Investigation of fault current contribution and management of AC machines

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Report

By

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Executive Summary

This report describes the work completed as part of the project *Investigation of fault current contribution and management of AC machines*. The project has been carried out for about 4.5 months from mid March till mid July 2014, involving suitable network model development, initial investigative studies, and further detailed analysis in specified areas. In addition to the initial report on the effects of loss of (or disconnection of) excitation on synchronous generator transient performance (the comments on “Fault Level Management Query Document” delivered on 24 March 2014 and included as Chapter 6) this investigative project in AC machine’s transient performance during the fault was carried out in two stages:

Stage 1: Initial Investigation: to quickly cover a wide range of possible conditions and identify the areas and phenomena for further investigation at the second stage of project.

Stage 2: Detailed Simulation and Analysis: focusing on detailed modelling and analysis of one or two to phenomena for a range of scenarios agreed following delivery of the interim report after first stage.

The main results of the analysis carried out during the project showed that:

- Passive flux discharge (whereby the excitation voltage is disconnected, open circuited) can result in an average reduction of up to approximately 9% of machine fault current, 200 ms after the fault occurs. This is dependent upon the precise machine parameters as well as the length of time for which the excitation system is disconnected from the machine.
- Advanced machine excitation (active discharge of excitation flux) can reduce the fault current contribution to a noticeable extent at timescales greater than 20 ms after fault occurrence (the required ‘break current’). This reduction is extremely dependent on the machine parameters and requires modification of excitation system. If high additional resistance is connected to the field winding it can potentially result in overvoltages on the field windings and must be very carefully assessed on a case by case basis.
- Neither passive nor active machine flux discharge during faults can reduce the initial peak fault current contribution (‘make current’) of synchronous machines.
- The fault current contribution by the synchronous machine following its disconnection from the bus is also reduced; however, practical implementation of such a scheme is not trivial and will require excellent protection coordination.

- It has been confirmed that Induction machines contribute far less to fault currents and their contribution decays within 150-200 ms due to the fast decay of the machine flux. If the synchronous machine is operated as a synchronous motor (rather than as a generator) its fault current contribution will be less than in case of operation as a generator. The disconnection of the excitation voltage in order to achieve passive flux discharge in this case has a similar effect (in terms of proportional current reduction) as in case of operation as a generator.
- A briefly review of Engineering Recommendation G59 in order to assess its implications for the application of advanced voltage regulation or machine disconnection found that G59 does not appear to restrict application of the investigated approaches, however, it does stipulate conditions under which the machines should remain connected to the network.

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Introduction

This report describes the work completed as part of the project *Investigation of Fault Current Management*. The project has been carried out for 16 weeks from April–July 2014, following the initial programme of work presented below.

1.1 Programme of work

The project was divided into two sections:

1. **Initial Experimental Investigation** to quickly cover a wide range of possible conditions and considerations.
2. **Continued Detailed Simulation and Analysis** to thoroughly investigate a range of agreed scenarios.

A high level project plan is included as Figure 1-1.

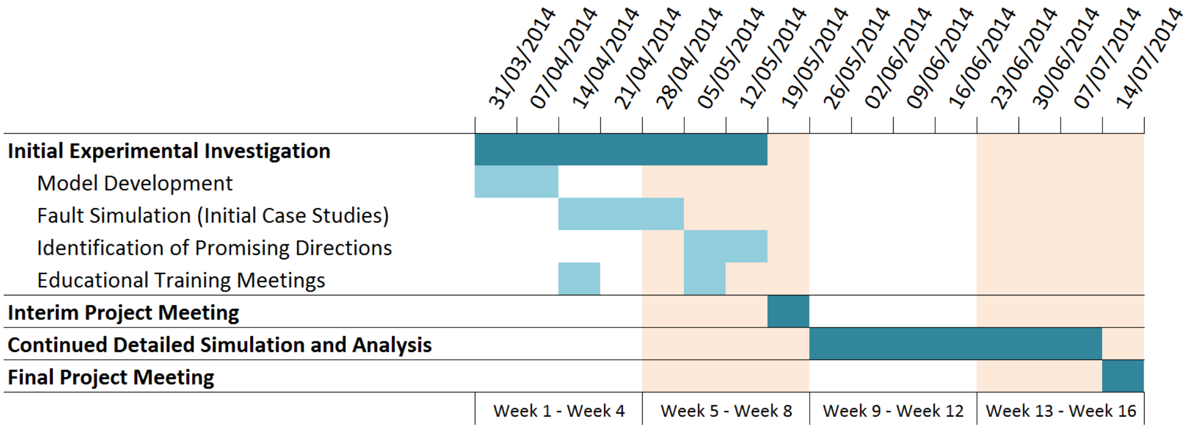


Figure 1-1: Project plan.

These sections of work were further broken down into the following tasks as described below.

1.1.1 Initial Experimental Investigation (Week 1 – Week 7)

Task 1: Model Development (Week 1 – Week 2)

- A proven simulation environment (DIgSILENT PowerFactory) will be used and relevant model of a synchronous generator including sufficient network representation and controllers will be developed.
- The model will consist of one synchronous generator of rating less than 10 MVA, controlled using a basic AVR and constant mechanical torque input. This generator will be connected to a strong network (equivalent model) through a transformer and two parallel lines.
- Three phase, electromagnetic transient (EMT) simulations will be used to monitor stator voltages and currents, excitation field voltage and current, and electromagnetic torque.
- A variation of this core model will be developed which also includes a large induction machine (rated at 300 kW) connected to the transformer 'network-side' bus. This machine will be modelled using typical controls and parameters.
- Relevant induction machine voltages and currents will be recorded during three phase, EMT simulations.

Task 2: Fault Simulation (initial case studies) (Week 3 – Week 5)

A number of initial simulations will be performed in order to establish areas for further exploration (during Section 2, Week 9 onwards).

These simulations will include:

- Different fault types of different durations simulated at different locations between the generator transformer and the strong equivalent network bus.
- Disconnection (and subsequent reconnection after different periods of time) of synchronous generator excitation system during fault conditions.
- Disconnection (and subsequent reconnection after different periods of time) of the synchronous generator during fault conditions. This will include connection of the synchronous generator to a breaking impedance when not connected to the network.
- In all cases, priority areas for investigation will be the peak network fault current and contribution of the machine (both synchronous generator and induction machine).

Task 3: Identification of Promising Directions (Week 6 – Week 7)

The studies performed during Task 2 will be analysed to produce a range of feasible options which look promising for further detailed investigation. Results will be summarised and a presentation produced. These promising directions will be taken forward to the Interim Project meeting for discussion and finalisation.

Take 4: Educational Training Meetings (when possible during Week 1 – Week 7)

Educational training meetings will be hosted by the University of Manchester with relevant ENW staff to facilitate knowledge transfer and ensure sufficient project contextualisation. This will enable ENW staff to more fully understand the phenomena involved University of Manchester staff to fully appreciate the practical considerations and drivers for the research project.

1.1.2 Interim Project Meeting (Week 8)

An interim project meeting will be held to discuss initial results and define the scope of scenarios for future investigation. At this stage, ENW input will be required to define typical machine, control, and network parameters to ensure result accuracy.

1.1.3 Continued Detailed Simulation and Analysis (Week 9 – Week 15)

The areas and scenarios finalised during the Interim Project Meeting (Week 8) will be performed and a thorough analysis of the impacts on system performance will be completed. It is expected that this work will include investigation into differentiating between fault contribution of induction machines and start up so that discriminatory control can be utilised to limit fault current contribution whilst leaving normal operation unaffected.

1.1.4 Final Project Meeting (Week 16)

The findings of the project will be written into a report and presented alongside recommendations for industrial network practice with respect to fault level management using advance voltage regulation of large rotating machines.

1.2 Schedule of Progress

It should be noted that the planned *Educational Training Meetings* never came to fruition. However, this was discussed at the interim project meeting (held on 21 May 2014) and it was jointly agreed that this was mainly the result of scheduling and time pressures and could not be helped. Following the interim project meeting and presentation of initial results it was agreed the majority of desired project outcomes had already been achieved.

This final project report presents and discusses the results of all studies, including those presented at the interim meeting and additional work completed following this. This additional work included (as instructed by ENW colleagues following the interim project meeting) studies of faults at 11kV feeder (as opposed to 33kV faults studied in the interim report), exploration of active flux discharge contribution to fault current reduction as reported in the most recent study by researchers from Canada, and the implication of *machine* or *machine excitation* disconnection during fault conditions on standard G59. Potential extensions of presented work and areas for further discussion and potential future analysis are also included at the end of the report.

