Testing of ground fault relay response during the energisation of megawatt range electric boilers in thermal power plants

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Testing of ground fault relay response during the energisation of megawatt range electric boilers in thermal power plants

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1 Abstract

Large controllable loads may support power systems with an increased penetration of fluctuating renewable energy, by providing a rapid response to a change in the power production. Megawatt range electric boilers are an example of such controllable loads, capable of change rapidly, with the advantage that the warmed water can be reused in a thermal power plant or at regional heating, thus, minimising the overall losses.

However, one problem was raised by those purchasing the boilers, mainly the possibility of an unwanted triggering of the protections relays, especially ground fault protection, during the energisation of a boiler. A special case for concern was the presence of an electric arc between the electrodes of the boiler and the water in the boiler during approximately 2s at the energisation, which can in theory be seen as a ground fault by the relay.

The voltage and current transient waveforms were measured for two separate energisation transients of the boiler and the results used to build a PSCAD model able to replicate the results for different system configurations.

The results of various PSCAD simulation, as well as the original measurements, are used as input signals for the testing of two ground fault protection relays, in order to assure that they are not triggered by the energisation of the boiler.

The test is performed via an OMICRON CMC 256 with Advanced TransPlay SW, which generates the signals that would be present at the secondary of the instrumentation transformers, resulting in a realistic simulation environment. The test of different cases demonstrates that the relays will not present unwanted triggering

2 Technology Description

The installed electric boilers have a nominal voltage of 10.5kV and a variable-step load between 0.2MW and 19.3MW. The electrodes have a fixed position and the load is changed by elevating/descending the central pipe used for running the water out (Figure 1). The electrodes are isolated from the outside shell by means of insulators and the grounding resistance of the boiler is 5kΩ. No circuit breaker is installed between the boiler and the busbar, in order to minimise the costs; i.e., the energisation is done by increasing the water level until there is contact between the electrodes and the water, whereas the de-energisation is made via the opposite process.

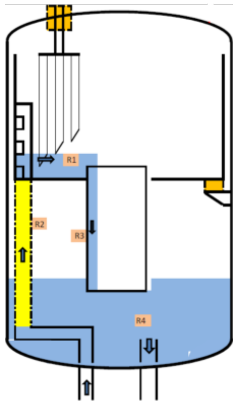

Figure 1 – Example of the water flowing in a boiler. The central pipe moves vertically controlling the water level

3 Phenomena Description

A main concern of power plants operators purchasing the boilers is a possible triggering of the ground fault protection by the boiler. The energisation, i.e., contact of the water with the electrodes, does not occur at the same instant for all three phases, mainly due to the water movement. Electric arcs, with an average duration of 2s, appear prior to the contact of the electrodes with the water; as a result, the relays may see the energisation of the boiler as a fault to ground and trigger the respective responses due to presence of a zero-sequence voltage U_0, a highly undesirable reaction

3.1 Electric Arcs

The electric field between electrode tip(s) and water surface increases steadily, as the water rises towards the electrodes. Depending on various conditions (e.g., temperature, pressure, electrode tip conditions and shape, etc…) a gaseous breakdown eventually happens between an electrode and the water surface. This ignition process relies on the gaseous breakdown mechanism and a simultaneous flash for all three phases is unlikely, as it would require perfectly equal conditions for all the electrodes. As a result, one electrode ends having more favourable ignition conditions and it ignites before the others, which are also being ignited within a short time.

This means that one phase ends connected to the ground via the water and the boiler's ground resistance. This phase-to-ground connection may be perceived as a ground fault in the electrical network that is galvanically connected to the generator and it will persist for the time it takes to energize all three phases, i.e., until the three phase electrodes are all immersed in the boiler fluid and a virtually symmetrical load exists. The critical point occurs when having an electric arc in only one phase, which results in a larger voltage unbalance, even if the electric arc has maximum impedance at this point, because of its length.

3.2 Isolation Transformer

A transformer able of electrically isolate the boiler and assure that it cannot trigger a protection may be mounted between the boiler and the busbar, something requested in some power plants. The installation of such transformer will result in a zero-sequence voltage at the boiler's terminals during its energisation [1].

