

The doubly fed induction generator in a pump storage power plant: Challenges and new developments for electrical protection systems

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Abstract: Doubly fed motor-generators (DFGs) are becoming more popular in pump storage hydro power plants. Differences to the well-known protection schemes of synchronous generators are discussed and challenges for the protection scheme for a DFG are analysed and new developments presented.

1 Introduction

Pump storage hydropower plants are a major player in the field of energy storage and will remain a key source of electricity storage capacity alongside with batteries. Global storage capacity was 8.5TWh in 2020, with a predicted increase of 7% up to the year 2030. Pump storage capacity will remain significantly higher than the storage capacity of batteries [1].

In the last decade, variable speed configurations have become increasingly popular. Advantages of variable speed units are a better efficiency with different water heads, possibilities to regulate the power during pump mode, reduced vibrations at part-load operating points and better transient response. The typical solution for larger units is the doubly fed motor-generator (DFG), where the rotor is connected via slip rings to a converter, which controls the rotor currents and therefore the speed of the unit. Figure 1 shows a typical arrangement:

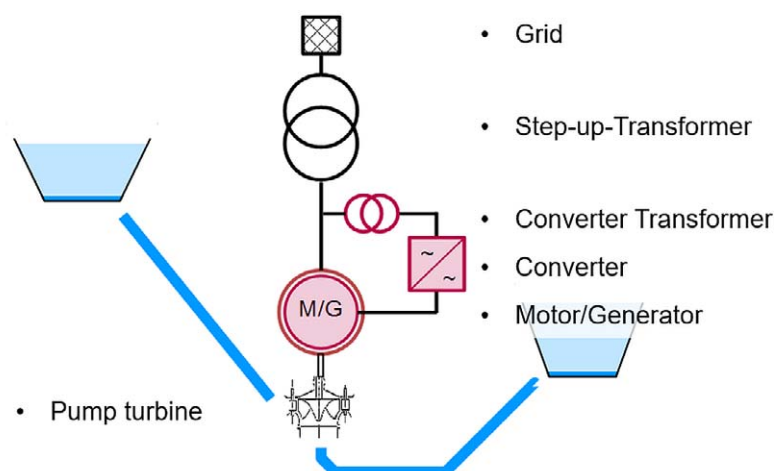


Figure 1. Var Speed Setup with doubly-fed generator

Starting in pump mode is accomplished by short-circuiting the stator terminals of the motor-generator and accelerating the dewatered pump turbine up to the operating

speed range by the converter. Figure 2 shows the system configuration and the operating modes with the corresponding designations.