2

Network Description

2.1 Scope

This chapter describes the network that was developed for the fault level simulations and analysis performed as part of this project. For some simulations, modifications have been made to this *base* network model. For these instances, the changes will be explicitly stated within this report.

2.2 Network Model

A generic distribution network model has been developed as shown in Figure 2-1. The model consists of a synchronous machine connected to an external grid through a transformer and parallel transmission lines. Parameters of all network components (lines, transformers, generators, motors) are adopted based on existing components in UK distribution networks.

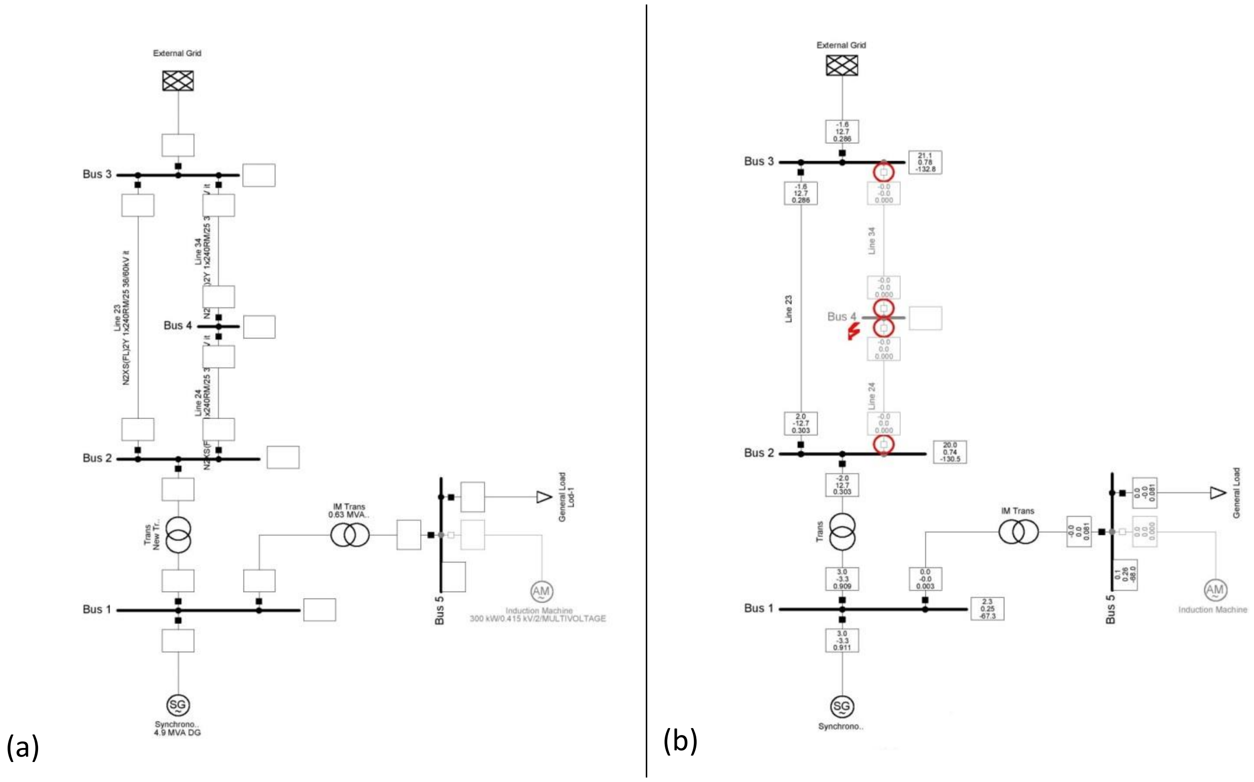


Figure 2-1: Network model shown (a) during normal operation, and (b) following a fault at bus 4.

2.3 Model Details

The network has been modelled using DIgSILENT PowerFactory making use of inbuilt models of different components where available and applicable. The details for the network are as detailed below.

2.3.1 External Grid

The external grid is modelled as follows:

- Short circuit rating 100 MVA
- X/R ratio 10

2.3.2 Busbars

Bus 1 and bus 5 are rated at 11 kV, the remaining buses (2–4) are rated at 33 kV.

2.3.3 Transformers

The 33/11 kV transformer connected to buses 1 and 2 is modelled as follows:

- Rating 5 MVA
- Vector configuration Dy11
- Resistance 0.011 pu
- Reactance 0.15 pu

The 11/0.4 kV transformer connected to buses 1 and 5 is modelled as follows:

- Rating 0.63 MVA
- Vector configuration Yyn0
- Resistance 0.0102 pu *(entered as short circuit voltage of*
- Reactance 0.0387 pu *4% with copper losses of 6.4 kW)*

2.3.4 Lines

The 33 kV lines have the following parameters:

- Resistance 0.0762 Ω km^{-1}
- Reactance 0.1382 Ω km^{-1}
- Susceptance 59.690 μS km^{-1}
- Length 20 km (bus 2–3)
  10 km (bus 2–4)
  10 km (bus 3–4)

2.3.5 Synchronous Machine

The synchronous machine has the following parameters:

Rotor Type	Salient pole	X_d''	0.168 pu
S_{rated}	4.855 MVA	X_q''	0.184 pu
R_{stator}	0.0504 pu	T_d'	0.53 s
$X_{leakage}$	0.1 pu	T_d''	0.03 s
X_d	1.5 pu	T_q''	0.03 s
X_q	0.75 pu	H (rated to S_{rated})	2 s
X_d'	0.256 pu		

The machine is excited using a simple manual (i.e. constant) excitation voltage. It delivers 3.5 MW to the network at an inductive (lagging) power factor of 0.95.

2.3.6 Induction Machine

The induction machine has the following parameters:

Rotor Type	Double cage	Rotor Leak. React.	0.01 pu
P_{rated}	300 kW	Running Cage Res.	0.00754 pu
V_{rated}	0.415 kV	Running Cage React.	0.2269 pu
Rated speed	1490 rpm	Starting Cage Res.	0.1358 pu
Stator Resistance	0.0318 pu	Starting Cage React.	0.1629 pu
Stator Reactance	0.01 pu	Inertia constant	0.8529 s
Mag. Reactance	2.957 pu		

The machine operates at an active power load of 0.25 MW and a power factor of 0.8 (lagging).

Note that the induction machine is not normally connected to the network. It is connected only for the studies presented in Section 4.4.

2.3.7 Loads

Only one local load is modelled as the external grid acts as a load. This load is located at bus 5 and is switched in (under steady state conditions) when the induction machine is not in service (and therefore not being investigated). The load is identical to the demand of the induction machine (0.25 MW) and is modelled using an exponential static load model as described by (2.1) and (2.2).

$$P = P_0(V/V_0)^{1.6} \quad \textbf{(2.1)}$$

$$Q = Q_0(V/V_0)^{1.8} \quad \textbf{(2.2)}$$

In (2.1) and (2.2), P and Q are the active and reactive components of the load when the bus voltage magnitude is V. The subscript 0 is used to designate the variable values at the initial operating condition.

2.4 Summary

- The network and all modelled components have been described and their parameters fully stated.
- This network model has been agreed with ENW as suitable for the studies being performed.

3

Advanced Voltage Regulation of Electric Machines

3.1 Introduction and Scope

This section briefly outlines the theoretical background behind the use of advanced excitation control to limit machine fault current contribution during faults. The idea of actively discharging the machine flux during faults is recently proposed in [1] where it is investigated analytically and it is demonstrated to be potentially very effective in reducing fault current contribution of the machine during the fault. The reader is directed towards this reference for further information relating to this approach.

3.2 Standard Excitation

A simplified diagram outlining the standard excitation of synchronous machines is shown as Figure 3-1. The process when a fault occurs is demonstrated by the diagrams in Figure 3-2 to Figure 3-4. It is evident that the fault current contribution of the machine is driven by the flux linkage. This is partially maintained by the excitation voltage during the fault.

