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New Protection Relay for Variable Speed DFI Motor Generators

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SUMMARY

The paper describes the development of a new innovative protection relay for protecting large variable speed Double Fed Induction (DFI) machines for pump storage plants. For these machines low frequency currents are supplied to the rotor by means of VSC (Voltage Source Converter) power electronic converters from the AC system. ALSTOM is developing new protection in order to provide the variable speed motor generators they are building a fully independent protection system and guarantee the safety of the plant in all conditions.
At the moment there is no protection relay available in the market to provide protection for the extremely low frequency currents and voltages in the variable speed rotors. To measure the low frequency current and voltage signals new cutting edge "Digital Substation" technology incorporating Non-Conventional Instrument Transformers (NCIT) with IEC 61850-9-2 LE process bus communications to the protection relays is used.

KEYWORDS

Non conventional instrument transformers, IEC61850-9-2 LE, variable speed machine, protection relay.

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1. Introduction

The power management and stability of the grid are of growing concern. Increase in the use of renewable energy generation systems such as wind turbines and solar plants has led to more gas turbines being installed as spinning and secondary reserve because these intermittent sources of renewable electrical generation cannot be easily and effectively dispatched to meet the demand.
This is not a long-term solution to reduction of CO2 emissions in the future. To overcome this problem, efficient and economic technologies to store large amounts of electrical energy are needed.
Pumped storage is still the most efficient and flexible form of storing electricity on a large scale. Pump storage is now evolving towards variable speed pump turbine technology that offers greater efficiency and dynamic power adjustment both during consumption and production modes.
This article describes the development of a new innovative protection system for protecting large variable speed Double Fed Induction (DFI) machines for pump storage plants. The rotors of these machines are fed by power electronic converters from the AC system; rotor speed depends on the frequency of the currents fed by the converter. During normal operation the frequency of the rotor currents is very low, during start up and breaking it varies from zero to rated grid frequency. A new protection system is required in order to provide the variable speed motor generators being built with a fully independent protection system and guarantee the safety of the plant in all conditions.
At the moment there is no protection relay (Protection Intelligent Electronic Device, PIED) available in the market to provide protection for the extremely low frequency currents and voltages in the variable speed rotors and in the stator during the initial start-up and run down. The new protection system will measure and monitor these signals considering the specifics of the start, stop and operation in both pump and generator modes. To measure the low frequency current and voltage signals new cutting edge "Digital Substation" technology incorporating Non-Conventional Instrument Transformers (NCIT: NCCT (Non-Conventional Current Transformers) and NCVT (Non-Conventional Voltage Transformers)) with IEC 61850-9-2 LE digital process bus communications to the protection relays is used.
The main development difficulties for the protection lay with the rotor protection design concerning (1) The dynamic variation of frequency (2) The extremely low frequency (3) The effect of the VSC converter modulating the voltage supply (PWM: Pulse Width Modulation) of the rotor.

2. Double fed induction machine protection overview

For large DFI machines, the standard generator protection relay (PIED-1 or 2) is not suitable to provide full protection for the rotor and stator therefore the protection scheme must be complemented by a new relay (PIED-3 and 4), to mainly provide the rotor protection and stator protection during the start up and run down of the machine (see Figure 1).
Redundancy of protective circuits imposes duplication of the relays (PIED-3 + PIED-4) as well as the acquisition chain (double NCCT and NCVT) in the same way as for the standard fixed speed machine protection (PIED-1+PIED-2). The new IED (PIED-3 and PIED-4) uses the IEC61850-9-2 LE digital signal protocol to interface with the NCITs required to measure the low frequency signals via a merging unit. The IED's IEC61850-9-2 architecture proposed is a point to point connection between the NCITs, merging unit and relay IEC61850-9-2 port. This is equivalent to conventional hardwiring between the CTs/VTs and the relay. Dependability can be achieved by using duplicate or redundant relays, merging units and NCITs in a similar way to the conventional protection where redundant protection relays are connected to separate CTs and VTs. Therefore, a specific design criteria is applied to the digital acquisition chain to segregate the digital signals routing and avoid common mode failures.
In the scheme, as for a conventional protection scheme, 100% stator earth fault protection is provided using a low frequency injection technique with the Main 1 stator protection relay (PIED-1). The rotor earth fault protection is also using the same low frequency injection technique using the Main 2 stator protection relay (PIED-2).

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The single line diagram in Figure 1 below gives an overview of a typical protection scheme.