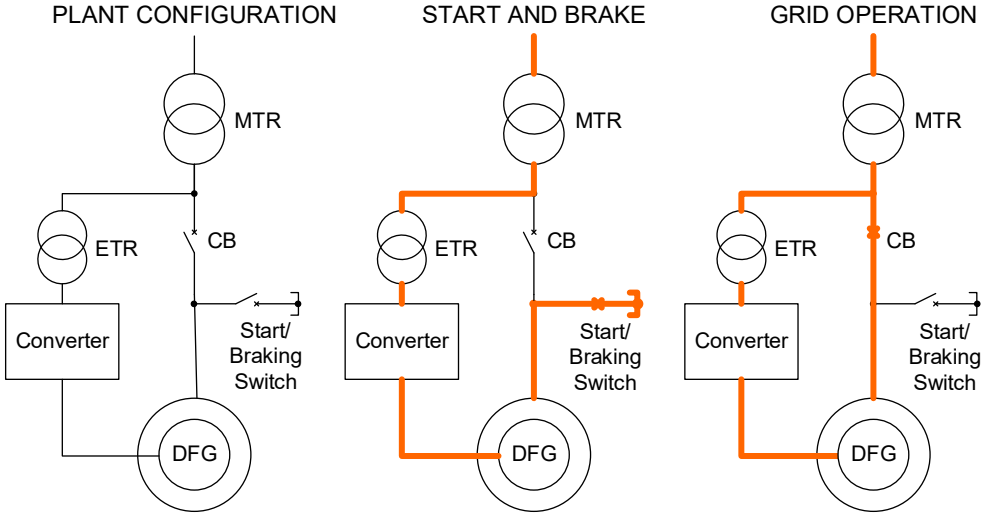


Figure 2. Operating states of the doubly-fed asynchronous machine

The electrical system of the doubly-fed asynchronous machine consists of a main transformer MTR, a converter transformer ETR, an asynchronous motor-generator DFG with slip rings, a converter in the rotor circuit, a generator circuit breaker CB and a starting/braking switch.

During the starting and braking process, the starting/braking switch is closed and the generator circuit breaker CB is open. The frequency of the rotor varies from 0Hz (direct current) to the order of the rated frequency. Figure 3 shows an example of the frequency curve during start-up in pump mode. The frequency of the stator in this operating state is very low, usually below 1Hz. Once a sufficient speed has been reached, the current is regulated to zero by the converter and the start/brake switch is opened. The converter energises the DFG by regulating the stator voltage to nominal value and the circuit breaker is closed.

In normal operation, the frequency of the stator corresponds to the frequency of the grid and the frequency of the rotor corresponds to the slip frequency (in the range of a few Hz).

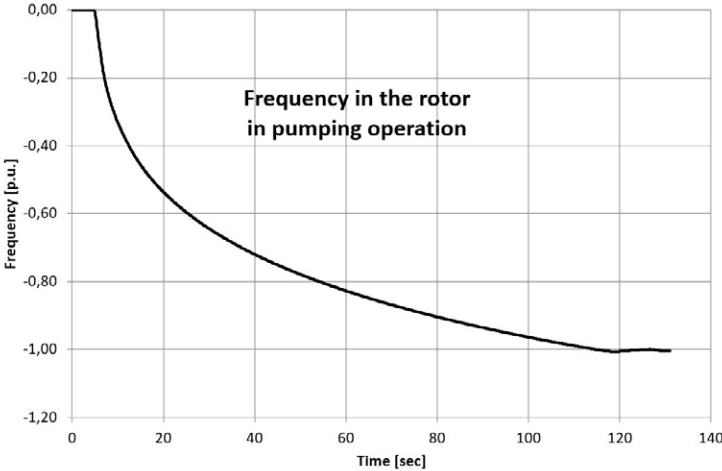


Figure 3. Frequency of the rotor in pumping mode during start-up

2 Requirements for the protection technology

The operating mode of the doubly-fed asynchronous machine used in variable speed pump storage plants places different and more challenging requirements on the protection technology than on a conventional synchronous machine configuration.

In particular, the low frequencies present at some operating points have an impact on the design of the primary devices. This applies especially to the current transformers installed in the generator star point and at the generator terminals. Linearised current transformers are usually used for most protective functions in order to minimise saturation effects.

In the rotor circuit, currents with a very low frequency and direct currents have to be measured. Special current transformers or transducers must be used for this purpose. Non-conventional transformers based on the Faraday principle, compensation transformers based on the Hall effect [3], or transformers based on the transductor principle [4] can be used. When selecting these transformers, attention must be paid to reliability, durability and personal safety.

For an asynchronous motor-generator, many protection functions (e.g. differential protection functions) are similar to the protection functions of a synchronous generator. However, since the DFG provides higher short circuit currents with potentially missing zero crossings it is particularly important to prove the correct behaviour of these protection functions by reliable simulation studies.

When selecting the protection device, particular attention must be paid to the wide frequency range and the operating modes (motor/generator operation). Protective relays that allow the operating modes to be switched in the protective function ensure clear project planning and simple testing.

To measure low frequencies, special hardware inputs and algorithms must be available in the protection device or reliable external devices must be used that are integrated into the protection concept.

3 Measurements from site

Figure 4 shows a typical no load voltage of a 300MVA DFG with a nominal voltage of 15.75kV. The rotor voltage is built by the converter with a pulse frequency in the range of kHz and the interference from the converter can be measured in the stator voltage.