This zero-sequence voltage affects neither the protection installed at the busbar nor the operation of the boiler. Thus, it would be a definite solution for possible unwanted triggering of the protection, but at the expenses of increasing the costs associated to the installation of a boiler.

4 Protection Technology

Two ground fault protection relays from different manufacturers are considered and compared. In the tests performed in this paper only zero-sequence protection schemes for ground-fault detection are liable of activation, for both current and voltage.

Current and voltage measurement transforms are used in power systems to acquire the input signals required by the relay, but given the fast changing nature of the waveforms some distortions of the input signals is expected [2], [3]. The waveforms' distortion depends mainly on the transformer's construction, both material and structure, and it is not possible to have one-fits-all conclusion or guideline on how to correct their impact. Consequently, the influence of the instrument transformers is not considered in this paper.

4.1 Data quality

The arc phenomenon is characterized by an unpredictable nonlinear behaviour with high frequency variations of the waveforms. The waveforms at the relays input terminals and the signals seen by the processors inside the relay are not 100% alike, due to data acquisition process and the high frequency variations of the input signals.

As a result, it is important to compare the input waveforms with the signals registered by the relays. This is done by using measurements made in a boiler installed in a thermal power-plant. The measurements were made two times for a boiler installed via a transformer, resulting in a high zero-sequence voltage on the boiler side of the transformer, which is not present when the boiler is directly connected to the busbar. This zero-sequence voltage is high enough to trip a relay, but it is confined to the boiler side of the transformer (YNd) not interfering with the relay installed at the busbar, as previously explained.

The measured voltage and current are played by an OMICRON CMC 256-6, via Advanced TransPlay, into the two relays. Table 1 shows the Pearson's correlation coefficients between the injected and seen currents and voltages for both relays. The signal injected via the Omicron has a frequency of 5kHz. Whereas, the Relay A can perform data acquisition at this frequency the Relay B has a maximum sampling frequency of 1.6kHz; to allow a comparison of the results, the sampling frequency of the CMC was also reduced to 1.6kHz for the test of Relay B.

Both signals have a high correlation, which is positive, but given the nature of the data it does not mean that the maximum peaks are being properly registered. Figure 2-Figure 5 show the voltage and current in one phase during part of the energisation for the measurements, CMC´s output and relay's used data. It is seen that the voltage is virtually alike in all three, whereas the current has more differences, more specifically the current seen by the relay cannot vary as fast and thus, some of the peak values have a slightly lower magnitude and some very high-frequency oscillations at lower magnitudes are not seen by the relay.

However, this does not affect the operation of the relays in this case. A fault-to-ground protection requires the presence of a fault for a minimum period of time, thus, a small error in the higher frequency variations is not relevant and the ability of the relays in detecting a fault-to-ground is not diminished.

Table 1 – Correlation coefficients of the relays data versus the data sent by the Omicron during the arc

	Relay A		Relay B	
	Meas. 1	**Meas. 2**	**Meas. 1**	**Meas. 2**
IL1	0.9958	0.9787	0.9155	0.9340
IL2	0.9952	0.9846	0.8545	0.9417
IL3	0.9971	0.9888	0.8909	0.9594
UL1	0.9981	0.9948	0.9482	0.9739
UL2	0.9981	0.9947	0.9337	0.9695
UL3	0.9980	0.9945	0.9331	0.9586

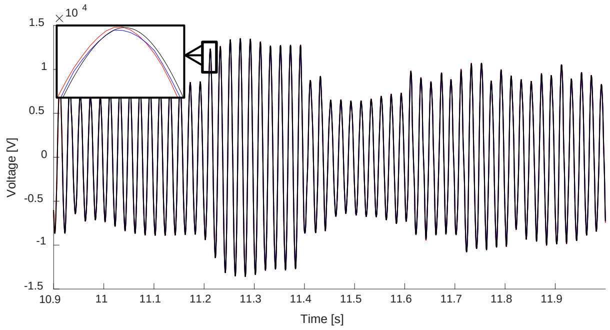

Figure 2 - Voltage in one phase during energisation: Black: Measurement data; Red: CMC´s output; Blue: Voltage seen by the Relay A

