High-Power Regenerative Converter for Ore Transportation under Failure Conditions

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Abstract—The use of three-level neutral point clamped (3L-NPC) voltage source inverters for drive applications in the megawatt range is becoming a standard solution. In combination with the same converter circuit in rectifier operation as Active Front End (AFE) it is able for four-quadrant operation. An existing plant, which has been in operation with eight converters since several years, has shown some failures, which lead to considerations of failure mechanisms and failure rates. All failures were on the AFE. A first failure of a power semiconductor leads to subsequent breakdown of others. Some failures are analyzed and failure conditions are described. Some failure reasons can be excluded and a probable reason is pointed out. Finally, a recommended solution is described and its result after its implementation is discussed.

I. INTRODUCTION

Nowadays a large amount of industrial facilities are incorporating high-power Active-Font-End (AFE) converters and medium level voltage systems, for handling larger amounts of energy more efficiently and safely. Previous reports have presented the incorporation of these systems especially in the mining industry, where line-side PWM converters can provide reduced network interaction, unity power factor and bidirectional power flow capability [1]-[4]. Three-Level neutral-point-clamped configuration (NPC) is employed increasingly for high-power applications, because its inherent capability for medium-voltage operation, concerning, low switching frequency and power semiconductors utilization, as discussed in [5] - [7].

However, despite the advanced stage of the semiconductor technology, burning issues of semiconductors devices are still a concern. Some critical application requirements impose very strong specifications to the semiconductors like minimum “on-stage” current, high blocking voltages, low switching losses, etc. Many mining facilities are located at high-level altitudes above sea level. This condition introduces extremely high stressing environment to the power systems and power semiconductors devices [8, 12].

This work presents a report of failures presented in an industrial high power medium voltage level downhill conveyor, including the study of semiconductor’s failure mechanisms and a solution for the recurrent failures presented by the downhill conveyor at the line side active-front-end converters.

The main contribution of this work is to resume some situations on power semiconductors working in highly rough environment conditions.

II. DESCRIPTION OF THE SYSTEM

The conveyor system here described consists of three individual conveyors, where two of them have three AC-Drives each and the third one has two AC-Drives only. The three conveyors have a length of 5905, 5281 and 1467 meters. The average inclination is about 11% downhill. With a transport capability of 5800 tons/h, a total of 15 MW can be regenerated to the network keeping unity power factor. Fig. 1 presents the single-line diagram of the electrical system. The conveyors are named as CV005, CV006 and CV007. CV005 and 006 have three motors each, meanwhile CV007 only two. This could be an important fact because of the harmonic issue concerning power quality and some important operational considerations.

Fig. 2 shows a diagram of one conveyor system (CV006). The fourth drive is not present in the actual implementation, but will allow upgrading in the future. Conveyor 3 has only two motors, as it is only 1467 meters long. The motors are induction motors of 2.5 MW each operated by three-level neutral point clamped converters (3L-NPC) with a second 3L-NPC at the line side acting as active front-end rectifier (AFE).
In the field, some major failures have been observed during a three-year period of continuous operation. A failure of the conveyor system produces a process interruption, which means a significant loss of time and money. In general, in a high power level application a lot of problems can be the source of damage conditions to any component, such as dust, wrong semiconductor installation, electronics failures, humidity, etc. As a fact, the conveyor system has been involved in a periodic kind of failure concerning only two of three power drive systems. A remarkable fact is that the conveyor operated with two drives only did not show any failure. Another fact is that only line side inverters were affected. With two 6-pulse connections a 12-pulse operation can be achieved, eliminating all harmonics $h = 6k \pm 1$ where $k = 1, 3, 5,...$ Naturally, the third drive will inject all 6-pulse harmonics to the mains. This non-eliminated (or mitigated) harmonics may be determinant in the failures observed. It is also observed that the most remote drives were affected. Another different source of failure may be endorsed to temperature issues. A temperature phenomenon may cause individuals GTO’s damage, leaving them in a short-circuit condition. Naturally, a microscopic analysis should suggest this failure. Another possible cause may be a spurious or wrong switch-on signal command. For GTO’s and other power semiconductors the on command should be accomplished with minimum requirement as voltage level, pulse timing, etc.