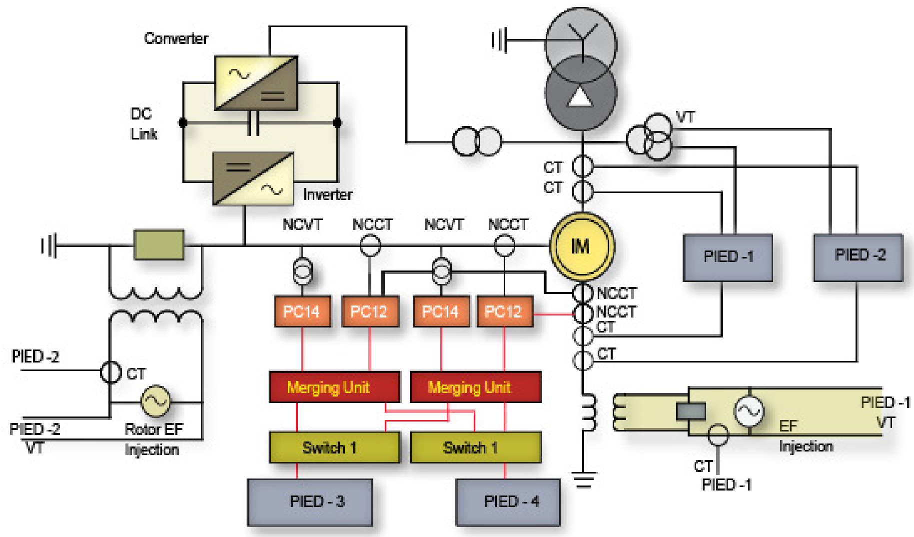

Figure 1 - Single Line diagram of typical protection scheme

- PIED: Protection Intelligent Electronic Device (Digital Protection relay)
- NCVT: Non-Conventional Voltage Transformer (voltage sensor)
- NCCT: Non-Conventional Current Transformer (current sensor)
- PC 12 and 14: Analog to digital signal converter (ALSTOM PCBUS protocol)
- Merging unit: Digital signal (PC BUS or IEC61850-9-2) to IEC61850-9-2 digital signal converter including time synchronsing (1 Pulse Per Second or IEEE1588 protocol)
- EF: Rotor Earth Fault protection devices
- Hardwired connection:
- Digital connection:

2.1 Stator protection

The standard generator protection relay (PIED-1 and 2) can provide adequate stator protection for the variable speed machine using conventional CTs and VTs to provide protection over the frequency range 5-70Hz. The relay can also be used where low frequency injection 100% stator earth fault protection is required. This provides earth fault protection when the machine is at standstill and during the run up and down of the machine.

Relays and instrument transformers commonly available from the market are unable to provide suitable generator protection at frequencies lower than 5Hz. To achieve low frequency measurements <5Hz requires NCITs which are connected to the relay using an IEC61850-9-2 LE interface, see section 4. Also, new filtering, frequency tracking and protection algorithms have been developed for the low frequency signal acquisition, see section 3.

A new relay has been designed to use NCITs which includes stator overcurrent and negative phase sequence overcurrent protection for frequencies 0.1 to 70Hz to provide protection during the machine start up, run down and normal running. Stator CT supervision is also provided to supervise the NPS (Negative Phase Sequence) overcurrent protection.

2.2 Rotor Protection

The rotor of a variable speed machine has a 3 phase winding with slip rings supplied with low frequency currents by means of voltage source converters from the AC system. The rotor power

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supply frequency is generally between 0.1Hz and 6 Hz during normal running and can reach up to the power system frequency (50 or 60 Hz) during machine run-up and run-down.

For the rotor protection NCITs are required to achieve low frequency measurements <5Hz, the same as for the low frequency stator protection, see section 4. New filtering, frequency tracking and protection algorithms have also been developed for the low frequency signal relay (PIED-3 and 4) acquisition see section 3.

A new relay has been designed to use NCITs to provide rotor overcurrent, overvoltage, neutral voltage and overfrequency protection from 0.1 to 70Hz. As for stator thermal protection, rotor thermal protection is provided from rotor temperature monitoring sensors. Non-conventional rotor NCVT supervision using a voltage balance scheme, where redundant rotor VTs are provided, is used to block the rotor neutral voltage protection.

3 New protection relay design for variable speed machines

The main relay development difficulties for the protection lay with the rotor protection design concerning (1) The dynamic variation of frequency (2) The extremely low frequency (3) The effect of the converter power modulation (PWM).

Figure 5 shows a typical rotor voltage input signal with the main PWM frequency components of 250Hz and its second harmonic 500Hz from a Simulink machine simulation.