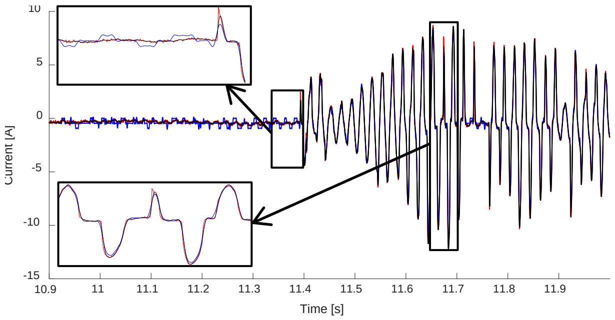

Figure 3 - Line current in one phase during energisation: Black: Measurement data; Red: CMC´s output; Blue: Current seen by the Relay A

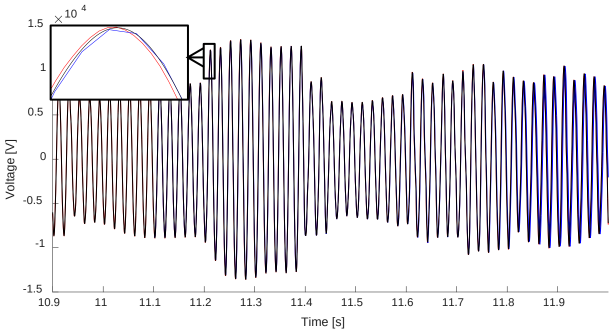

Figure 4 - Voltage in one phase during energisation: Black: Measurement data; Red: CMC´s output; Blue: Current seen by the Relay B

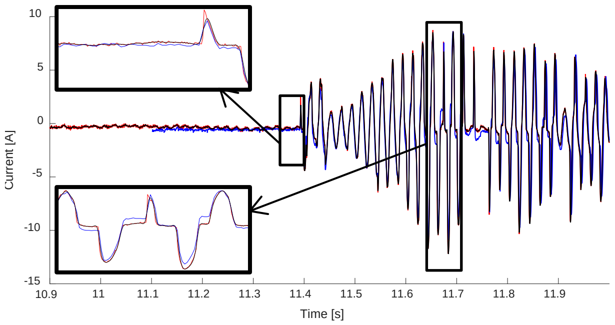

Figure 5 - Current in one phase during energisation: Black: Measurement data; Red: CMC´s output; Blue: Current seen by the Relay B

5 Triggering

5.1 Simulation models

The field measurements were performed only for the case of a boiler installed via a transformer and cannot be used to assess the operation of a relay when having the boiler directly connected to the busbar.

Time-domain simulations models were developed to simulate these cases. The simulation of the electric arc starts by defining a reference arc. Different reference formulae, some with more than one century, exist for estimating the resistance of an electric arc [4]-[7]. They have different constant values, but are a variation of (1), normally. Where R_{Arc} is the arc resistance, l is the arc length, I is the current and a and α constants whose values depend on the system conditions and authors.

$$R_{Arc}(t) = \frac{a \cdot l(t)}{I^{\alpha}(t)} \qquad (1)$$

The measurements show that the current increases slowly, while the length of the arc decreases. Thus, it is expected a faster drop of the resistance in the first instants and a slower decrease of the resistance in the final part of the arc, in accordance with the theory. The time between the appearance of the first arc and the contact of the electrodes with the water was approximately 2s in both measurements, as well as in previous tests. Therefore, a 2s arc is considered. Figure 6 shows the reference arc estimated using the measurements' data.

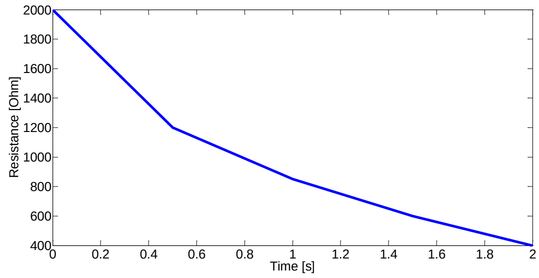

Figure 6 – Reference arc in function of time

The randomness of the arc is simulated by multiplying the reference arc, at each time step (10µs), by a varying random number between 0.6 and 1.4 with a Gaussian distribution. As a result, the arcs have a random unpredictable behaviour and the respective impedances are different for each phase and each simulation. Figure 7 shows the resistance of each phase for a period of 0.3ms during the electric arc.