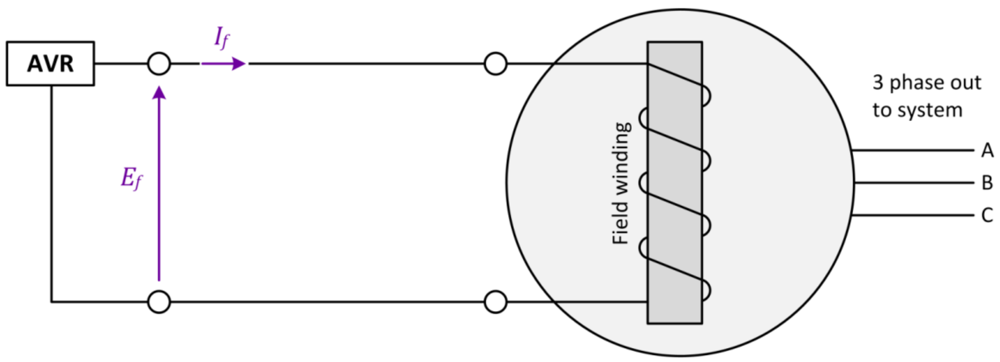


Figure 3-1: Standard excitation of a synchronous machine.

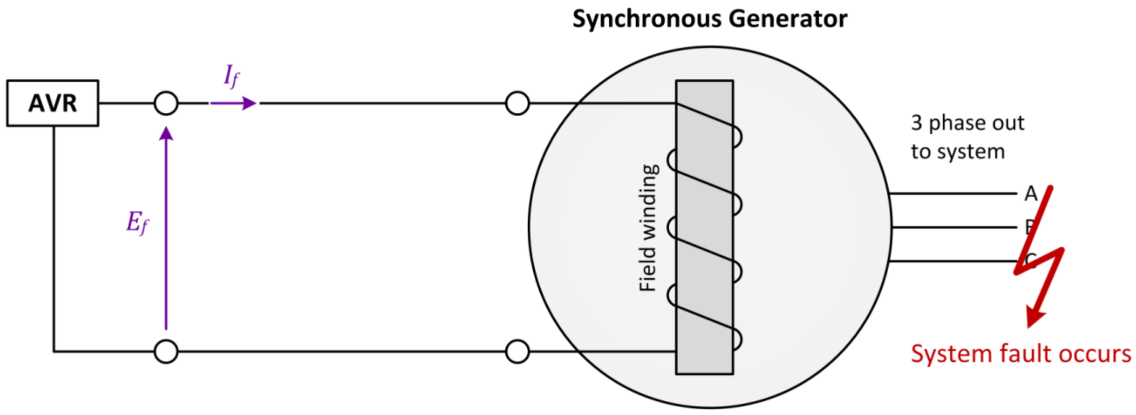


Figure 3-2: Standard excitation – a fault occurs.

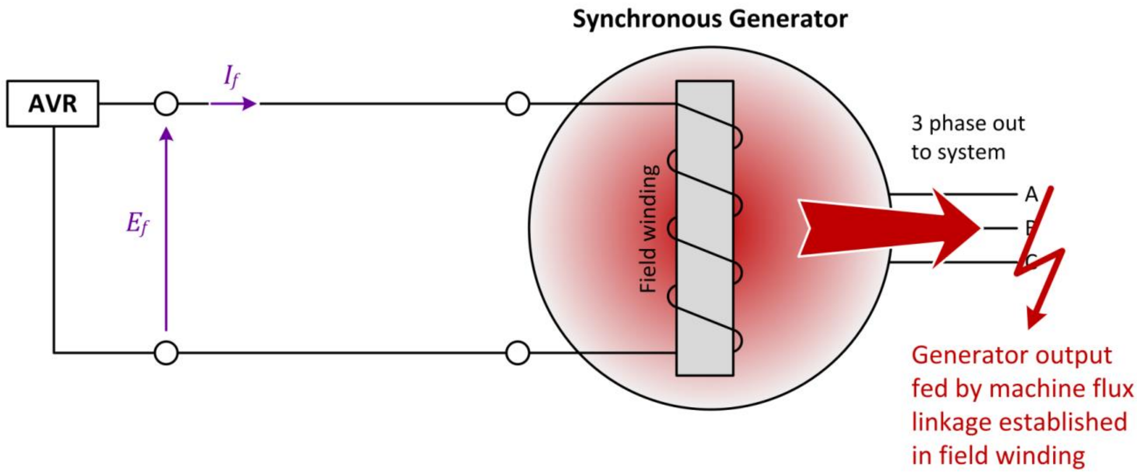


Figure 3-3: Standard excitation – feeding the fault.

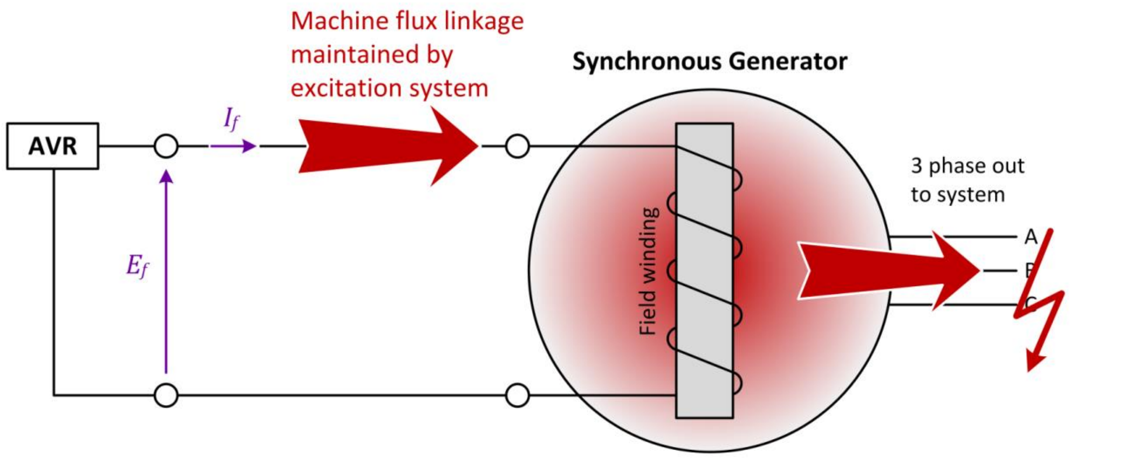


Figure 3-4: Standard excitation – maintaining the machine flux linkage.

3.3 Passive Flux Discharge

Passive flux discharge (also referred to as excitation disconnection) aims to reduce the machine fault contribution by stopping the excitation system from maintaining the flux linkage. To achieve this, a switch is added to the system as shown in Figure 3-5. Practically, this switch would be a solid state device capable opening very quickly when a fault is detected. The installation and design of this switch are beyond the scope of this report.

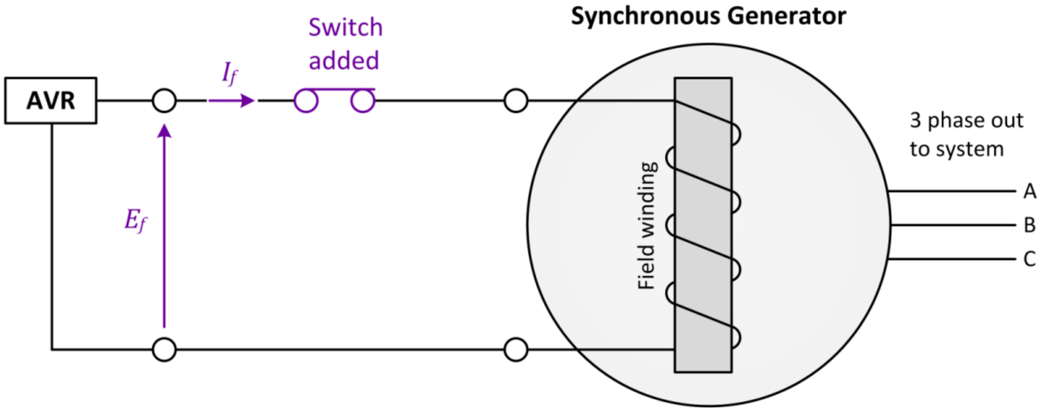


Figure 3-5: Passive flux discharge diagram for synchronous machine.

The new process when a fault occurs is demonstrated by Figure 3-6 and Figure 3-7. When fault conditions are detected, the switch opens and the excitation voltage is removed. This causes the flux linkage in the field windings to naturally discharge, resulting in a faster decay in fault contribution from the machine.

It should be noted that even with standard excitation the flux linkage will discharge. However this process is much slower as the excitation system acts to maintain the machine flux.