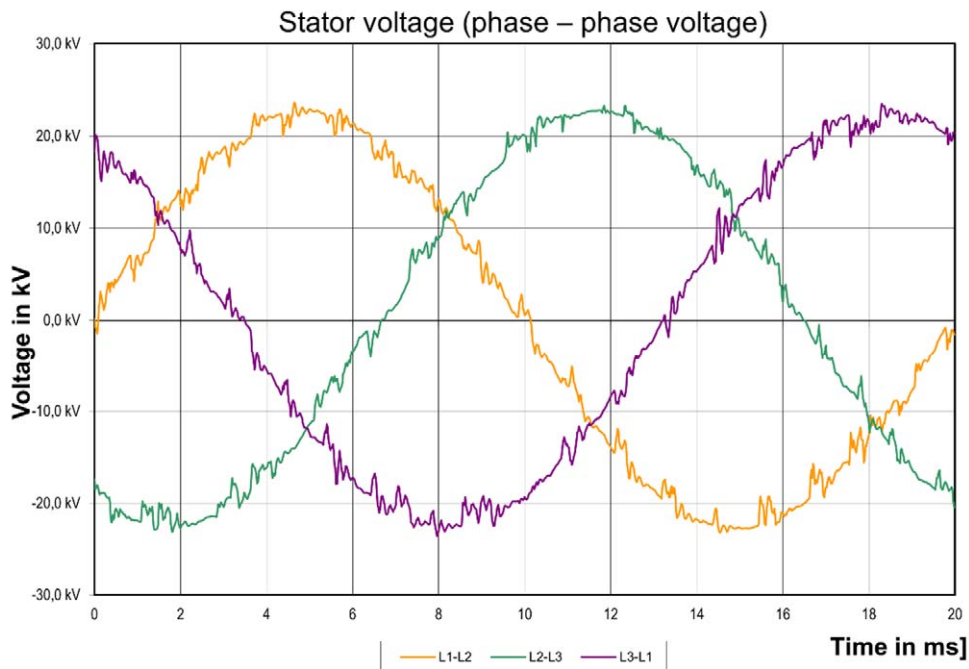


Figure 4. Stator voltage (phase to phase) during no load conditions

Figure 5 shows the corresponding frequency spectrum from the voltage L1-L2. The total harmonic distortion factor (THD) of the stator voltage is significantly higher than from a synchronous generator.

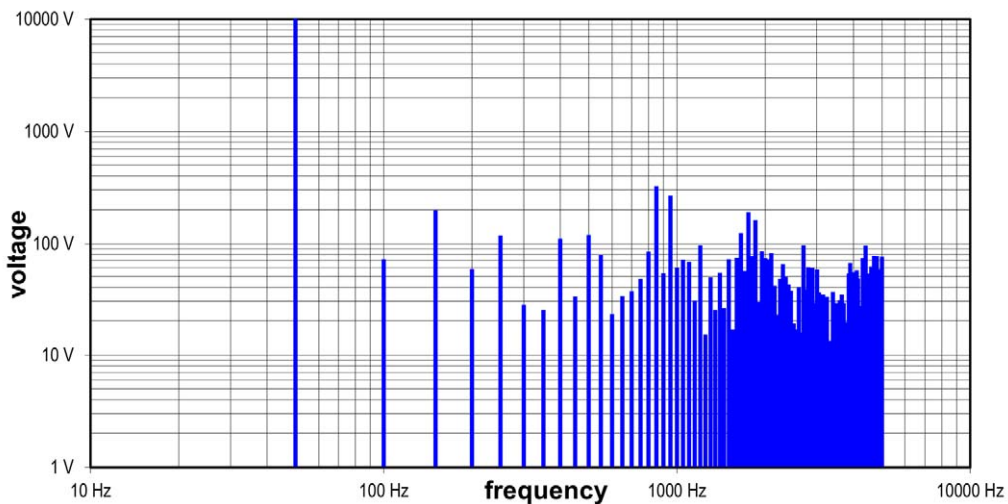


Figure 5. Frequency spectrum of the stator voltage (L1-L2)

