PROTECTION TESTING OF A 100% STATOR GROUND FAULT USING A PHASE DOMAIN SYNCHRONOUS MACHINE MODEL IN REAL TIME

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Abstract

This paper utilizes a significantly improved phase domain synchronous machine model [3] to test a multi-function relay model created for a real time digital simulator. One of the features of the machine model is its capability of simulating stator internal faults. Third harmonic voltage on the neutral and terminals of the machine and its variation with load and stator-ground faults is accurately represented. This feature makes the machine model a good candidate for testing a "100% stator-ground fault protection scheme" based on the third harmonic voltage. The performance of the relay model for "stator differential protection", "100% stator-ground protection" and the "loss of field excitation protection" schemes is verified and the results are presented in this paper.

1 Introduction

The Real Time Digital Simulator RTDS® is commonly used to perform closed-loop testing of power system protection and control devices. Effective protection of generators requires that many fault scenarios be considered before the generator is adequately protected against electrical faults. Utilization of a synchronous machine model capable of producing 3rd harmonic voltages for the entire load range and for ground faults near the neutral enables adequate testing of the protection application.

Setting a "100% Stator Ground Protection Scheme" [8] based on 3rd harmonic voltage requires taking voltage measurements at various loading conditions, and is the recommended method for providing a secure setting. Unfortunately, as these measurements require the generator to be loaded from 0 to 100% load, a less secure method for stator ground protection must be used until the measurements are taken.

Testing "Stator Phase Differential Protection" with previous real-time synchronous machine models was not possible and the currents of faulted windings were not available from the generator model. With Park's dq0 type models, currents are only available at the generator terminals. However conventional dq0 data can be used to generate the inductances of faulted windings and used to simulate the machine directly in the phase-domain. The phase domain machine model provides access to the currents of faulted windings in addition to the currents at the terminals. Therefore it is possible to fully test the stator differential protection during the simulation.

2 Description of the Synchronous Machine Model

This paper utilizes a detailed synchronous machine model which considers the actual distribution of the windings, shape of the pole-arc and the effects of operating point dependent saturation [3], [4]. The correct modeling of winding and permeance-related time harmonics (phase belt harmonics) [3], [4] is therefore assured. The embedded approach [4], [6], as opposed to the normal interfaced approach used in conventional machine modeling, is utilized in the RTDS Simulator. The time delay inherent in interfacing is eliminated, making the simulation more numerically stable. More details about the machine model are explained as follows:

2.1 Inductance Calculation

Using a modified winding function approach (MWFA) [4] and considering the actual curvatures of the pole-arc, the inductances of the machine windings are computed for each rotor position [3], [4]. This method uses an integral formulation to compute the self and mutual inductances of the windings, which makes it considerably less time-consuming compared to the Finite Element Approach. To account for additional effects (such as stacking factor and the magneto-motive force (MMF) drop in the stator and rotor slots) the permeance function is modified into an 'effective permeance function' as proposed in [3], [4] using experimentally measured L_d, L_q and L_0 values. The effects of operating point dependent saturation are also taken into account in the computation of inductances by adjusting the permeance function based on the magnitude and angle of total MMF in each loading condition [4],[5],[7]. Therefore the effects of cross-magnetization phenomenon are included in the model. In addition to the inductances of the healthy windings, the inductances of faulted windings can also be computed using the above procedure. This makes the model suitable for representing internal faults.

Previously, authors have proposed methods [10] to compute the inductances of faulted windings based on the dq0 theory. Although this method is fast and requires minimum data, it does not represent winding-related time harmonics since it only considers sinusoidal distribution for the windings and permeance.

2.2 Time-Domain Simulation

Generally the inductances of a synchronous machine are functions of rotor positions and status of saturation. In the phase-domain model, the values of machine inductances are changing in each time-step. The machine model updates the inductance matrix based on the values of rotor position and magnetizing currents (i_{md} and i_{mq}) in that time-step.

The RTDS Simulator network solution incorporates the machine model using an embedded approach. With an embedded approach [4], [6] the equivalent discrete admittance matrix of the machine is added to the total admittance matrix of the network in every time-step. This technique creates a model which is accurate and less prone to numerical instability.

As shown in Figure 1 , stator phase A is divided into two sub-windings A1 and A2 and the rotor damper grid is represented by d- and q-axis damper windings. Stator nodes NA1, NB1, NC1, NJA, NN0 and rotor field nodes NF1 and NF2 are normal power system nodes and can be connected to any power system components.