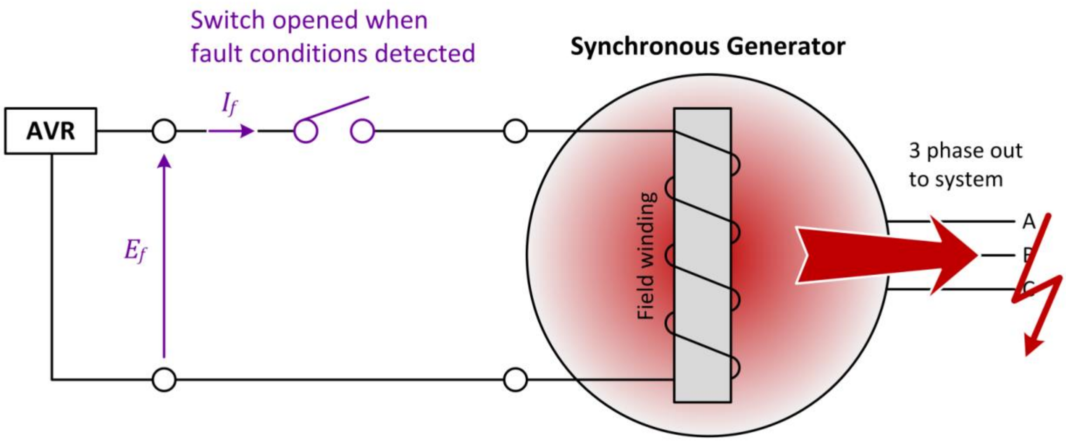


Figure 3-6: Passive flux discharge – switch opens when fault is detected.

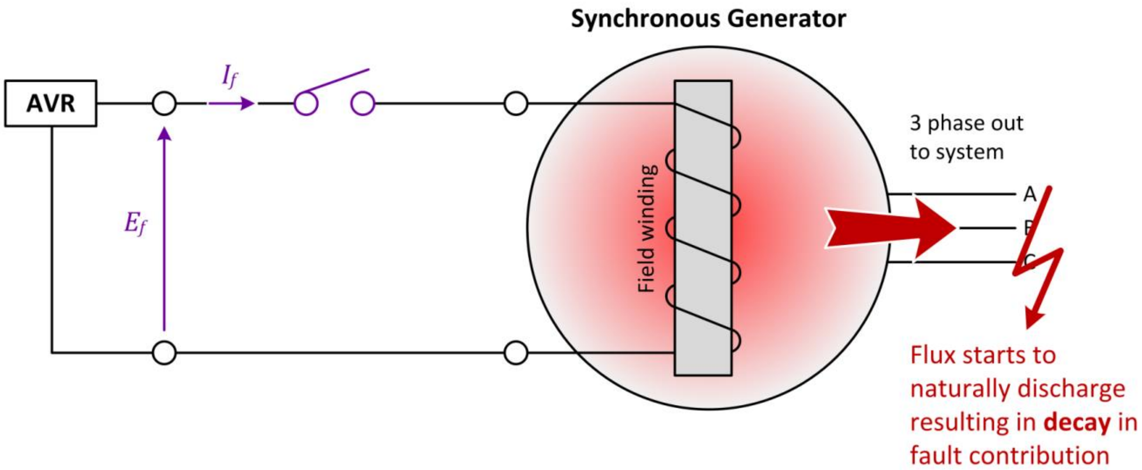


Figure 3-7: Passive flux discharge – flux discharges during fault.

3.3.1 Modelling Passive Flux Discharge

For simulations, modelling of passive flux discharge can easily be achieved by setting the excitation voltage E_f to zero when disconnection occurs. The excitation voltage is a standard machine input and as such is available for control in all standard power system software packages (including DIgSILENT PowerFactory).

3.4 Active Flux Discharge

With *active flux discharge*, not only is a switch added to remove the excitation voltage during faults (as with *passive discharge*) but an additional switch and resistance are added as shown in Figure 3-8. The aim of this additional branch is to be switched in during faults (at the same instance that the excitation system is disconnected) in order to place additional resistance in series with the field winding. The installation and design of this additional switch are beyond the scope of this report.

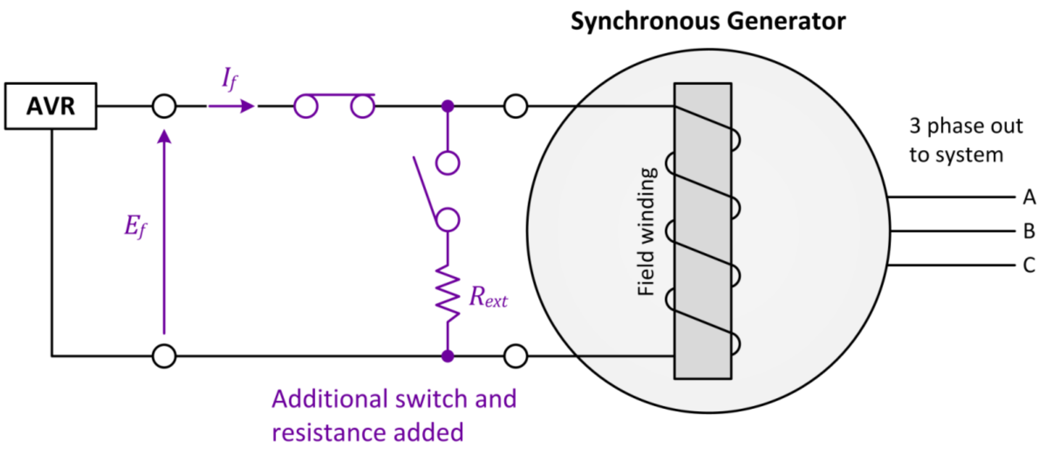


Figure 3-8: Active flux discharge diagram for synchronous machine.

The process when a fault occurs is demonstrated in Figure 3-9 and Figure 3-10. The new resistance R_{ext} causes a greater discharge of the flux resulting in an even faster decay in fault current contribution from the synchronous machine.

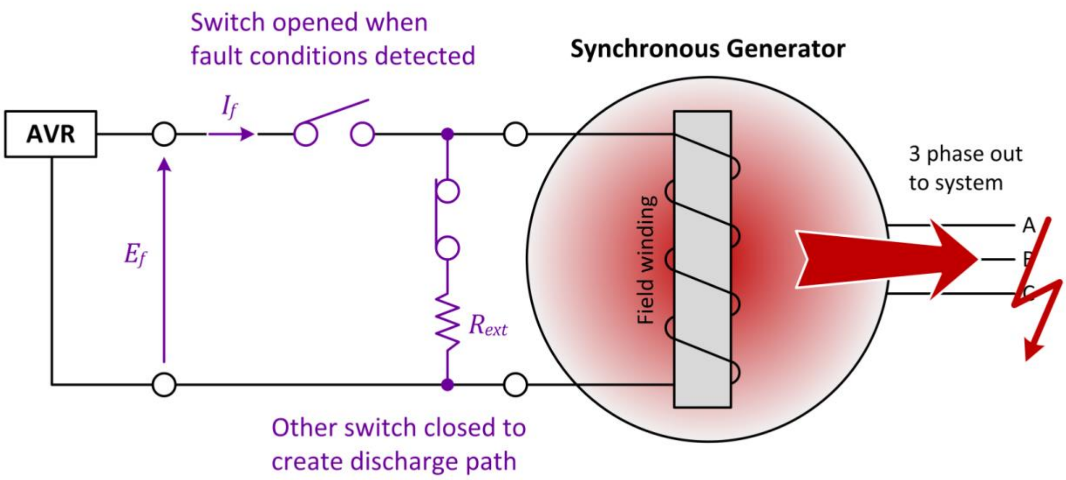


Figure 3-9: Active flux discharge – switches operate when fault is detected.