Since the requirements of operation are extremely high and based on the importance of the problems raised from failure situations, a description concerning some problems is presented. Further, a data based report of all the failures and their nature are described. Some data acquired under normal condition and at the failure time will follow.

III. DESCRIPTION OF THE FAILURES

During the normal operation as well as during some test maneuvers failure conditions have been observed. Some of them are of same nature but others have a different origin and consequences. The table below shows a historical failure report including dates, number of damaged GTO’s, the AFE’s phase and the conveyor where failure occurred.

As can be seen in the Table I, an evident pattern related to the number of damaged GTO’s exists. Only in case 7 the pattern is different. This is due to the operation at the failure time. In this case some tests were in progress, so, the damage cause is very different from the others.

The repeated failure pattern, as observed in Table I shows four GTO’s damage. Every case results in three GTO’s burned in a converter leg and only one in one of the other legs. For instance, case five resulted with 3 GTO’s damaged in phase 1 and one at phase 2. This is observed for all cases from 1 to 6 and for case 8.

A. Typical failure sequence description

Fig. 3 shows a scheme of an Active Front End connected to the network. As described above, all the failures where at mains side, so, the scheme is for that case.

Assuming a first failure of one GTO, the subsequent failures of the others can easily be explained. Whichever the first GTO failure cause may be, one of them will produce one or more GTO breakdown, causing the failure pattern mentioned before.

In Fig. 4 a scheme showing why all four GTO are damaged is presented. Let’s assume that the voltage pattern is like SHE does. This means, in this particular case, three fixed commutation angles within a quarter of period. The sequence describing the failure is drawn in the Fig. 4.
As observed in Fig. 4, if GTO-A fails (for any reason) at stage T2, a subsequent malfunction originates GTO’s B and C burning during stage T3, causing a short circuit in capacitor C1. All the energy contained in it is suddenly discharged through GTO’s A, B and C. The current circuit is closed through diode Dy to the middle point. The last GTO in the burning sequence is damaged by an overcurrent due to the short circuit across the network and the burned GTO’s. The specific studied case has as consequence the damage of one more GTO on any other phase, depending on the mains voltage and current flow at the failure moment. In Fig. 5 a possible path for current is depicted.

Figure 4. Failure sequence for one leg GTO’s burning.

Figure 5. Possible path for current due a failure of GTOs 1.1, 2.1 and 3.1.

IV. Recorded Situations

In the actual industrial installation some registers during failures have been recorded for analysis purposes. The most important ones are presented in the next figures.

A. Normal Operation

In Fig. 6 the data of one drive is displayed, the other three drives behavior is quite similar. Here, start and stop maneuvers are performed. As can be seen in fig. 6c, a normal value of current under standard load is about 600 Amp. The normal dc-link value is about 4300 volts. This means that stable blocking voltage of the semiconductors is 4300/2 volts, which is far from their maximum DC-blocking voltage. As normal condition a slight difference between both dc-link capacitors is always present within a reasonable voltage range (Fig 6b).

B. Failure Situations

Following, two different situations are presented. Both of them are associated with two different failure situations. First one was recorded during a start maneuver, and the second one was recorded during normal operation.