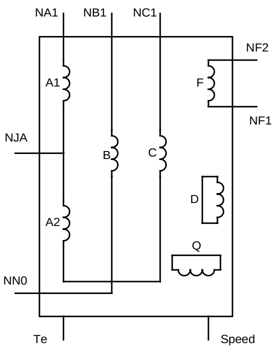

Figure 1: Configuration of the embedded synchronous machine model developed in the RTDS environment.

The machine model is primarily intended to use MWFA-based inductances (see Section 2.1). In this case the winding and permeance-related time harmonics such as the third harmonic voltage on the neutral and terminals will be represented correctly, and the model is qualified to be used for protection schemes based on these harmonics. If the information about the windings distributions is not available, the model uses dq0-based methods [10] to compute the inductances of faulted windings. In this case, the machine model does not generate time harmonics and it is not suitable for testing protection schemes such as "100% stator-ground protection" using the third harmonic on the neutral. However it can still be used for elements such as stator differential protection.

2.3 Description of the Experimental Machine

The machine model is applicable to any synchronous machine, but is intended for use with utility generators. The model was experimentally validated [4] using a laboratory synchronous machine and was used for the studies presented in this paper. The specifications outlined are as follows.

The machine under study is a 3kW, 4-pole, 60 Hz, 1800 rpm, 208 V (line-to-line), star connected salient-pole synchronous machine. The rotor pole-arc of the experimental machine is not exactly circular but has different curvatures along the pole-face. The stator has a single layer, 3-phase, random-wound concentric winding distributed in 36 stator slots. Each phase of the stator winding has two series connected coils. There are 16 turns/slot/phase with a total of 96 turns per phase.

3 Description of the Multi-Function Relay Model

The multi-function relay model is a full transient model that utilizes a threading technique developed by RTDS Technologies [9]. The "threading" technique used in the RTDS Simulator relay library allows the execution of detailed multi-function relays to be spread amongst the simulation time steps that occur between the sampling instants of the relay's protection algorithm. Table 1 shows the available elements of the relay model.

The 87P, 64G, and 40 protection elements were tested in this paper using the synchronous machine model.

Device	Description
87P	Phase percentage restrained differential, can include unit step−up transformer, and unit auxiliary transformer
87N	Ground differential for low impedance grounded generators
50/51N	Neutral Overcurrent Protection
50/51P	Phase Overcurrent Protection
64G	100% Stator Ground Detection for high impedance and resistance grounded generators
40	Loss-of-Field Protection
32	Loss of Prime Mover Protection
AE	Accidental Energization Protection
24	Volts per Hertz Protection
46	Negative Sequence Overcurrent Protection
27	Undervoltage Element
59	Overvoltage Element
81	Over and Under Frequency Protection
81of	Off Nominal Frequency Time Accumulators for Steam Turbines
78	Out-of-Step Protection
21	Distance Backup with Load Encroachment
25	Synchro-Check Element for Breaker Close Supervision
60	Loss-of-Potential Logic

Table 1: Available elements of the protection relay model

4 Simulation Results for Testing the Relay Model

In this section, using the RTDS Simulator, the capability of the multi-function relay model to detect and clear synchronous machine faults is demonstrated. Also, the simulation results presented in this section demonstrate the capabilities of the detailed machine model in properly modeling faulted conditions of a synchronous machine.

Three protection schemes are examined: “stator differential protection” (87P), “100% stator-ground protection” (64G), and “loss-of-field excitation” (40). Figure 2 shows the circuit as drawn in RSCAD, the Human-Machine Interface for the RTDS Simulator [11]. The machine is run at rated speed, and excitation voltage is set so that rated terminal voltage is achieved with a 1.0 pu, 0.8 pf Δ-connected series R-L load. Node NJA demonstrates a point in the stator phase-A winding which divides phase-A into two sub-windings A1 and A2. This node can be used for simulating turn-ground faults. As can be seen, the neutral and terminals are connected to ground using the neutral resistance and the charging capacitances respectively. If the neutral is grounded through low impedance, the differential scheme can be used for protecting the machine during a stator-ground fault [8], [12]. This scheme however cannot detect a stator-ground fault if high-impedance grounding is used due to low levels of fault current. Alternatively, schemes such as “100% stator-ground protection” can be used in these situations [2], [8],[12].

