Mining

The behavior of the cycloconverter fed gearless drive under abnormal electrical conditions

Reprint

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Reprint: “WORKSHOP SAG 2003” October 8-10, 2003 Viña del Mar, Chile

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The behavior of the cycloconverter-fed gearless drive under abnormal electrical conditions

Several cases of abnormal electrical conditions are studied in simulations and the corresponding behavior of the cycloconverter-fed gearless drive is shown. The protection philosophy is explained, which avoids interruptions of operation and damages of equipment. The cycloconverter proves to be a robust converter with low probability of faults and able to control abnormal electrical conditions.

1. Operation principle of the cycloconverter

The following picture is a typical circuit diagram of a cycloconverter.

The black rectangles are transformer windings respectively motor windings. The cycloconverter is combined of thyristors. Each motor phase receives its alternating voltage and current by two antiparallel three-phase bridges, the positive part of the sinus wave by the upper bridge (section 1) and the negative current by the antiparallel bridge (section 2).

The cycloconverter converts three phases of the mains power supply to one phase of the motor supply. Therefore for the shown six-pulse system are nine primary phases and for a twelve-pulse system are required eighteen phases and the corresponding transformer design.

This shows a normal operation situation. The current circuit is shown in two motor phases only. The third phase is not shown to reduce complexity.

A thyristor is able to block voltage in both directions. To let current flow in its positive direction, the thyristor must be switched on (gate triggered), while the voltage across the semiconductor is positive. Once triggered, the thyristor cannot be switched off before its current becomes zero.

Here is shown how the cycloconverter cuts out of the incoming line three-phase voltage of 50 Hz or 60 Hz one phase of the motor voltage of a low rated frequency, for gearless drives the rated frequency is selected between 5 to 10 Hz. The output voltage of the cycloconverter to the motor is variable, for the gearless drive is used 0 Hz to 120% of the rated frequency.

A cycloconverter is a line-commutated converter as all converters which have thyristor-controlled rectifiers at their input.

In the above example, switching thyristor 1.3, when voltage v is higher than voltage u, realizes the commutation of current from thyristor 1.1 to thyristor 1.3.
The following simulation shows normal operation, it can be seen how motor currents are combined from transformer secondary currents.

The corresponding motor values in normal operation:

The above pictures of normal operation are used to explain the difference under abnormal electrical conditions.
2. Power outages

2.1 Disconnection of power supply

The first case to study is not really abnormal, but very common: A total power failure, caused by disconnection of an upstream feeder. This is a situation which the protection system of the gearless drive has under complete control. The undervoltage detection of the gearless drive monitors the feeding voltage received from the potential transformers installed in the feeding switchgear.

The undervoltage detection immediately orders a blockade of all triggering impulses. So no other thyristor is switched on.

As there is no commutation to the following thyristor, the emf voltage (electromagnetic force) of the motor becomes higher than the voltage of the transformer phase. That way, the emf voltage of the motor is forcing the current to go to zero.

As soon as the current reaches zero, the operating thyristors block the voltage in both directions. The current is off.

The simulation shows how the emf voltage of the motor reduces all thyristor and transformer currents to zero.

The simulation shows, also in the following picture, how the motor currents (last three lines) and the motor torque (first line) go to zero. It shows the motor voltages (line 3 and 4) changing from a rippled converter supply to the natural sinusoidal form of a generator. This is shown because the simulation does not consider the closing of the mill brake and the stop of mill and motor.

In reality, the mill continues turning in case of a mains power outage due to its inertia until the brake applies or it moves until its kinetic energy is consumed by friction. The application of the brake is realized by the PLC of the gearless drive, as soon as the lubrication system of the mill bearing signals an oil pressure or oil flow problem. The lubrication system supports power outages for a certain time due to its oil accumulators. After that, mill and gearless drive stop safely.
2.2 Feeding circuit breaker opens without signal to gearless drive system conduction-through

Good engineering practice requests a signal to the closed-loop control from any tripping device of the feeding breaker of the gearless drive. The signal should arrive at the closed-loop control before the breaker starts tripping. Receiving the "tripping" signal, the closed-loop control blocks immediately the triggering signals of the thyristors and extinguishes the current of the cycloconverter. The extinguishing is so fast (measured 16 milliseconds) that the breaker opens normally without current.

Following this rule, the cycloconverter and its closed-loop control can easily handle the situation. If the rule is not followed, opening of the feeding circuit breaker will probably lead to the following scenario, which is called conduction-through of the cycloconverter.

The closed-loop control receives information of the feeding voltage from potential transformers, which are connected to the busbars of the feeding switchgear. When the feeding breaker of the gearless drive opens, the closed-loop control cannot derive this fact from the voltage of the busbars and continues triggering of the thyristors.

The emf voltage of the motor is driving a current through the cycloconverter via a circuit, incidentally created by thyristor triggers, which are synchronized with the medium voltage busbar. Here is shown the example where thyristor numbers T1.1 and T1.6 are triggered and the current flows via the transformer secondary windings V1 and U1. The resistance of these windings is limiting the current to low values. Refer to currents I11, Iu1 and Iv1.