The protection relay must take proper measures to filter the first harmonic component, e.g. Fast Fourier Transformation (FFT). In contrast to synchronous machines, in doubly-fed asynchronous units a stator ground fault cannot be detected by measuring the 3rd harmonic. This is due to the different mechanical design of the rotor poles and the resulting lack of propagation of the 3rd harmonic. Furthermore, various other functions in the protection and control system of a power plant potentially may not work

properly since the algorithms are typically designed and optimized for the protection and control of synchronous machines. Frequency measuring algorithms in protection functions or in the synchro check function often use a zero-crossing algorithm to determine the frequency. These algorithms may not work properly for typical signal conditions observed for asynchronous units.

4 Challenges for rotor earth fault protection for DFGs

The usage of frequency variable converters for the rotor excitation of doubly fed motor-generators, instead of a DC current for synchronous generators, presents a variety of challenges for the protection relay. The classical rotor earth fault protection for synchronous generators injects a low frequency signal, measures the voltage and current from the rotor to earth and calculates the resistance. The frequency of this identification signal is determined by the rotor earth capacitance and therefore varies from unit to unit. Typically, the frequency is in the range of 1 to 3Hz. Therefore, at low slip frequencies, the signal of the converter would interfere with the identification signal. To overcome this issue, the connection between the rotor and the protection relay is established via an artificial star point, which is realised with three resistors (please refer to Figure 6).

For the protection of overvoltages, a varistor is mounted in parallel to the protection device.

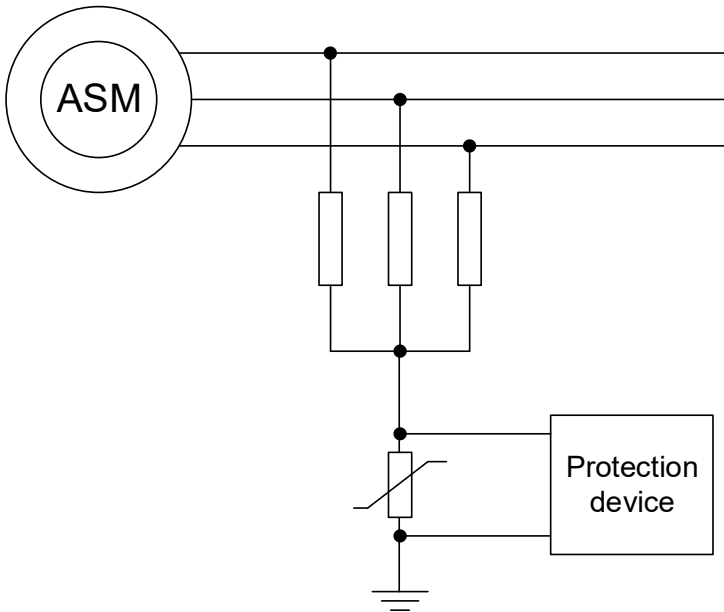


Figure 6: Connection of the protection relay to the rotor

The connection via the star point eliminates the converter frequency, but also has disadvantages. The first drawback is that the protection relay is not able to determine which rotor winding is the faulty one. It is only possible to detect the presence of an earth fault, the detailed analysis must be carried out separately by measurements during the inspection. The second disadvantage of the star point connection is that common mode voltage of the converter acts as a source of interference for the protection relay. It should be noted that the shape of the expected interference is not known to the protection relay. Furthermore, there is typically no such information

available by the converter manufacturers. Even if the information were available, it would be difficult to apply this in a practical application as a protection relay has to work in combination with converters from different vendors. Moreover, measurements in the field showed that the common mode voltage of a converter can change significantly with the actual operating point of the machine. How a converter is designed, and which control method is optimal for controlling the common mode voltage, is an extensive field of research [5] [6].

