistant firing pulse control¹ could have insufficient margin to trigger re-commutation during network fault events. This is because the firing pulses delivered to the valves may be delivered at the wrong point in the commutating voltage waveform, leading to sustained commutation failure.

Clearly the higher the impedance (lower fault level) between the converter station and the synchronous generators of the power system then the greater the phase shift at the converter station

¹ Refer to "Power System Stability and Control", Prabha Kunder, EPRI, page 519 for further explanation

for a given power interruption. Figure 6 illustrates a lag in phase angle after fault clearance due to the loss of supplied power provided the HVDC inverter. This phase lag would increase with higher system impedance.

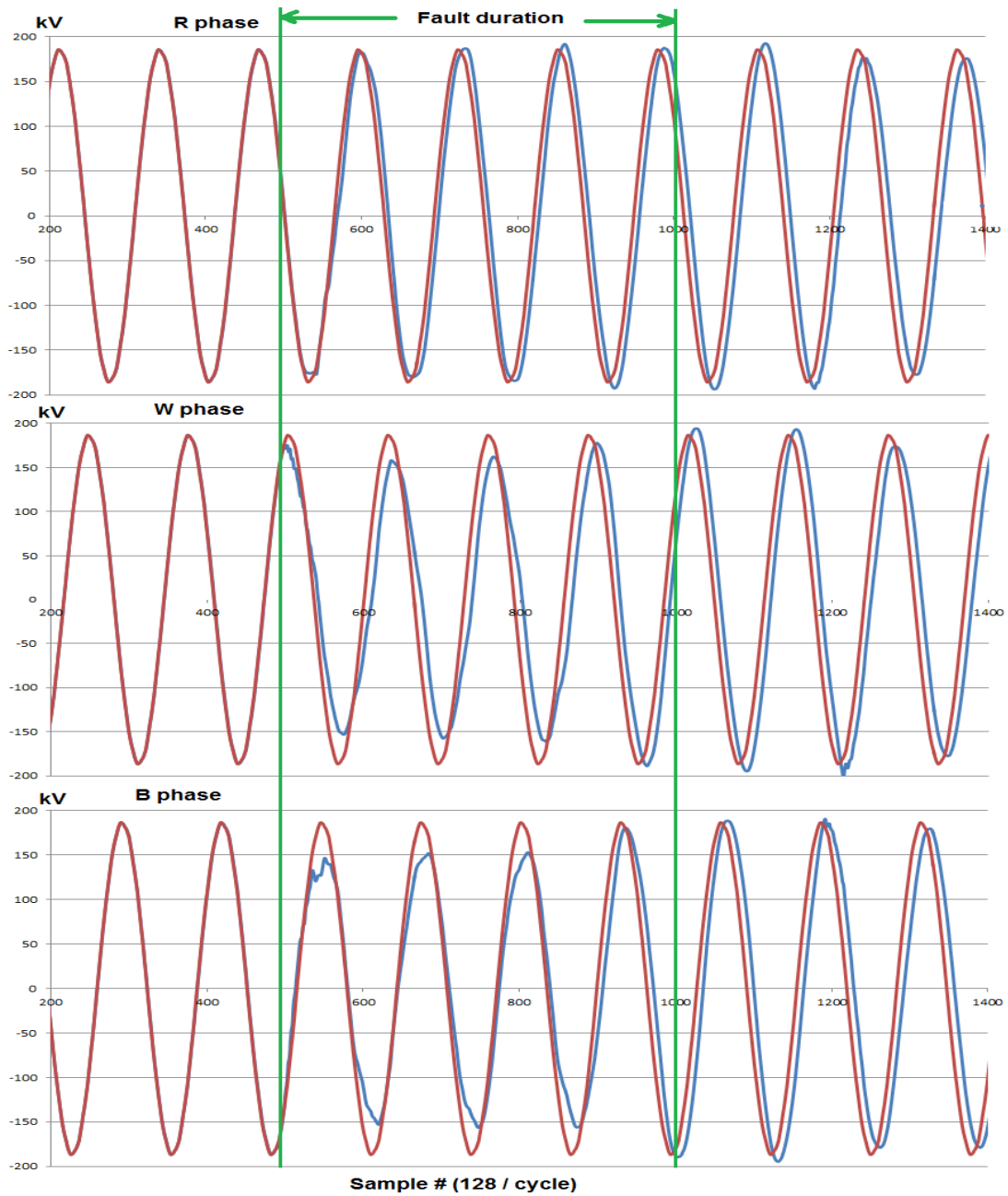


Figure 6: Voltage waveforms at GT 220 kV substation for remote transmission fault

6 Summary

This paper describes the mechanism by which a line commutated HVDC converter which relies upon a fixed method of equidistant firing pulse control can experience extended commutation failures. Such an outcome can occur when a voltage phase angle is advanced due to the occurrence of an asymmetrical network fault event.

7 References

- [1] J. Arrillaga, Y.H. Liu, N.R. Watson, "*Flexible Power transmission the HVDC Options*", John Wiley & Sons, Ltd. 2007, ISBN 978-0-470-05688-2
- [2] Åke Ekström, "*High Power Electronics HVDC and SVC*" The Royal Institute of Technology, Stockholm, 1990
- [3] Alstom Grid, "*HVDC: Connecting to the future*", First Edition, 2010
- [4] Arrillaga. J, High Voltage Direct Current Transmission, ISBN 0-85296-941-4, The Institution of Electrical Engineers, 1998.