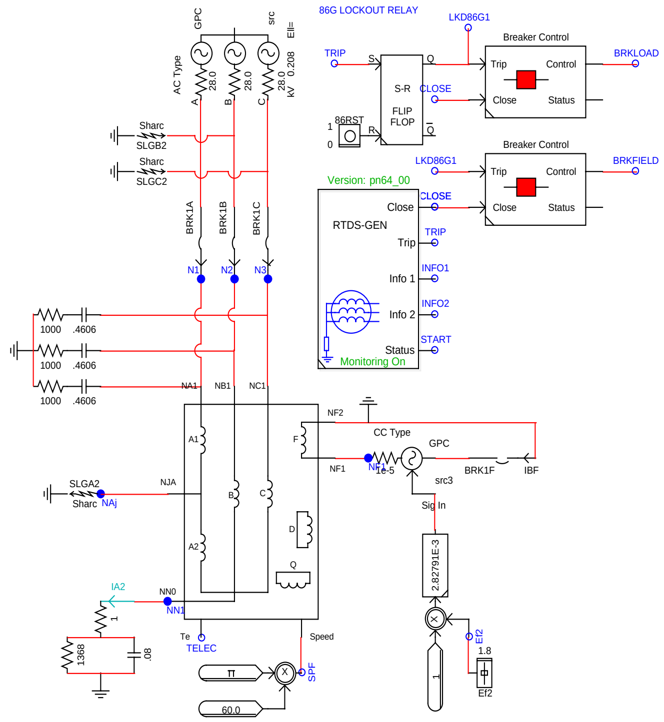

Figure 2: RSCAD draft circuit used for the simulation.

4.1 Stator Differential Protection (87P)

In this example, the neutral of the machine is grounded through a 1.2 Ω resistance. The stator differential element of the relay model (e87) is enabled and in RUNTIME a fault is applied between the node NJA and ground. The fault is at 33% of the winding from neutral side. A large current flows into the sub-winding A2 (ISTATA2 in Figure 3) which is quite different compared to the phase A breaker current (IB1A). This causes the relay to send the TRIP signal to the load breaker and open it. Figures 3c and 3d show the variation of operate and restraint current for phases A and B respectively. It is obvious that the faulted phase A experiences a considerable amount of operate current during the fault.

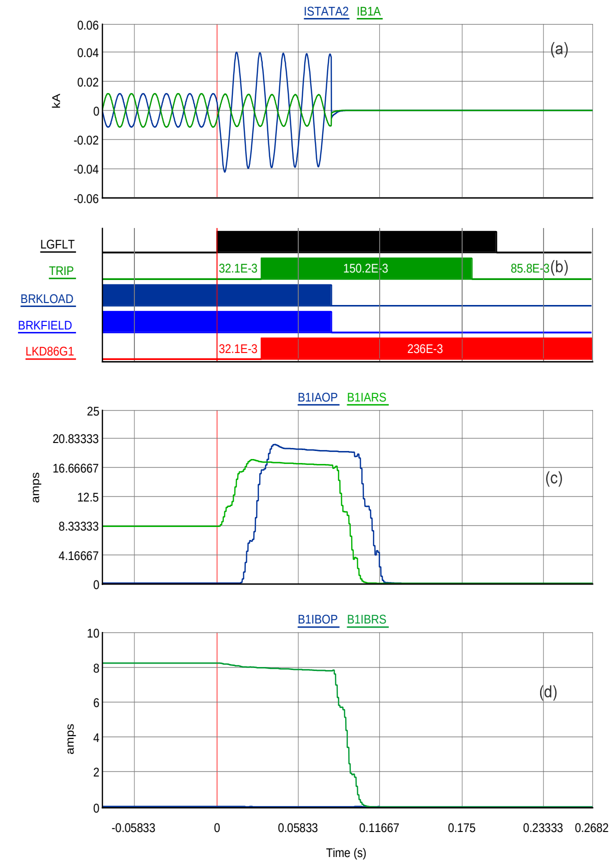

Figure 3: Simulated signals for the stator differential protection: (a) stator A2 and breaker currents, (b) control signals, (c) phase A operating and restraint currents, (d) phase B operating and restraint currents

Figure 4 shows the variation of phase A operate current versus restraint current overlaid on top of the differential characteristics of the relay model. As can be seen, these two curves cross each other indicating the successful operation of the relay.

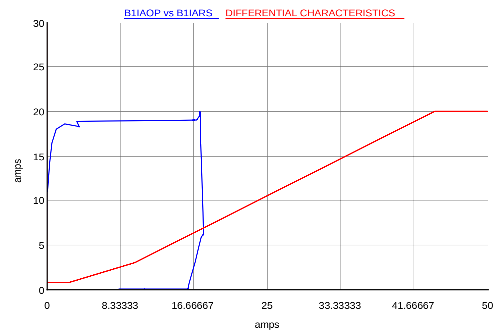

Figure 4: variation of phase A operating current versus the restraint current overlaid on the differential characteristics of the relay (33% of the neutral)

In another test, the fault is applied very close to the neutral (at 2% of the winding). In this case the operate current is not large enough to activate the relay as shown in Figure 5. This is evidence to the fact that differential protection is not always successful when the fault is very close to the neutral (less than 5%) [12].