During the development phase of the rotor earth protection for DFGs, measurements were taken in a real power plant. Figure 7 and Figure 8 show the current through the protection relay forced by the common mode voltage of the converter in two different operating points. These distinct waveforms have a very different spectrum, with the broadband signal working range in Figure 8 being the most challenging task for the development of suitable protection algorithms. To overcome this problem, a comprehensive signal analysis algorithm was derived which uses an adaptive strategy to deal with the disturbing interference.

The common mode voltage of the converter is not the only source of voltage in the artificial star point. In the case of an earth fault in one winding, a displacement voltage will be measured in the neutral point of the resistors, followed by a zero-sequence current forced through the protection relay. The voltage level depends on the fault location and increases with increasing distance from the star point of the rotor winding. This current can be measured and used as an independent criterion for the rotor earth protection and is considered as the main protection function against rotor earth faults. The challenge is also to differentiate between the zero-sequence current and the current from the common mode voltage of the converter. The protection range of this method is largely determined by the coupling impedance of the protection relay and its current resolution. In practice a very large range from the rotor infeed to the star point of the rotor can be covered. This method requires an active converter and is therefore not working on generators in stand still. Furthermore, it is not suitable for high impedance faults. Nevertheless, the current measurement method allows faults to be identified quickly, thereby enabling immediate shutdowns.

The combination of these two functions ensures fast tripping in the event of earth faults and can also be used as a warning for high-resistance changes.