In order to access worst-case scenarios the reference arc from Figure 6 is considered to start at 0.2kΩ, instead of 2kΩ, in some of the tested cases, resulting in lower impedance, leading to a larger zero-sequence current and consequently, a larger zero-sequence voltage.

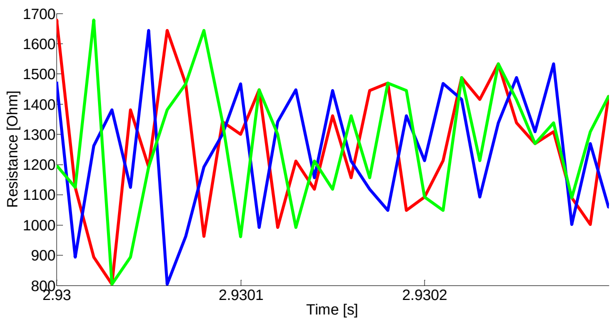

Figure 7 – Example of the phase resistances of the electric arc in the simulation model

A circuit breaker is also inserted between the boiler and the busbar to simulate the ignition of the arc in each phase at different instants; a time interval of 0.1s between switching is chosen.

As written in section 2 a 5kΩ impedance is present between the boiler and the ground. This is simulated via a resistor, but in order to access worst case scenarios this resistor is eliminated in some of the test cases and a solid grounding is considered instead. The modelling of the generator was made using the data of the synchronous generator installed at the power plant where the field tests were performed.

Figure 8 shows the single-line diagram of the simulated system, including also the equivalent grid and the 10.5/32kV step-up transformer between the generator and the network, whereas Figure 9 shows the circuit in PSCAD.

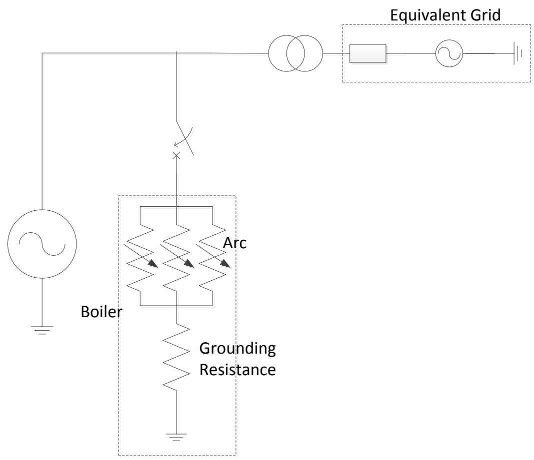

Figure 8 – Single-line diagram of the simulated system

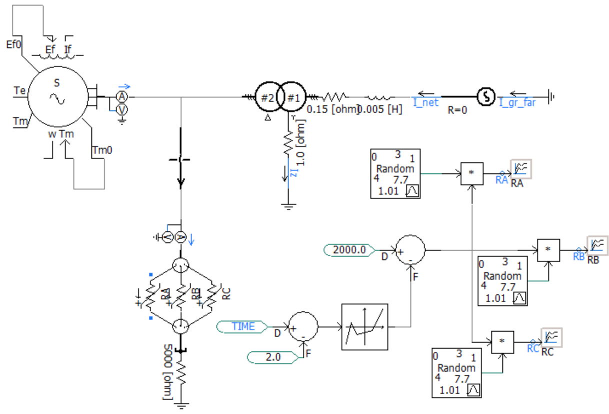

Figure 9 – PSCAD circuit used in the simulations (generator data is internal)

Besides simulating the randomness of the electric arc two other test parameters are included in the simulations:

- Solid and isolated earthing of the generator;
- Different shunt capacitances installed between the generator and the boiler;

The earthing of the generator is simulated for both limit cases as it influences both the zero-sequence current and voltage seen by the relay.