1) Failure during starting

In Fig. 7 a pre-charging condition is performed until dc-link voltage reaches about 4300 V.
By time 47 sec. aprox., a low level charge is applied to the dc-link for test proposes. This test allows detecting a dc-link short-cut or a damaged semiconductor. After the test the normal charge continues for running on the system. Just in the moment the dc-link reaches 4300 volts a fast discharge occurs as shown in Fig. 7.a. As can be seen in Fig. 7.b, the voltage between capacitor C1 and C2 grows up violently (negatively) confirming a short-circuit through capacitor C1 and 3 GTO’s. It is highly probable the three GTO’s result burned and keep a short-circuit condition. Even more, the voltage diagram for the dc-link shows that all the voltage present in it is supported only by capacitor C2 at that time. This is clear looking at the following equation:

\[ \Delta V_{DC} = V_{DC1} - V_{DC2} \]  

The voltage difference is negative as C1 is short-circuited and C2 is not, therefore

\[ V_{DC1} = 0 \]

then

\[ \Delta V_{DC} = -V_{DC2} \]

The short-circuited GTO’s in the first AFE leg and the conducting GTO’s of the other legs also short-circuit the line transformer, which results in severe over-current at the line side. In Fig. 8 a more detailed view is presented with the same information presented in Fig 7 (7.a, 7.b and 7.c). Clearly, in a first moment the dc-link voltage (Fig 8.a) suddenly drops off from 4300 V to 2200 V aprox. This means a short-circuit must be at capacitor C1, as suggested before. Between time 59.7 and 59.8 aprox., a resonance (or maybe a continue current through mains) is detected, Fig. 8.c. Obviously the dc-link voltage raises and drops as the current at the mains flows in and out. A mayor concern is the reaction time for system blocking. From the figure, almost 100 ms (five periods) happen from the fault to the halting.

2) Failure during normal operation

In Fig. 9 an oscilogram shows dc-link voltage (Fig 9.a), capacitors C1 and C2 voltage difference (Fig 9.b) and line current in d-q coordinates (Fig 9.c)

![Figure 9](image)

By time 164.3 sec, a failure is detected and the complete system is stopped, shutting-down the two other conveyor’s drives. In Fig. 10 a detailed view is presented. Here the exact moment of the failure is isolated for a better understanding of the process during the failure.

![Figure 10](image)

Figure 10. (a) dc-link voltage, (b) Difference between capacitor A and B. (c) Line current in d-q coordinates at line side inverter

Note: any value above abs(1000 V) in figure 8.b and above abs(3000 A) in Fig. 8.c means saturation from the measurement instrument.

As can be seen in Fig 10.c a large over-current at the line side is produced due to a short-circuit of the AFE’s transformer through damaged GTO’s and the ones that are conducting normally.
V. FAILURE MECHANISMS

Although semiconductors compared to other technical equipment offer an outstanding reliability, mostly because of the lack of any mechanical moving parts, their reliability is not ideal. The most obvious reason is that the mass of a power semiconductor is in the range of one or two kilograms and that the mass of the active silicon part even is in the range of a few grams only, but they have to handle power in the megawatt range. Whereas other technical equipment takes some duration of fault to reach the crucial temperature, semiconductors are much more sensible to overload and will be damaged in the fraction of a second or even in a fraction of a millisecond.

GTO's like any other semiconductor may fail because of different reasons, the main categories of which are: Overvoltage, overcurrent, overtemperature, mechanical and external reasons.

These main reasons can be subdivided into several failure mechanisms and may have different origins. These will be discussed in detail for the described drive system with two three-level neutral clamped inverters in a back-to-back arrangement.

In general, any violation of data sheet specifications may cause failure of the semiconductor, so a close inspection of the data sheet is helpful to understand possible failures.