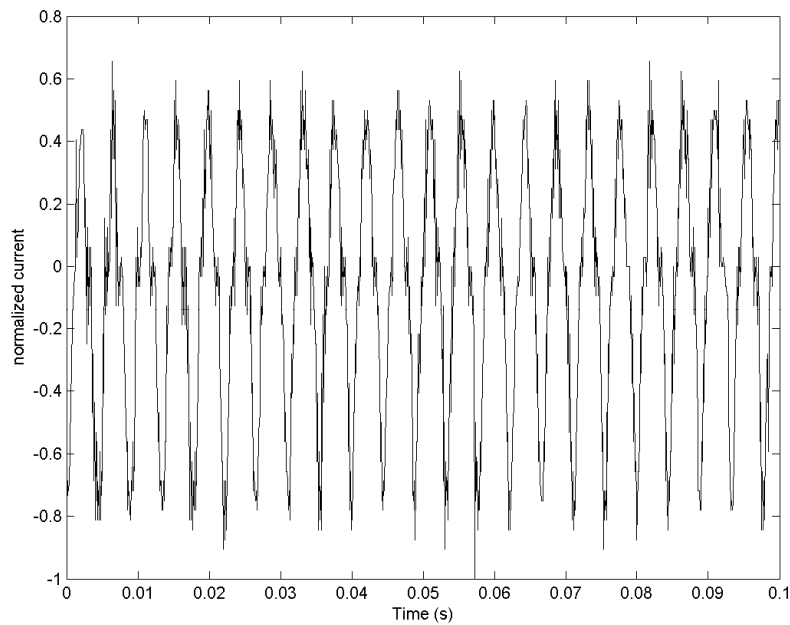


Figure 7: Interference current at 25% converter output voltage

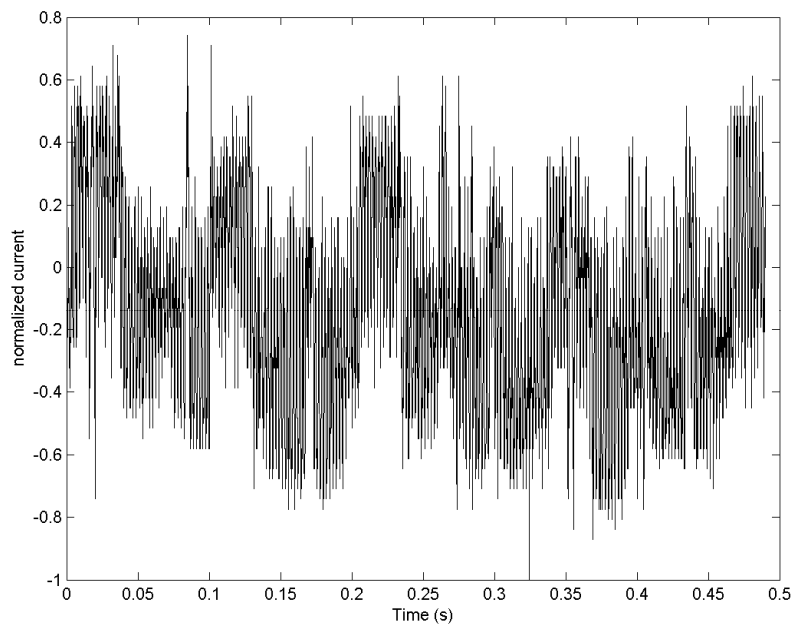


Figure 8: Interference current at 50% converter output voltage

Figure 9 shows the measurement of the injected voltage to the rotor (U_{RAW}) and the measured current against earth (I_{RAW}). The influence of the converter shown in Figure 7 and Figure 8 can be observed in the current I_{RAW} measured by the protection relay, while in the processed signals U_{64R} and I_{64R} the influence is cleared and can be used for reliable resistance calculation.

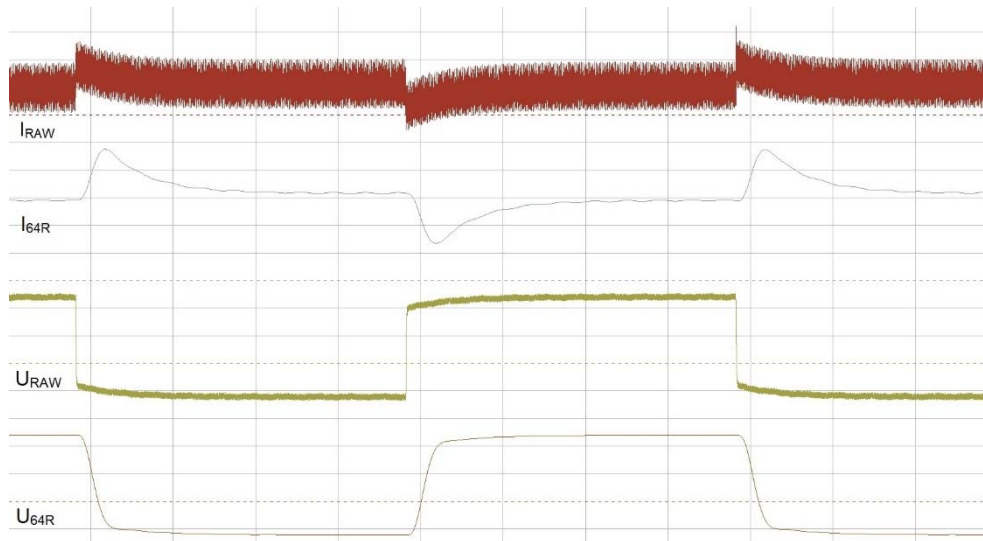


Figure 9: Signal levels for the rotor earth fault measurement

5 Conclusion

For the main electrical protection of a doubly-fed motor-generator similar protection functions are used as for the protection of a synchronous machine. For the protection functions related to the stator the main differences are the presence of low frequencies, current waveforms with possibly missing zero crossings and influences in the signal forms due to the converter. The protection device must be able to handle these challenges and the proper functionality should be proven by simulation and tests.

The rotor of the asynchronous machine is designed differently compared to a synchronous machine. The protection functions related to the current of the rotor must be able to cope with the signals from the primary measurement system since classical current transformer can not be used due the low frequency of the current signal in most operating points. A challenge is the development of the rotor earth fault protection due to the interference of the converter which varies in different operating modes. The paper describes a solution which is proven by practical implementation in the field.

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