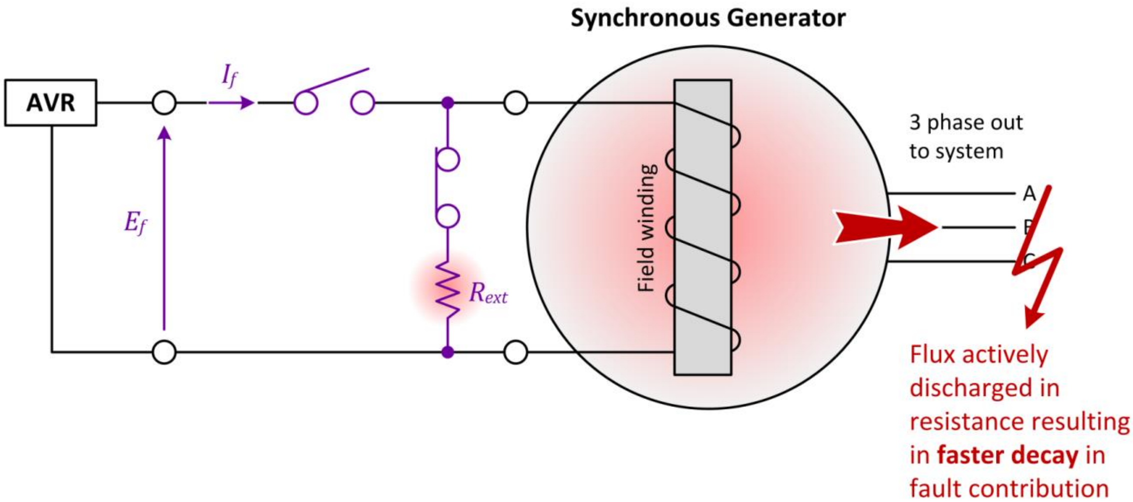


Figure 3-10: Active flux discharge – flux discharges in external resistance during fault.

3.4.1 Modelling Active Flux Discharge

It is not possible to directly model active flux discharge as the required parameters are not available for editing in commercially available power system software. This is the case in DIgSILENT PowerFactory where the internal machine circuits and components (including the field winding resistance R_f) cannot be accessed.

The effect of this active (or forced) flux discharge however can be emulated to a large extent in simulations by dividing the *d-axis* transient time constant ($T_d{}'$ or $T_{do}{}'$) by a k factor. This factor relates to the size of the additional resistance as a proportion of the original field winding resistance R_f according to (3.1).

$$k = \frac{(R_f + R_{ext})}{R_f} \tag{3.1}$$

For example, a k factor of 2 means that the new resistance $(R_f + R_{ext})$ is twice the original winding resistance R_f, and is equivalent to halving the *d-axis* transient time constant. The *open circuit d-axis transient time constant* describes the decay of the field current and is given by (3.2) in which L_f is the field winding inductance.

$$T_{d0}' = \frac{L_f}{R_f} \tag{3.2}$$

It should be noted that this emulation is not possible using most power system software as it is typically not possible to alter machine characteristic parameters (such as time constants) during the middle of a transient simulation. For the purpose of this study, a more flexible, dedicated model, had been developed using Matlab/Simulink in order to overcome this limitation. The model of synchronous generator used is of lower order (a fifth order model compared to full eight order model of synchronous machine available in DigSUILENT/Powerfactory) which does not display the very fast dynamics at the instant of fault occurrence (electromagnetic transients) however it is still sufficiently accurate to represent qualitatively the phenomenon of interest.

3.5 Summary

- Descriptions have been provided to explain the way in which the fault current contribution from a synchronous machine is affected by the excitation system and how it can be manipulated by changing the excitation circuitry.
- The alterations required to enable passive and active flux discharge have been described at a high level, however precise details relating to the practical implementation of such schemes has not been given and is outside the scope of this project.
- It should be noted that the modified schemes (passive and active flux discharge) will not affect the steady state flux linkage within the machine and therefore will not affect the fault contribution at the instant of occurrence (as is shown in the studies presented later). This flux linkage is dependent on the machine parameters and operating point.
- Details have been provided relating to the modelling of the different excitation schemes and how software limitations have been overcome through additional model development.

4

Simulation Results & Discussion

4.1 Introduction and Scope

The previous two chapters have outlined the network used for the studies into fault level management using advanced machine excitation and the theoretical basis for the modifications suggested. This chapter describes the results that have been obtained and their relation to the previously presented theory. These results enable a quantification of the level of fault current reduction that is possible using advanced voltage regulation.

Simulations have been performed using DIgSILENT PowerFactory version 15.0 in all cases other than those presented in Section 4.3 (Active Flux Discharge) for which Matlab/Simulink was used.

4.2 Passive Flux Discharge (Excitation Disconnection)

Passive flux discharge has been investigated by simulating a three phase fault at Bus 4 (as shown previously in Figure 2-1). This fault is maintained for a period of 1 s. The resulting three phase machine currents when standard constant excitation (i.e. no excitation disconnection) is used are shown as Figure 4-1.

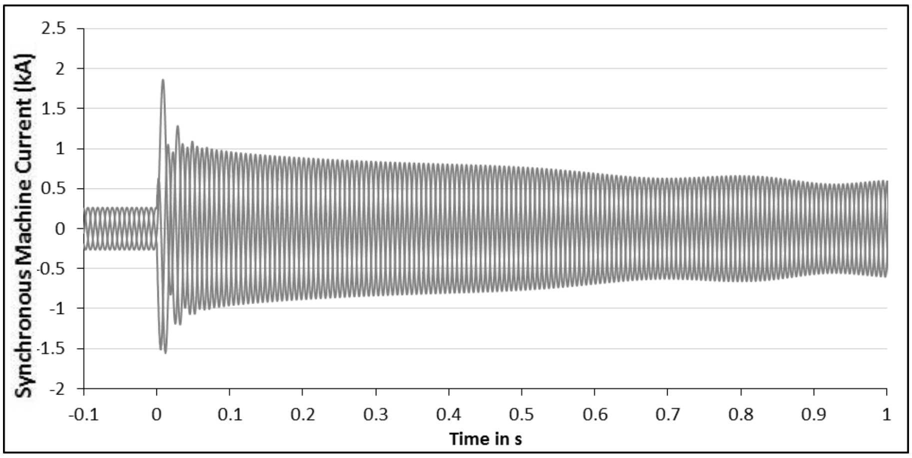


Figure 4-1: Three phase synchronous generator current during a 1 s fault.

It is noted that a 1 s fault represents a ***very extreme*** *case in typical fault studies and that faults would typically be cleared much faster (around 80–150 ms for severe, or transmission level, faults). In distribution systems though, it is possible to have faults lasting 1 s or even slightly longer. However, the during fault behaviour (currents, voltages, machine angles, etc) for a shorter (say 200 ms) fault is same as for the first 200 ms of a 1 s fault. Therefore, all the required information and detail can be obtained by simulating a single long(er) lasting fault.*

The waveform in Figure 4-1 represents the base case scenario against which the performance of different disconnection schemes will be assessed. By zooming into the first 500 ms of the fault and marking the extreme value (maximum value of current) for each individual phase current one can produce Figure 4-2. It is clear that the different phase currents do not display the same *during fault* behaviour due to different flux linkage at the instant of fault (as discussed in the Appendix).

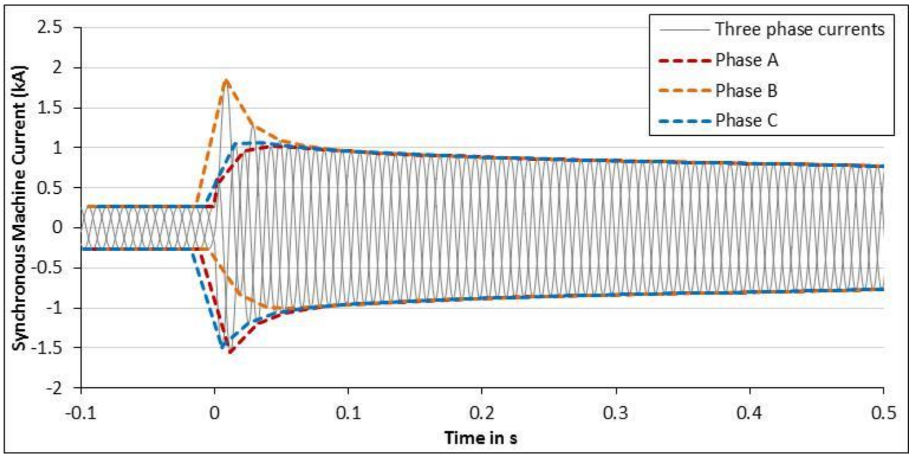


Figure 4-2: Generator currents with no disconnection – zoom of first 500 ms.

Excitation disconnection is introduced 10 ms after the fault occurrence. This would be possible using very fast dedicated (typically solid state) switches. Figure 4-3 displays the extremem (maximum) positive values (as traced previously in Figure 4-2) for phase A only with the introduction of excitation disconnection. Three lengths of disconnection have been considered in this example: 50 ms, 100 ms, and 200 ms. It is clearly evident that the *passive flux discharge* scheme results in some reduction in the machine current magnitudes, but only after approximately 50 ms from the fault instant.