A. Overvoltage and overcurrent

The data sheets contain at least two definitions of maximum voltage. One is the repetitive peak off-state voltage ($V_{DRM}$) under the condition that the gate is negative biased versus the cathode. This voltage is allowed for some ten microseconds only. The other much lower data ($V_{DClink}$) is the permanent dc voltage for 100 FIT failure rate (1 FIT is 1 failure in 10^6 hours of operation). Whereas the former is a strict limit, which should never be exceeded, the latter is a reference, which is significant for the inverter reliability. Many inverters are designed in such a way that this value is about 1.15 times the actual dc voltage applied to the semiconductors at nominal line voltage, in case of 3L-NPC this is half the dc-link voltage. In case of the inverter under consideration the dc-link voltage is controlled by the line-side converter and can be regarded as almost constant and not depending on line voltage. The $V_{DClink}$ of the GTO under consideration is 1.27 times the actual half dc-link voltage, which results in a major degree of reliability. In case of a first failure the full dc-link voltage will be applied to another GTO. This in most cases will lead to a subsequent failure of the second or even a third semiconductor of the same leg as the permissible voltage and current are exceeded by far. The maximum peak non-repetitive surge current $I_{TSM}$ and the limiting load integral $I^2t$ are important for failures within or outside the inverter. These parameters describe the ability to withstand severe overcurrents as a consequence of internal or external failures. During such a failure, junction temperature rises far beyond the specified limit and the semiconductor is not able to block voltage after the failure. For protection in many cases either fuses and/or crowbars for the dc-capacitor are used. The converter under consideration is built for fuseless operation. In case of failure of a first inverter leg overcurrents will be fed from the line side or from the load and from the dc-capacitor. The GTO's data sheet defines the maximum current that can be switched off ($I_{TQOM}$). This current should never be exceeded at switch-off. In case of an external short circuit or of an internal shoot through of an inverter leg there is no chance for any of the GTO's to switch off the short circuit current.

B. Overtemperature

The case of overtemperature and its possible origins is not as simple. It is necessary to distinguish between global overtemperature and local overtemperature, which are caused by totally different mechanisms and it is also necessary to distinguish between overtemperature which leads to a failure at once and a moderate overtemperature, which leads to aging by a slow but permanent change of important parameters due to changes of crystalline structure or passivation and to a subsequent failure in the long run. The maximum operating junction temperature range is -40...125°C for GTO and up to 140°C for diodes, where the lower limit is not relevant in practical operation.

1) Global overtemperature

Cooling of the GTO has to be designed in such a way, that the power losses generated in the silicon do not lead to higher operating junction temperature than the maximum specified in the data sheet.

The losses in the device under consideration consist of the losses of the GTO and the losses of the integrated antiparallel diode. As only one of them can be working at a time, the losses can be regarded separately, as far as the thermal resistance from junction to case is involved and consequently thermal resistances of GTO and diode part are specified separately. The relation of contribution of GTO part and integrated diode to the losses of the device is depending on the power factor of the line side inverter and on output voltage and power factor for the motor side inverter.

The losses of the GTO part of the semiconductor consist of conduction losses, turn-on losses, turn-off losses and the comparably low blocking losses. Neglecting the latter losses can be approximated as

$$P_{loss} = V_{TO} \cdot I_{TAV} + r_T \cdot I_{TRMS}^2 + \frac{1}{T} \left( \sum F_{on} + \sum F_{off} \right)$$

While the conduction losses can easily be calculated by knowledge of the current waveforms of the inverter, the calculation of the switching losses is much more depending on other quantities like the snubber networks, di/dt limiting inductors, gate drive and modulation technique applied. The data sheets give the dependence of the switching energies for turn-on and turn-off depending on the dc-link voltage and switching current under the condition of defined snubber networks. It should be pointed out that the maximum stress on the different semiconductors at different positions in the inverter occurs at different points of operation and that these points have to be regarded separately. So these calculations...
have to be done for different load angles, different voltages and different output frequencies.

Although the switching times of a few microseconds are comparably short switching contributes very much to overall losses because of the high peak power. For example the contribution of one switch-off the current $I_{TDM}$ at half the maximum voltage with a defined snubber network amounts to 12Ws, which is equivalent to the conduction losses at maximum current for one millisecond. Switching will cause a sharp rise of junction temperature and a subsequent second switching within a few microseconds will surely raise junction temperature beyond the specified limit. That is why in the data sheet minimum on-time and minimum off-time of 100 microseconds each are specified. These limits have to be met by the modulation pattern applied and the control has to be designed so that this time will always be respected even during dynamic changes.