The insertion of an artificial shunt capacitance is done with the goal of simulating the capacitances to ground of other elements, as the connection cable or the step-up transformer. This stray capacitance provides a return path for possible zero-sequence currents, influencing their magnitude. The zero-sequence current seen by a relay installed next to the generator will be barely affected by this, as the shunt capacitance is present after this point, but the zero-sequence voltage may change, depending on the system conditions. An exaggerated value of 1μF is considered, in order to access worst-case scenarios.

Table 2 shows the test cases used to verify the behaviour of the two relays.

Table 2 – Test cases with information on the grounding of generator and boiler

	Generator	Boiler	extra
Case 1	solid	solid	
Case 2	solid	5kΩ	
Case 3	open	solid	
Case 4	open	5kΩ	
Case 5	solid	solid	arc of 0.2kΩ
Case 6	open	solid	arc of 0.2kΩ
Case 7	solid	5kΩ	arc of 0.2kΩ
Case 8	open	5kΩ	arc of 0.2kΩ
Case 9	solid	5kΩ	1μF shunt
Case 10	open	5kΩ	1μF shunt
Case 11	open	solid	1μF shunt
Case 12	open	solid	1μF shunt

6 Relay testing

The sensitive earth fault protection scheme is activated in the two relays and both zero-sequence current and the zero-sequence voltage are measured. In order to access worst-case scenarios the different settings, e.g., current and voltage thresholds, will be tuned to the minimum values allowed by the relays, even if this results in values substantially inferior to those used in real systems.

For Relay A, the zero-sequence voltage threshold is for V_0>0.1kV with no time delay, whereas the zero-sequence current threshold fires for $3I_0$>150A (0.05A in the secondary) with no time delay; all values are the minimum ones allowed by the relay, i.e., worst-case scenario values.

For the Relay B, the zero-sequence voltage protection is triggered for V_0>1% (V_N=10kV) with a time delay of 0.3s, whereas the zero-sequence current protections triggers for I_0>0.005pu (I_N=6500A) with a time delay of 0.05s; again, all values are the minimum ones allowed by the relay and the nominal values are those of the generator.

It is important to refer that settings of sensitive earth fault protections are usually adjusted to be somewhat less sensitive to radial unwanted trips like transients. This is often done by employing a time delay in the range of 1s, however, the tests made in this paper consider time delays much smaller than 1s, in order to assess worst-case scenarios.

The relays are unaffected for all 12 cases, except Case 6, which is seen by both relays via the zero-sequence voltage protection. The trigger is not activated for the Relay B, only the alarm is, as V_0 decreases to below 1% in less than 0.3s, but it trips for the Relay A that allows no time-delay. The difference between alarm and trip is in the time delay; both relays send an alarm if a value is detected over the threshold, but they only trip the phases if the limit is infringed for a period longer than the time-delay. As relay A has a time-delay of 0s, the trip and alarm are equivalent.

Case 6 is characterised by a generator with an isolated earthing, an arc impedance ten times smaller than the real one and a solid grounding of the boiler, this together with a delta connection on the generator side of the step-up transformer and the arcing of the phases at different instants results in a strong unbalance of the voltage during the period where not all three phases have an electric arc, alike a single or double fault-to-ground in a network connected to the delta side of a transformer. Case 3 is alike to Case 6, except that the real arc resistance of the boiler is considered and that is sufficient to avoid detection by the relay, since that in this case the voltage unbalance is much smaller, even when considering an unrealistic grounding resistance of 0Ω for the boiler.

Figure 9 shows the voltage in the busbar and the current in the boiler for both Cases 3 and 6, allowing verifying the influence of the arc values in the zero-sequence voltage.