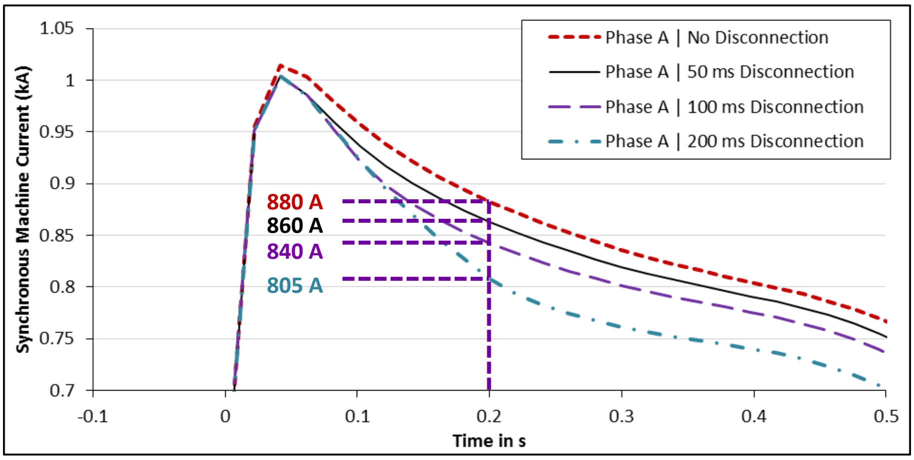
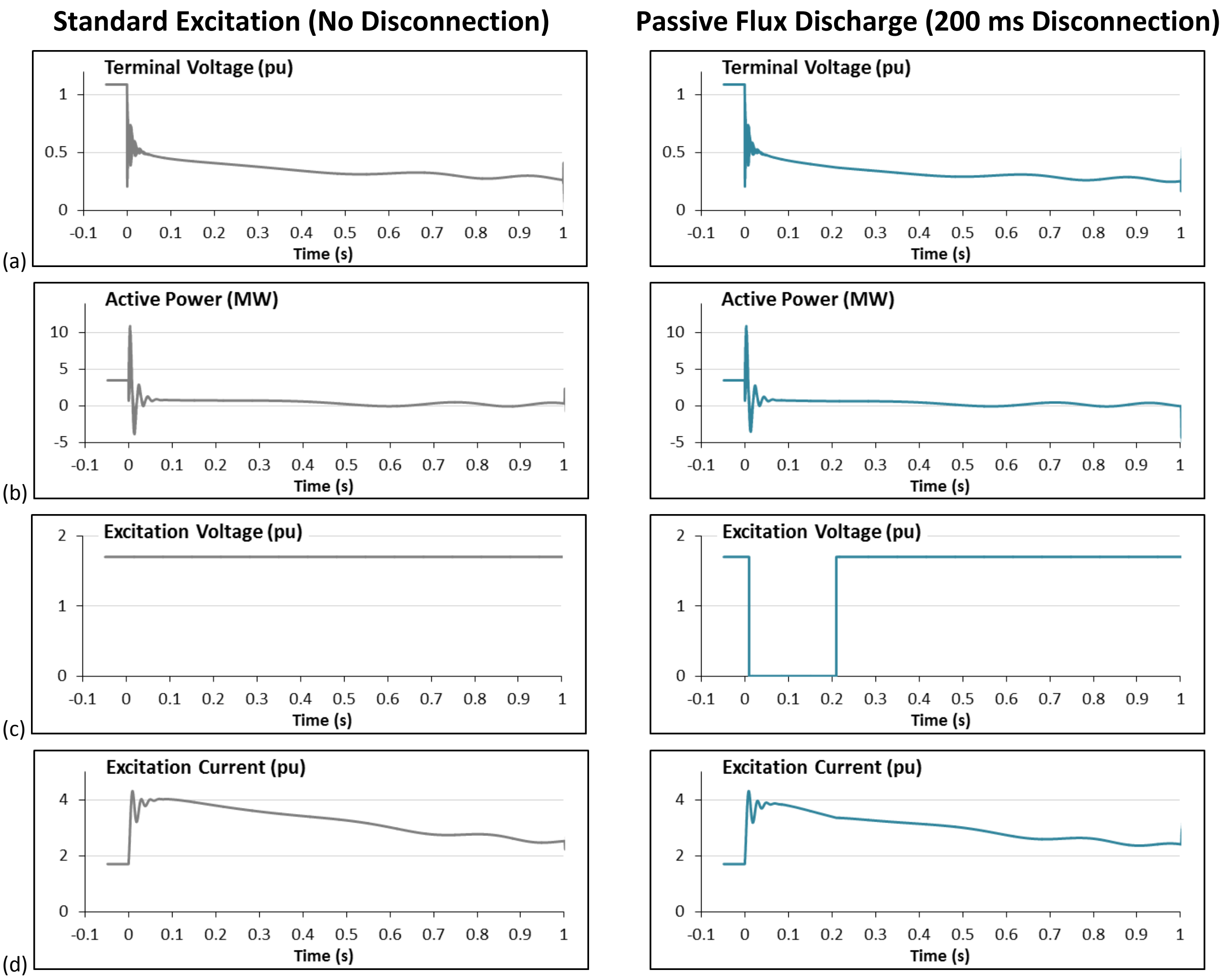


Figure 4-3: Generator currents with varying lengths of excitation disconnection – phase A extreme positive values.

It must also be noted that the scale of the *y-axis* (vertical axis) has been zoomed considerably and that the highest level of reduction is equal to approximately 75 A (or 8.5% of the fault current at *no disconnection* case) after 200 ms – when disconnection lasting 200 ms is implemented. With respect to the rated current output of the machine (378 A peak), this reduction equates to 19.8% of rated current.



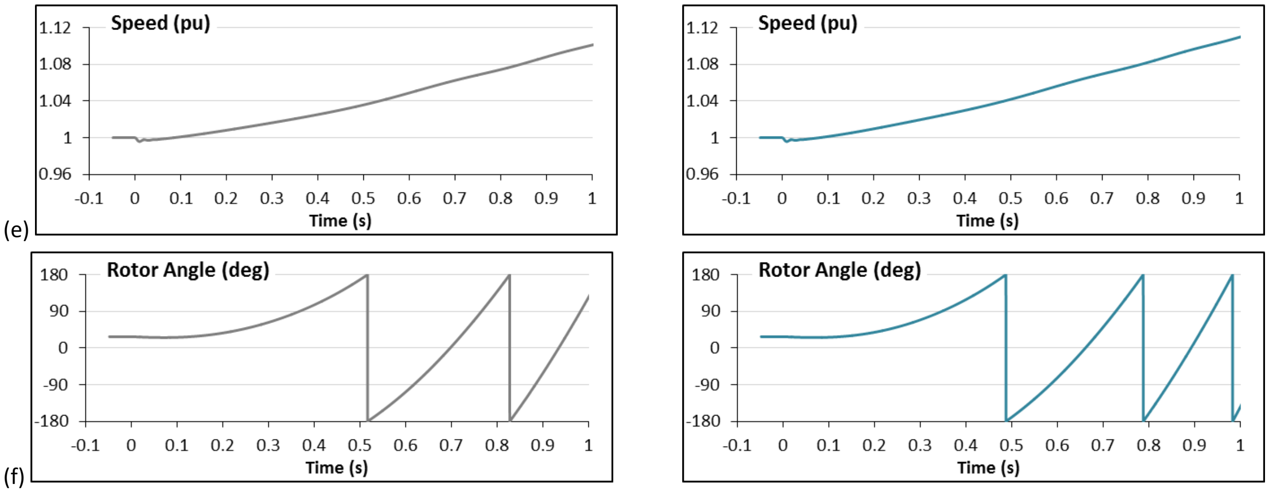


Figure 4-4: Generator outputs during three phase network fault with no disconnection and with 200 ms disconnection of the excitation voltage. Parameters shown are (a) terminal voltage, (b) active power, (c) excitation voltage, (d) excitation current, (e) speed, and (f) rotor angle.

In addition to the machine currents, additional machine outputs have been monitored during these simulations, specifically:

- Terminal voltage
- Active power
- Excitation voltage
- Excitation current
- Speed
- Rotor angle

These parameters have been plotted with no disconnection and with disconnection of the generator excitation system at 200 ms after the fault in Figure 4-4. The simulation of the excitation disconnection is clear where the excitation voltage can be seen to drop to zero (third figure from the top in second column) for a period of 200 ms. It is also evident (albeit only slightly) that the excitation current drops slightly faster during the fault with disconnection. However, this difference is only small, hence the small level of fault current reduction seen.