Missing the power supply voltage, the current is reduced to zero in the first milliseconds by the emf voltage of the motor. But the closed-loop control continues triggering because it has no information that the feeding voltage is off. On the motor side, the emf voltage as an alternating voltage is changing its polarity and the motor is becoming a generator until it stops moving.
The next trigger pulse is for thyristor 1.2, but the commutation from thyristor 1.6 to 1.2 is missing because the feeding voltage from medium voltage supply was disconnected. Therefore the current continues in thyristor 1.6 and is not reduced to zero when thyristor 1.3 is triggered. Therefore a short circuit is created by thyristors 1.6 and 1.3 and the emf voltage of the motor drives a current via this short circuit.

The same sequence can happen in the converter of another motor phase or in all three phases, what leads to a two- or three-pole short circuit at the motor terminals and closes the circuit for a short circuit of the motor terminals.

An unfortunate situation, which occurs only because the closed-loop control continues triggering not having received a signal by the tripping device of the feeding circuit breaker. The short-circuit current of the thyristors 1.1 y 1.6 varies sinusoidal with the low frequency of the motor, but for the worst case, the two-pole short circuit, it never crosses zero, where the thyristors could extinguish it. The short-circuit current continues and is fed by the generator operation of the motor until the magnetic flux has been removed or it is stopped by its brake. The resulting short-circuit motor torque is oscillating between plus five times and minus five times rated torque. The forces on the equipment and its fixation are correspondingly varying between plus and minus five times of the nominal values.

As said before, this situation can easily be avoided by a signal of each tripping or opening device of the feeding breaker to the closed-loop control before the breaker opens. This way, the closed-loop control of the gearless drive can control the situation safely and remove the energy from the drive without creating any unfavorable forces. The closed-loop control only needs this necessary information from outside of the gearless drive.

2.3 Power outage without immediate voltage reduction

Normally, electrical equipment switches off in case of an outage of electrical supply by absence of the supplied energy. More sophisticated equipment has undervoltage detection and requests a signal from the feeding circuit breaker when it switches off. But in a certain case this is not enough. The case is a power outage without immediate voltage reduction. Such a case seems to be impossible but it happened in reality. And it happened in a typical power supply network for a mining plant, shown in the following.

The external power supply is realized by an overhead line via 220 kV substation with two transformers to the medium voltage distribution. There are connected two synchronous motors (2 x 6.8 MW) for the two ball mills and a 12 MW gearless drive for the SAG mill with its filter circuits. A 14 MVA load and its compensation of 2 x 2 Mvar can represent the low-voltage loads.

In this plant, short-circuit currents appeared in the gearless drive when the electrical power company disconnected the external supply. The undervoltage detection of the gearless drive did not trip the gearless drive. Measurements of the short circuit currents showed a frequency in the range of 50 Hz, much higher than the frequency of the motor.

As the short circuits could not easily be concluded from the mains power outage, Siemens realized a profound investigation of all possibilities of short circuits with the result that no result of all imaginable simulations showed the same behavior as the reality.

Then was investigated the behavior of the plant network and found a nearly unbelievable behavior of the voltage in the case of external power disconnection. This is shown in the next picture.
The voltage did not drop in the first 240 milliseconds, but the frequency decreased by 20%. As detailed calculations have shown, the line voltage was supported by the high quantity of power capacitors in the plant. Those and the synchronous motors avoided the normal voltage reduction after the external disconnection of power supply. The synchronous motors of the ball mills changed themselves to generators for that short time and injected part of the kinetic energy of the ball mills into the plant network. Consuming the kinetic energy, the synchronous machines reduced their speed and in this way the frequency of the network voltage.

Investigations show that the gradient of voltage reduction depends on the configuration of capacitors of the plant network and that the gradient of frequency reduction depends on the load of the ball mills and the configuration of the electrical loads in the plant.

In the actual case, short-circuit currents occurred because the closed-loop control could not synchronize the cycloconverter to the fast decline of frequency and the undervoltage detection did not extinguish the cycloconverter because voltage did not drop.

Nowadays, the protection software of the Siemens’ gearless drive includes detection of power outage by detection of fast decline of supply frequency.

2.4 Run-through of short power outages

Short power outages are very common in power distribution networks. There may fall a piece of wood on an overhead line and be burned by the short-circuit current or two cables of an overhead line are touching one another, moved by the wind. The existing substations have protection devices, which operate in case of such a short circuit, disconnecting the line and reconnecting immediately. The result for the consumer is a short voltage dip or a short power outage.

The manager of a plant obviously wants also to continue operation in such a case and not interrupt production, because undervoltage detection stops the mill drive.

The Siemens’ gearless drive provides a run-through of the mill of short power interruptions up to 200 milliseconds. The following measurement record shows the behavior of this system. It was taken in a plant in Chile in October 2000. The measurements show a power outage for 120 milliseconds.