The Fourier algorithms such as the Discrete Fourier transform or DFT, commonly used in standard protection relays, are no longer suitable for this application, as the sampling rate has to be tuned to the fundamental frequency (normally the grid frequency, 50 or 60Hz) before the Fourier methods can correctly calculate the fundamental component and its harmonics.

A fundamental change in the new PIED-3 and 4 software from the standard protection models is to replace the frequency tracking so that the protection execution rate does not slow down with the tracked rotor frequency, which can be as low as 0.1Hz during normal running. For this reason, the protection algorithms had to be redesigned to achieve fast operating protection using sampled values and better accuracy protection with RMS measurements.

As Fourier methods cannot be used, the frequency measurement is based on detecting zero crossings of the current (amps) channels. The measuring channels therefore must be pre-shaped by filtering out unnecessary frequency components before frequency can be measured.

The frequency measurement serves two purposes in the PIED (1) For providing rotor overfrequency protection (2) For RMS calculations.

The new relay uses IEC61850-9-2 LE to interface to the NCITs required to measure the low frequency signals.

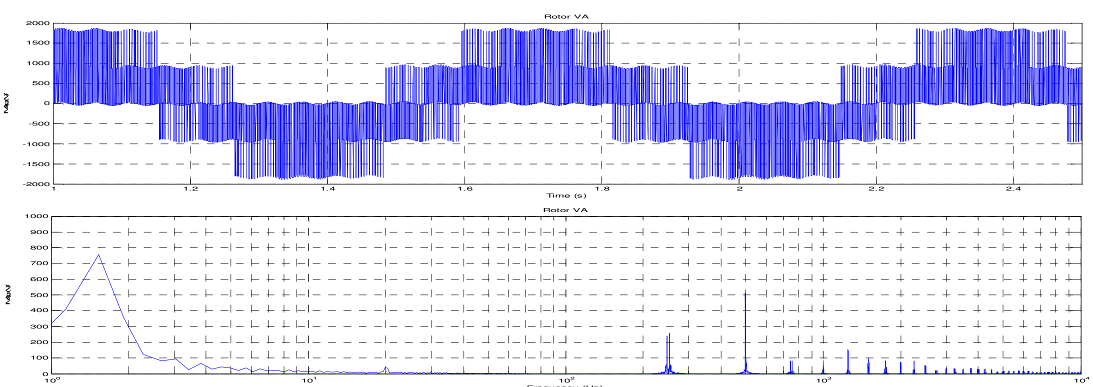

Figure 5 –Typical rotor voltage (Phase A) (top) and it’s frequency spectrum (bottom)

4. Current and voltage measurement

Current and voltage sensors (NCCT and NCVT) are required for this application to be capable of measuring fault currents up to 170kA and voltages up to 12kV in the frequency range of 0.1Hz to 70Hz. Conventional CTs and VTs are not capable of measuring very low frequency signals very

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accurately so non-conventional current and voltage sensors are required to provide these measurements.
For current measurement two types of current sensor could be used: (1) Rogowski CTs and (2) Optical CTs. For voltage measurement a resistive voltage divider NCVT can be used.
Testing with Rogowski CTs (NCCT) and resistive voltage dividers (NCVT) taking place at EPFL and a DFI machine is shown in Figure 7. The NCITs output is converted to a numerical signal by a primary converter unit (PC12 for current and PC14 for voltage) for the Rogowski CT and resistive voltage divider sensors. The PC12 and PC14 units are connected to a merging unit which provides an IEC61850-9-2 LE digital output which can be connected to the PIED-3 and 4 IEC61850-9-2 LE port. The optical CTs have a direct IEC61850-9-2 digital output from the merging unit which can be connected to the PIED IEC61850-9-2 LE port.
The PIED-3 and 4 provides 12 9-2LE input channels: IA-1, IB-1, IC-1 for rotor currents, IA-2, IB-2, IC-2 for stator currents, VA-1, VB-1, VC-1 for rotor voltages, and VA-2, VB-2, VC-2 for rotor voltages from a second (duplicated) acquisition chain for voltage sensor supervision purposes only. The 9-2LE sample values carry quality flags for each channel. Only the quality flags of the corresponding input channels will affect the function. Testing comparing the performances between conventional relays and NCIT relays has shown that the protection performance is equivalent in terms of accuracy and operating time.
The Rogowski CT is an inherent ac sensor, which experiences phase shifts and attenuation when the frequency approaches dc. In contrast, the optical sensor is able to maintain accuracy across the frequency spectrum, even at dc.
Figure 8 shows the recorded waveforms from a 3 phase rotor fault with a pre-fault rotor frequency of 5Hz from testing at EPFL. For frequencies <0.1Hz a significant phase shift is produced by the PC12 high pass filter. Despite the phase shift at lower frequencies, when a fault occurs, the fault is observed on the phases almost instantly because the fault has a high di/dt so it is seen as a higher frequency component.
The NCIT voltage sensors are resistive divider types and will therefore not produce any phase shifts. The phase advance caused by the Rogowski sensor with respect to the voltage sensors is not expected to have significant effect on the protection, since the protection algorithms do not use combinations of the current, voltage and the angle between them, e.g. as with power, impedance and directional overcurrent protection.
The performance of the Rogowski sensor at lower frequencies is not a problem for the protection performance as although an increased phase advance of 30 degrees is observed at 0.1 Hz, this reduces to a small value at frequencies >1Hz and is negligible when there is a fault. Also, the actual attenuation is less than 0.5 dB at 0.1Hz and considering that a 2 or 3 phase fault current is several per units higher than nominal, an attenuation of 0.5 dB is not significant.
The optical current sensor neither phase shifts nor attenuates the signal. However, the optical sensors are relatively expensive and more difficult to install and maintain compared to the Rogowski current sensors.