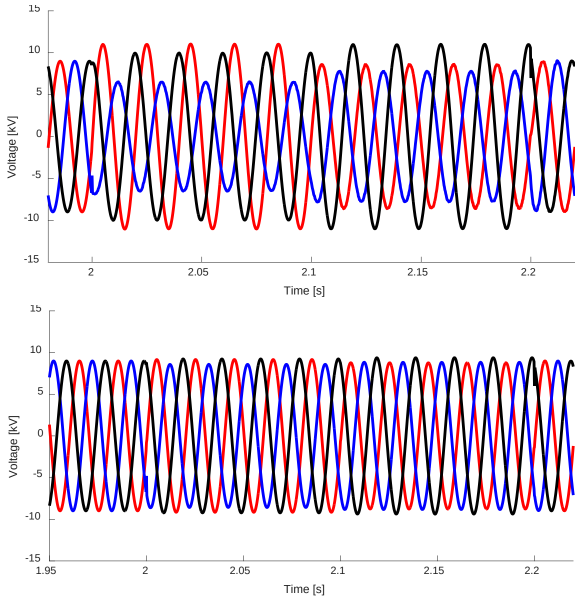

Figure 10 - Voltage in the busbar for Cases 6 (up) and 3 (down). Switch-on: Phase A: 2s; Phase B: 2.1s; Phase C: 2.2s

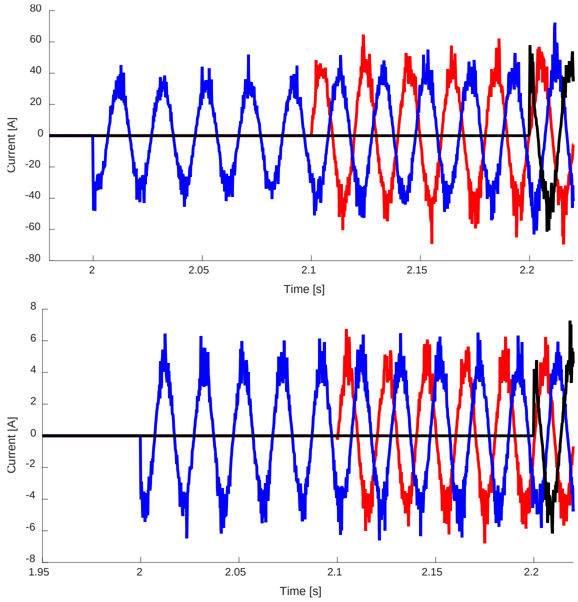

Figure 11 – Current in the boiler for Cases 6 (up) and 3 (down). Switch-on: Phase A: 2s; Phase B: 2.1s; Phase C: 2.2s

In summary, a relay will not be triggered by the energisation of the boiler, as the only test case that resulted in a reaction from the boiler was for an arc with impedance 10 times smaller than the measured one and a grounding resistance of 0Ω in opposition to the real 5kΩ.

7 Discussion

The triggering of the ground fault protection relay caused by the energisation of an electric boiler installed in a power plant is something that could happen in a theoretical scenario and thus, worthy of attention by both the seller and buyers of such technology. A preventive study, alike the one conducted in this paper, must include a series of different factors that are not easy to consider and have a high significance.

A first aspect is the electric arc and respective modelling. Electric arcs depend on a large number of factors resulting in a random behaviour on every occurrence. The modelling of all possible arcs is impossible, but the simulation data can be adjusted around a reference arc obtained by means of measurements, in order to simulate a large range of cases, as it was done.

A second aspect is the choice of the parameters used for the system and relay. The former was solved by using the data sheets from a power plant where a boiler was installed and the latter by adjusting all the relays' settings to worst-case scenarios, as relay installed in a real system would have bigger time delays and larger zero-sequence current and voltage thresholds. As a result, if the relays did not see the energisation of the boiler as a problem with the used settings it is even more unlikely to have then affected for typical settings.

For all these reasons the obtained results can be generalised for a large number of different systems even, but not all, when considering that the simulation model is based in a specific system. Moreover, cases like solid/isolated generator earthing and arcing at different instants where included in the test cases.

8 Conclusions

This paper demonstrated the a earth-fault protection relay will not react to the energisation of an electric boiler, as the large grounding resistance of the boiler is sufficient to avoid it, even when using the minimum thresholds of two different relays.

Nevertheless, it is import to refer that the conclusions of the paper cannot be extend for any systems, since that parameters as low short-circuit powers or long distance between generator and boiler were not tested.

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