At the moment of restart, the speed setpoint was set equal to the speed actual value. So the torque setpoint starts at zero and the torque actual value at nearly zero. Therefore, the speed of the motor continues reducing and the mill is caught softly.

Three seconds after the end of the power outage the speed reaches its original speed value.

The run-through of short power outages is successfully in operation in all Siemens’ gearless drives, installed since 1988.

This feature avoids unnecessary interruptions of operation of the gearless drive and of production by the mill.
3 Switching of the wrong thyristor, in antiparallel bridge
To trigger a wrong thyristor (2.6 in this case) will only cause a current in this thyristor when the voltage can drive a positive current through the thyristor, therefore voltage $u$ must be higher than $v$.

In the case such a wrong thyristor is triggered there would occur a high current in the shown circuit limited only by the reactance of the transformer.

The thyristors support this current without damage and operation could continue. The overcurrent protection detects the overcurrent, blocks the trigger impulses and extinguishes the current within milliseconds.

The operation can be restarted without delay.

4 Ground fault in cables or motor
There may be a connection to ground, e.g. by an external damage.

The simulation shows that normal operation continues. This happens because there is no second connection to ground.

In reality, the earth fault detection will operate and stop the gearless drive. This is done to avoid a high fault current in case of a second ground fault.
5 Thyristor fails, it cannot block reverse voltage

Let us assume that a thyristor fails. This happens in the form that it becomes conductive in both directions and cannot anymore block voltage. Here is studied the worse case: Thyristor T 1.1 cannot block reverse voltage at the end of its operation when the current commutates to thyristor T 1.3.

The transformer is immediately shortened via T 1.1 and T1.3, fed by the transformer primary side and limited only by the impedance of the transformer windings.

The overcurrent protection immediately blocks the trigger impulses and sends a tripping command to the feeding circuit breaker. All currents decrease to zero and the thyristors are blocked with the firing pulses removed.

The simulation shows the worst case that the thyristor T 1.3 also fails due to the high short-circuit current and the short-circuit current flows until it is interrupted by the feeding breaker. In reality, the thyristors of Siemens’ short-circuit-proof cycloconverter can also support the short-circuit current of this case and T1.3 blocks the short-circuit current when it arrives the first time zero.

The cycloconverter controls the situation completely and extinguishes the short-circuit current.
6 Short circuit at the motor terminals

In all design studies of motors, the short circuit at the motor terminals is the typical short circuit as design criteria for the motor. Let us assume that from normal operation, two terminals of the motor are short-circuited, what is the worst case.

The transformer voltage drives the occurring short-circuit current over the already operating thyristors. The overcurrent protection blocks the trigger impulses of the thyristors and other thyristors are not switched on.

The short-circuit current through the thyristors flows for the positive half sinusoidal wave and extinguishes when it arrives zero.

The thyristors are designed to resist this short-circuit current and can block the voltage when the current becomes zero. Additionally arises a current over the short circuit, driven by the emf voltage of the motor.

This short-circuit current cannot be interrupted and flows until the brake of the mill has closed, the mill stops, or the field has been removed. The motor and its fixation to the foundation must be designed to resist the resulting short-circuit forces.
7 Precautions for short circuits

In the design of electrical equipment has to be considered that short circuits cannot be completely avoided. All electrical equipment must resist the high forces which result from short-circuit currents. This is requested by all electrical standards. The Siemens’ cycloconverter for gearless drives is fuseless and short-circuit-proof. This means, that the cycloconverter is designed to disconnect the short-circuit current when this is possible or to resist it without damage until it is off.

As in general the short-circuit current is several times the rated current, the resulting short-circuit forces also are several times as high as the normal operating forces.

In regions with seismic activities also the corresponding forces have to be considered. Regarding Zone 4 of Uniform Building Code (UBC) result vertical and horizontal forces on the fixation. The vertical forces on the motor fixation resulting from earthquakes sum to those of operation, but are less than the nominal operational forces and the sum does not exceed the double of the nominal forces.

The worst case is the short circuit, because the corresponding forces are five to six times the nominal forces. If the short-circuit forces are not considered in the design of the motor fixation, the motor may lift at one side and due to the vector sum of the acting forces the lifted part may move.

Regarding the gearless drive motor this must be considered in the design of its inner structure, the fixation of its coils, the fixation of the motor on its foundation and in the design of the foundation.

During normal operation, weight and the nominal torque cause the force on the foundation. The motor torque causes a lifting force on one side of the motor and a downward force on the other side of the motor. The sides change according to the direction of rotation. Additionally appear thermal dilatation forces by changing temperatures. The magnetic force in the air gap causes a radial force to the center of the mill.

The case studies show that the cycloconverter easily controls abnormal electrical conditions if the indicated design criteria are applied. The gearless drive with all its components must be designed to resist short-circuit forces, because short-circuit currents occur during abnormal electrical conditions, even if they are controlled and extinguished by the cycloconverter itself.
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