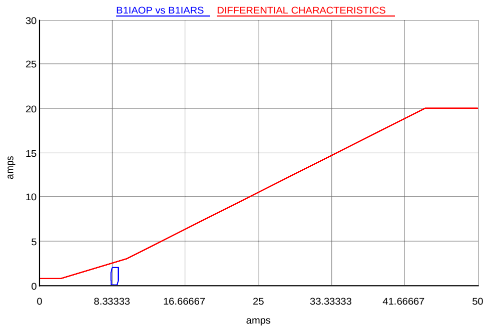

Figure 5: variation of phase A operating current versus the restraint current overlaid on the differential characteristics of the relay (fault at 2% of the neutral)

4.2 100% Stator-Ground Fault Protection (64G)

In this example, the neutral of the machine is grounded through a large resistance of 1.4 kΩ. The "100% stator-ground element" of the relay model (e64) is enabled and in RUNTIME, a fault is applied between the node NJA and ground. The fault is at 33% of the winding from neutral side.

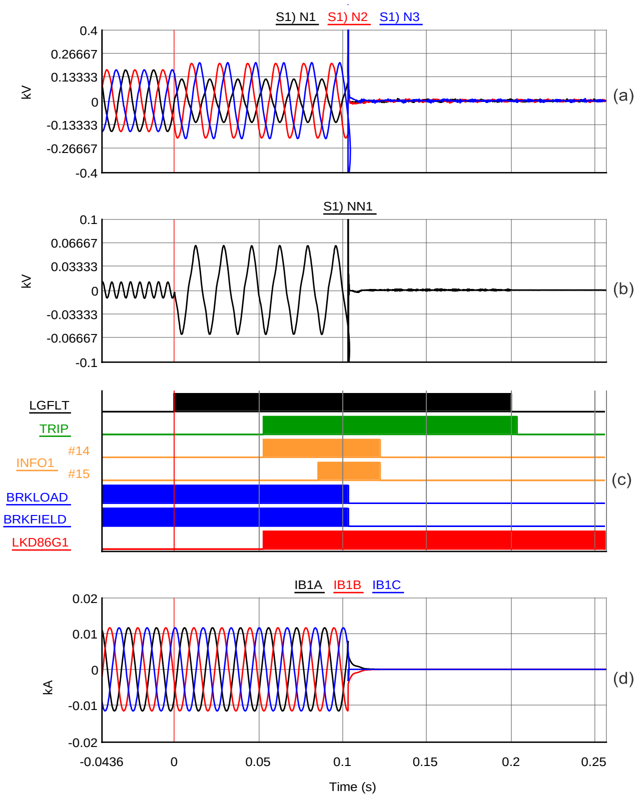

Figure 6: Simulated signal for the "100% stator-ground protection, (fault at 33% of the neutral): (a) terminal voltages, (b) neutral voltage, (c) control signals (d) breaker currents

As can be seen in Figure 6b, before the fault the neutral voltage is mostly third harmonic with no fundamental component. After the fault, the neutral voltage contains the fundamental harmonic as well, as the machine is operating in an unbalanced condition. In addition, the third harmonic component of the neutral voltage changes in value. The relay elements uses these changes to detect the fault and send a TRIP signal to the breakers as shown in Figure 6c. Figure 6c also shows that, both neutral overvoltage element (64G1) and neutral third harmonic differential element (64G2) are operating in this case. This is shown by signals INFO1 #14 and #15.

The simulation is repeated with a stator-ground fault very close to the neutral (at 2% of the winding). In this case, the neutral overvoltage element is not able to detect the fault since the fundamental component of the neutral voltage is very small. However the neutral third harmonic differential element (64G2) detects the fault as shown in Figure 7c. This is shown by signal INFO1 #15.