By help of simulation programs the time dependent losses can be calculated for the devices and temperature of the junction may be evaluated.

2) Local overtemperature
A hot spot, that is local overtemperature, can occur even when the overall losses are far below their admissible maximum. The effect is due to an uneven distribution of current density over the semiconductor chip. This effect is already known from thyristors, when poor firing pulses of insufficient steepness or insufficient height or insufficient duration are applied. The load current then concentrates on a part of the semiconductor leading to local overload. A similar effect may also occur when the maximum rate of rise of current is exceeded. In the converter under consideration the rate of rise of GTO current is limited by additional inductances to values well below the critical value.

Different from conventional thyristors in GTO’s additional measures are applied to reduce internal current gain in order to be able to switch off the device. For the GTO’s under consideration this results in a considerably higher holding current $I_h$ of 100A (specified at 40°C) of the device. In operation, when the actual current comes down below the holding current, part or all of the conducting area may extinguish. Partial extinction is dangerous, because a subsequent rise of current will be concentrated on the still conducting part of the semiconductor and will lead to local overload. This effect is the most probable reason for the majority of the failures observed. One possible method to avoid this is to apply additional firing pulses when the GTO is already conducting or to care for a minimum load of the inverter. At start-up in spite of the torque required the line side power is around zero and in this case line side currents are low. This may be overcome by adding a positive and a negative reactive current component to the AFE’s.

C. Outside and mechanical reasons
Failures are possible also because of mechanical reasons, as poor mounting to the heat sink with a wrong mounting force, excessive acceleration that is unlikely within a static plant or external flashover as a consequence of dirt and moisture. Surface creepage distance of 33 mm and air strike distance of 14mm normally are sufficient to fulfill all requirements of 4,5kV GTO’s in an industrial surrounding. Load cycles that mean large temperature fluctuations for large size semiconductors, stress them very much. The effect is due to the different thermal expansion coefficients of the different materials. There exist applications like railway drives where the extreme load cycles put extreme stress on the devices. In comparison a continuous working conveyor belt does not face any problem from this effect.

Cosmic radiation in form of neutrons or heavy ions can hit the crystalline structure and deposit energy along its trajectory. This creates electron-hole pairs, which lead to local field enhancement. In addition to the already existing high electrical field this can lead to excessive local field strength at a sufficiently wide zone within the chip and will further damage the chip [9]. This results in a destruction of the semiconductor, which is known as single event burnout SEB. Cosmic radiation will statistically hit the semiconductor, an effect that cannot be avoided but reduced by shielding. For a semiconductor this means that the probability of failure is very much depending on the blocking voltage of the semiconductor, when it is hit. Consequently the definition of its reliability in FIT is given for a reduced voltage level and for sea level and has to be related to the actual altitude above sea level of operation of the plant and the actual blocking voltage.

At last some types of failures within the gate-controls and their power supplies may also lead to failures of the GTO as well. Good engineering of the drive units minimizes this risk.

D. The GTO
The GTO (5SGR 30L4502) used in the drive under consideration is a GTO advertised to be optimized for low on-state and low switching losses. The actual switching frequency applied is at 150 Hz and can be regarded as comparably low. On its chip with 91mm diameter the device includes the antiparallel diode of ITAVM = 570A which contributes to reducing the inductance of circuits and to a reduction of complexity of design by reduction of the number of components.

During the last years a different element has been coming up and nowadays the technology of the hard driven GTO or IGCT would be the technology of choice for drives with these requirements. This type of semiconductors is delivered with its gate drive circuit as one unit. Gate current for switch-off has to be higher than the current to be switched off. Then the device switches much faster than the normal GTO. Minimum on- and off-times of comparable devices are reduced to about 10µs enabling for different pulse patterns and even for snubberless operation, which further reduces the number of components and brings about increased reliability.

E. Calculation of expected MTBF
Reliability is a crucial point for large drives, because a failure of equipment causes major economic losses in a production or service process.