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Figure 7 - Testing with NCITs at EPFL

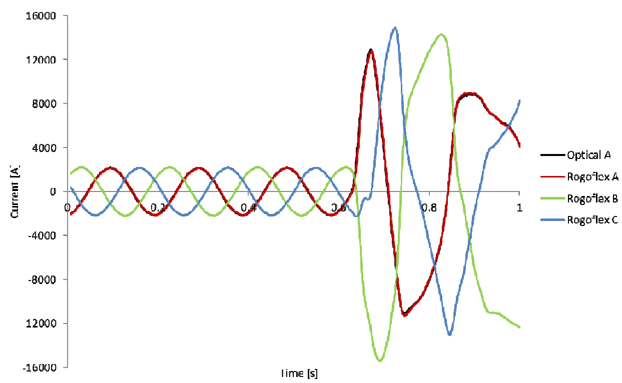

Figure 8 - 3 Phase rotor fault implementation at 5 Hz

5. Conclusion

This article describes the development of a new innovative protection relay for protecting large variable speed DFI machines for pump storage plants. New cutting edge “Digital Substation” technology solutions have been developed and implemented in a new relay to meet the challenging requirements to protect variable speed machines. Using a complete package covering the entire variable speed machine (both stator and rotor) implementing the latest NCIT and IEC 618509-2 LE process bus technology offers the user significant benefits.

In general, the advantages of the Rogowski solution outweigh those of the optical solution. The optical sensor neither phase shifts nor attenuates the signal. Nevertheless, the Rogowski solution still provides satisfactory accuracy for protection purposes. Also, the installation, ease of maintenance and replacement of the Rogowski sensor is better and the Rogowski solution is significantly cheaper for this application.

Using NCITs and IEC61850-9-2 LE for this special generator protection scheme shows how standard generator protection schemes may evolve in the future. Use of non-conventional CTs has particular benefits for generator applications where the CTs can physically be very large with very high CT ratios up to 20,000A and higher in some applications whereas NCITs are much smaller and can measure very large currents very accurately.

Also, the X/R ratio of generator fault currents can be very high, up to 120 and higher, causing problems with CT saturation with conventional CTs whereas Rogowski and optical CTs don’t suffer

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from this problem; this will provide a robust solution against protection malfunction caused by current transformer saturation.

Use of IEC61850-8-1 station bus standard is growing in generator protection schemes. A full digital substation approach using the IEC61850 station and process bus would provide many benefits such as using providing a standard interoperable solution making integration of different vendors products easier.

Also, with the IEC61850 standard, there are a number of natural opportunities to maximise dependability. First of all, GOOSE (Generic Object Oriented Substation Events) messaging has a repetition feature whereby a change of state will not just cause one message to change, but will be repeated in subsequent messages - initially quickly, and then at longer intervals thereafter.

Redundancy is another common means by which the network can be designed to be immune to single device failures, ensuring message transfer dependability. IEC 62439-3 Parallel Redundancy Protocol (PRP) standard and IEC 62439-3 High-availability Seamless Redundancy (HSR) protocol standard can provide double star and ring architectures with ‘bumpless’ redundancy.

Security is also enhanced by the use of fibre optic Ethernet connections for any links which run outside of a single local cabinet, such that there are no long, cross-site runs of copper-based communications. This eliminates the risk of induced interference – boosting both security and dependability.

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