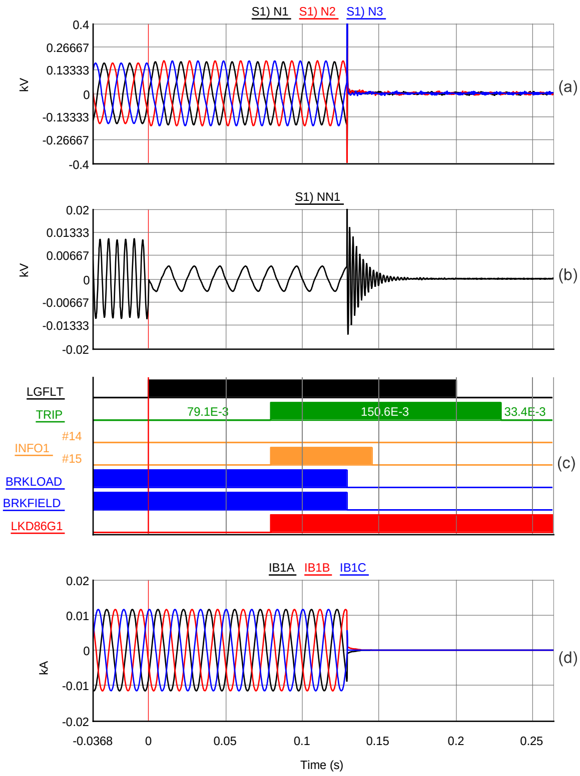

Figure 7: Simulated signal for the "100% stator-ground protection, (fault at 2% of the neutral): (a) terminal voltages, (b) neutral voltage, (c) control signals (d) breaker currents

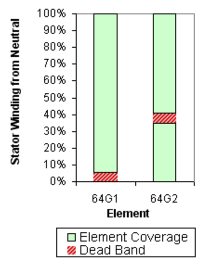

Figure 8: Element Coverage for the "100% stator-ground protection"

The machine 3rd harmonic terminal and neutral voltage measurements were taken at 0% and 100% load. As can be seen in Figure 8, the 100% stator ground protection can provide about 95% coverage from the 64G1 element operating on fundamental voltage. The 64G2 element operates on a 3rd harmonic voltage differential scheme to provide the remainder of coverage near the bottom of the winding.

4.3 Loss-of-Field Excitation (40)

The last example is the operation of the "loss-of-field excitation element". Generators are normally operated so they are slightly overexcited and thus normal stable operation is in the 1st quadrant. However, when the excitation field is lost the generator must absorb reactive power and operation is in the 4th quadrant. This area of operation is unstable and should be avoided. If there is no excitation and the system can sustain the voltage and provide the necessary reactive power, the machine will act as an induction generator. Otherwise loss of synchronism will occur. Overheating that can damage the machine can also occur if the excitation is sufficiently low.

Using a circuit breaker, the excitation current of the synchronous machine is disconnected as shown in Figure 9a. The relay element detects the fault using the MHO characteristics and sends the TRIP signal to the load breaker (see Figure 9b). Figure 10 shows the variation of the imaginary part of the impedance seen from the terminals versus the real part overlaid on the MHO characteristics of the relay.

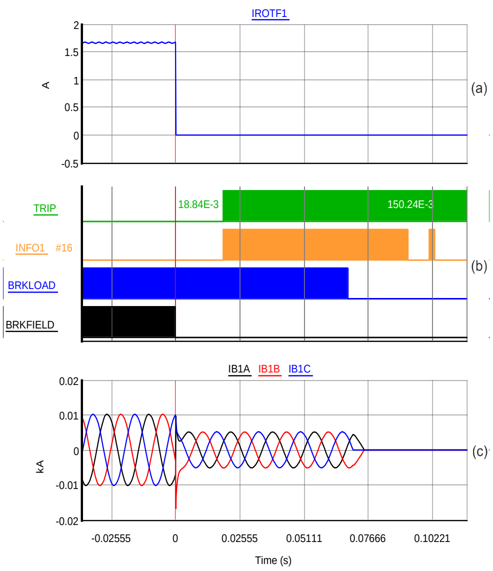

Figure 9: Simulated signal for the "loss of field excitation protection: (a) the field current, (b) control signals, (c) breaker currents

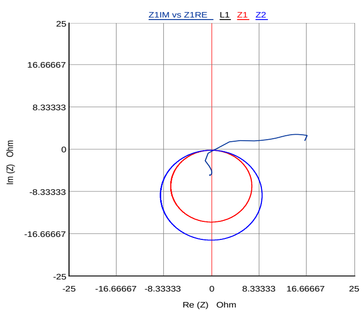

Figure 10: variation of Imaginary part of impedance versus the real part (during the loss of field excitation) overlaid on the MHO characteristics of the relay

5 Conclusions

The capabilities of a new real time multi-function relay model, implemented on the RTDS Simulator, in detection of synchronous generator faults were demonstrated. The paper also describes a detailed real-time synchronous machine model which can be used to simulate synchronous machine stator faults. One of the capabilities of the machine model is proper representation of harmonics such as the third harmonic voltage on the neutral and terminals of the machine. This enables the model to operate '100% stator-ground fault protection schemes" as demonstrated. The machine model will be used in future research to test physical protection devices.

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