The power electronics part of the drive under consideration consists of two 3L-NPCs of 12 GTO’s with integrated antiparallel diodes and six additional diodes each. In total this...
is 36 components. A big influence on reliability of high voltage semiconductor devices is their sensitivity to cosmic radiation. Reliability is depending on the amount of cosmic radiation depending on elevation above sea level, shielding and geographic location, voltage applied and temperature. For MOSFET’s, which show similar effects of single event burnout (SEB) and are much better investigated it was found, that sensitivity is higher at 30°C than at 80°C by a factor of ten and that a reduction of voltage stress by 10% of the maximum voltage leads to an increase in reliability by a factor of 100 [11]. For GTO’s no temperature dependence is observed [9,12], whereas dependence from blocking voltage is similar. The reverse conducting GTO semiconductor devices under consideration are specified at 100 FIT for the total temperature range. Assuming 100 FIT at sea level in open air for each of them and for each of the additional diodes, this results in a MTBF of 277,777 hours. Installation at about 3000m above sea level would increase FIT rate for the power semiconductors by a factor of about eleven. On the other hand the reduction of blocking voltage applied compared to the $V_{\text{DClin}}$ of 2800V results in a decrease of failure rates. So assuming 100 FIT for the reverse conducting GTO’s in this application is not an optimistic assumption. However, regarding the power semiconductors only, it is a very optimistic view. The converter system under consideration contains additional 36 diodes in the snubbers, 36 capacitors, 24 resistors and 12 inductors within the snubber networks as well as 24 gate drive units for the GTO’s and their power supplies. Assuming 50 FIT for each of these additional electrical components and 100 FIT for the more complex gate drives, MTBF results at 88,000 hours at sea level.

In [13] an estimation for the reliability of IGCT, which because of their structure are quite comparable to GTO’s, is optimistic to achieve the result of less than 400 FIT for an IGCT, its gate driver, its gate driver power supply and its part of the quite simple multipurpose clamp containing 4 elements. For the GTO-converter under consideration the increased number of snubber elements may be compensated by the simpler design, so that using these numbers ends up with MTBF of about 90,000 hours.

The actual MTBF (7 failures in 8 plants in three years operation with 330 days per year and 24 hours of daily operation) observed from the plant amounts to about 27,000 hours of a back-to-back converter, which is far from the theoretical estimated value and may indicate an additional problem.

VI. FINAL DISCUSSION

By this time a major revision regarding a downhill conveyor system, operation failures and semiconductors failures mechanisms have been presented. A review of the failure causes is summarized as follows.

As calculated in the MTBF, the failure rate is definitively high. This indicates that some situations did not were considered.

The first record concerning failures was due to a poor isolation of a semiconductor. In this case an external element caused an electrical arc in a clamping diode, causing the burning of some semiconductors, as showed in Table I.

The second register concerns to the recurrent failure described before. After a fully study of the GTO’s datasheet and operational aspects a remark was pointed out. During start condition a minimum holding current should be injected to the semiconductors for avoiding an uneven current distribution or a hotspot. This situation was discussed together with the vendor. Finally, after checking-up the other causes, for avoiding this condition the proposal was to apply a higher reactive current during starting of the conveyors. Since there are at least 3 AFE’s in conveyors CV05 and CV06, two of them in every conveyor may be fed with reactive current in inductive and capacitive way. This solution, performed during starting sequence only has been implemented and the recurrent failure has been solved.

VII. CONCLUSIONS

In the present work a description of a downhill conveyor has been presented. Beside this, a series of possible failures mechanisms have been presented and analyzed. In the actual application some of them have been discarded by the operative conditions at the failure moment whereas other very probable reasons could be pointed out. The fact that the plants are installed at more than 3000m above sea level leads to consider the effects of cosmic radiation on high voltage power semiconductors. Some considerations of reliability were included and finally a solution to a mayor problem was explained. Recently, information from the field has demonstrated the validity of the proposed solution.

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REFERENCES