By focussing on different time periods during the fault, the effects of disconnection can be more thoroughly quantified.

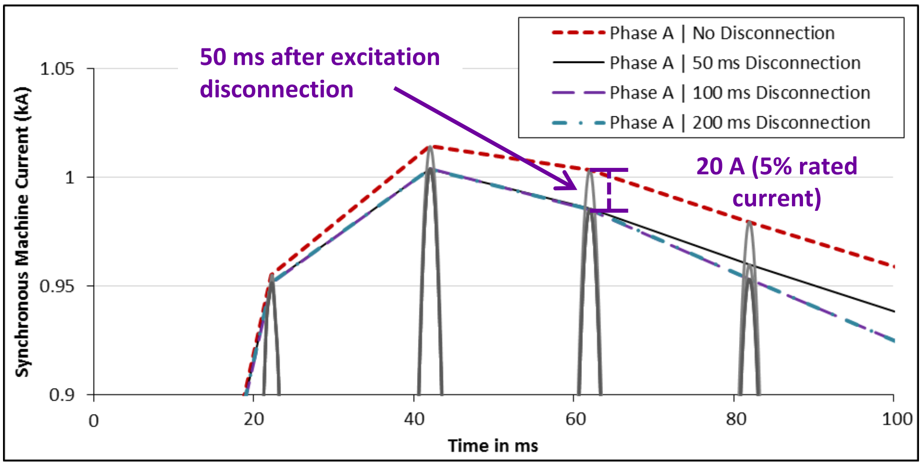


Figure 4-5: Generator currents with excitation disconnection – phase A extreme positive values, 0–100 ms.

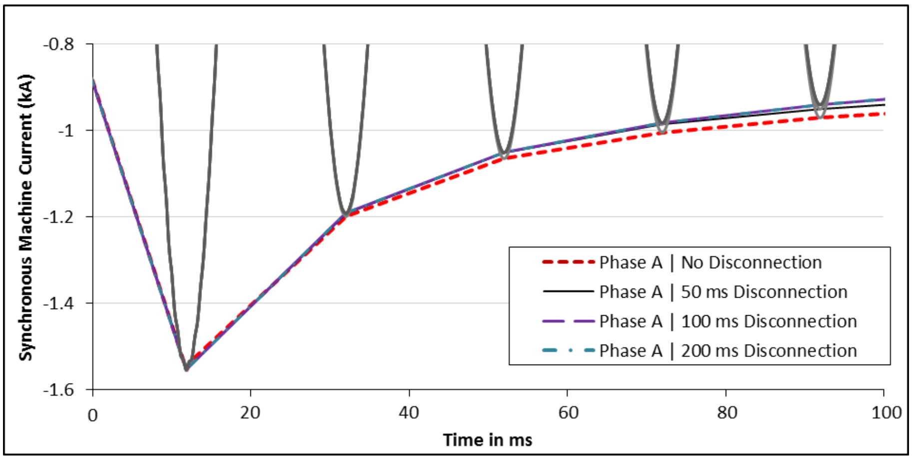


Figure 4-6: Generator currents with excitation disconnection – phase A extreme negative values, 0–100 ms.

Figure 4-5 and Figure 4-6 show the phase A for first 100 ms during the fault (both positive and negative extreme values). The point at which the excitation disconnection begins to have an effect is more clearly evident in this plot where it can be seen that reductions in fault contribution begin approximately 40 ms after the fault (30 ms after the disconnection begins). By 60 ms after the fault occurrence (50 ms after the excitation disconnection), a reduction of 20 A is obtained. This relates to just 5% of rated current or less than 2% of *base case* (no disconnection) fault current value. It is clear from Figure 4-6 that there is no reduction in the peak extreme negative value (the first cycle value) and a negligible difference by the second cycle peak.

Figure 4-7 and Figure 4-8 show the same positive and negative extreme values for phase A but for the period of 300–400 ms. It can be seen that by this point (further into the fault duration), greater reductions in fault current are seen, equal to between 65–75 A. However, it should be noted that in most instances, faults will be cleared before this period is reached, and so these benefits may not be experienced.

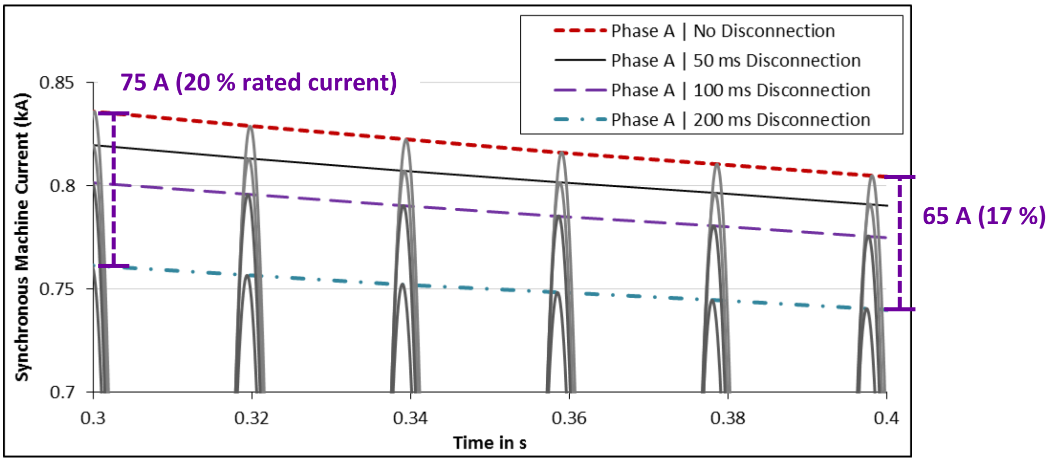


Figure 4-7: Generator currents with excitation disconnection – phase A extreme positive values, 300–400 ms.

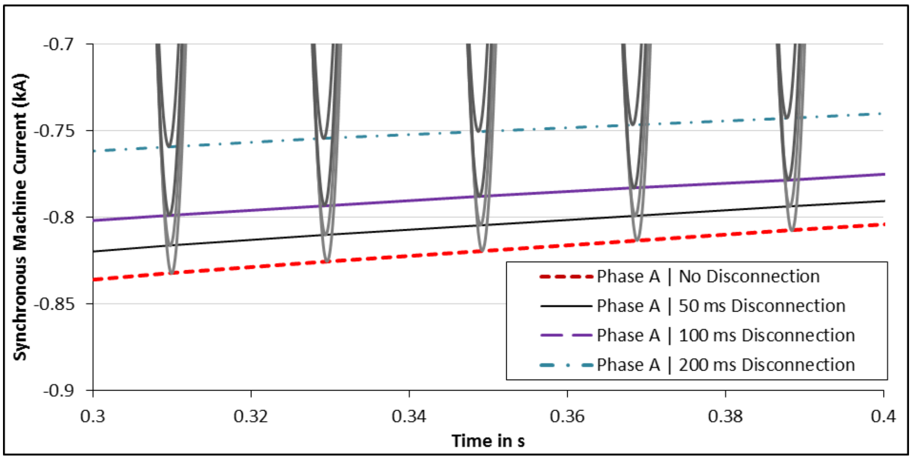


Figure 4-8: Generator currents with excitation disconnection – phase A extreme positive values, 300–400 ms.

Similar reductions are seen across all phases as briefly demonstrated by Figure 4-9 and Figure 4-10 in which phase B and phase C extreme peak values are plotted. In all cases (as expected), the longer the excitation system is disconnected, the greater the level of passive flux decay and therefore the large the reduction in fault current contribution. However, as shown previously in Figure 4-4(f) and discussed in the Appendix, disconnection of the excitation system, especially during longer lasting faults, may lead to machine losing synchronism with the rest of the network. Therefore the length of disconnection must be carefully considered.

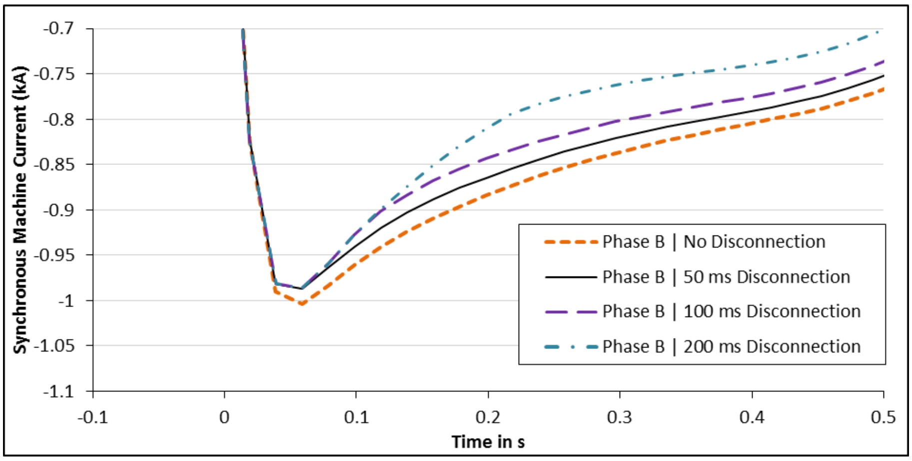


Figure 4-9: Generator currents with excitation disconnection – phase B extreme negative values, 0–500 ms.

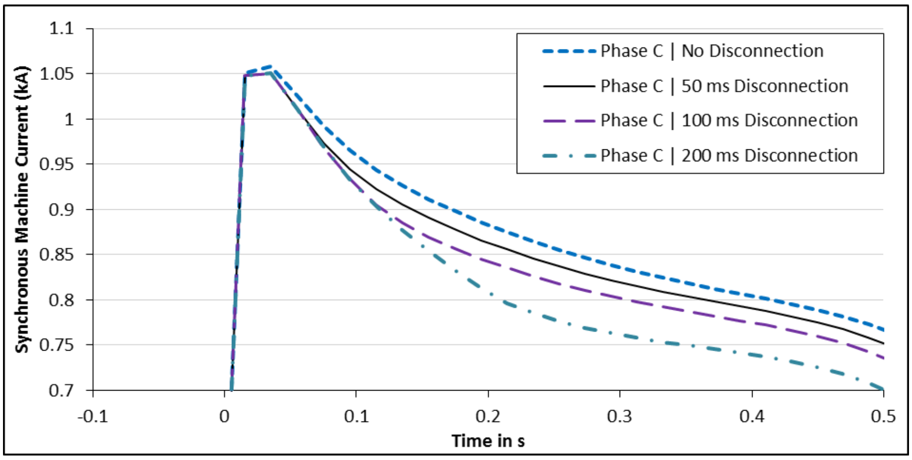


Figure 4-10: Generator currents with excitation disconnection – phase C extreme positive values, 0–500 ms.

4.2.1 Passive Flux Discharge Summary

Passive flux discharge has been demonstrated through simulations to be a feasible method of reducing fault current contribution of synchronous machines. It has been seen that small reductions (up to approximately 8.5% of *base case* values) can be obtained for individual phases, with greater reductions seen the longer the excitation system is disconnected. As previously discussed, no improvement is made to the first peak, and only very small reductions are made within the first 50 ms (the most severe fault period).

4.2.2 11 kV Fault Example

At the request of ENW, additional studies relating to passive flux discharge have been performed on a slightly modified network model to demonstrate the effect of 11Kv faults.

4.2.2.1 Network Modifications

The modified network is shown at a high level in Figure 4-11 in which the portion of the network relating to the induction machine has been neglected for simplicity. The modification consists of the addition of a double 11 kV circuit connecting the distributed synchronous generator to the original 11 kV bus (bus 1 in Figure 2-1). For these additional studies, faults are located at a new bus halfway along one of these parallel 11 kV circuits (as clearly shown in Figure 4-11).

The aim of these studies was to validate the previously obtained results for situations when the fault occurs on an 11 kV portion of network (rather than on a 33 kV portion as previously simulated).

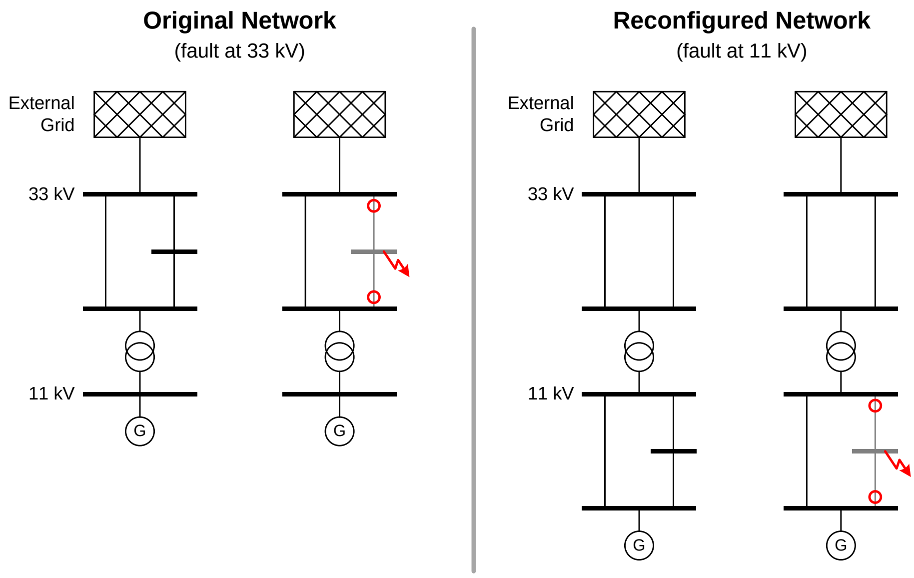


Figure 4-11: Network models for the original system and the reconfigured '11 kV fault' system.

Each line in the double 11 kV circuit has the following parameters:

- Resistance 0.1556 Ω km^{-1}
- Reactance 0.1194 Ω km^{-1}
- Susceptance 75.398 μS km^{-1}
- Length 5 km

4.2.2.2 Simulation Results

The simulation results are not analysed to the same level of scrutiny as previously as the aim is simply to validate that excitation disconnection has the same effect when the fault is more severe (i.e. on the 11 kV network and therefore closer to the generator).

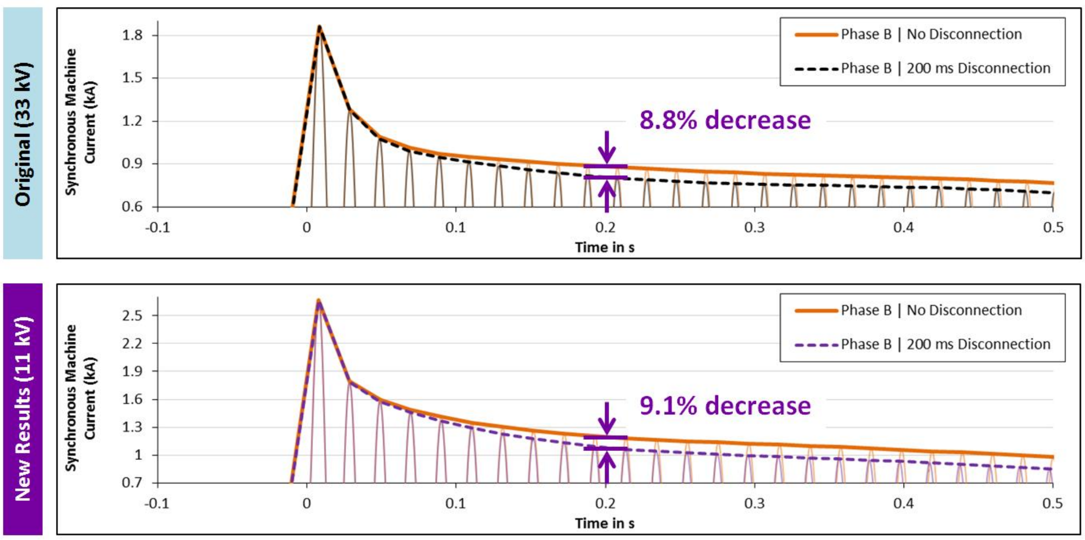


Figure 4-12: Generator currents with excitation disconnection for original network and reconfigured with fault on 11 kV bus – phase B extreme positive values, 0–500 ms.

Figure 4-12 displays the generator current extreme positive peak values for phase B (the worst performing phase) for both network configurations. The shape of the traces is clearly the same (despite the more severe fault, note the difference in axis scaling and higher values of peak fault current in case of 11kV fault due to the fault proximity to the generator). It can be seen that at a time of 200 ms after the fault, approximately the same level of reduction is achieved (9.1% for the 11 kV fault compared with 8.8% previously). Plotting the positive sequence currents (as in Figure 4-13) clearly reveals that there is no appreciable effect of excitation disconnection within the first 50 ms in either case (as has been previously demonstrated).

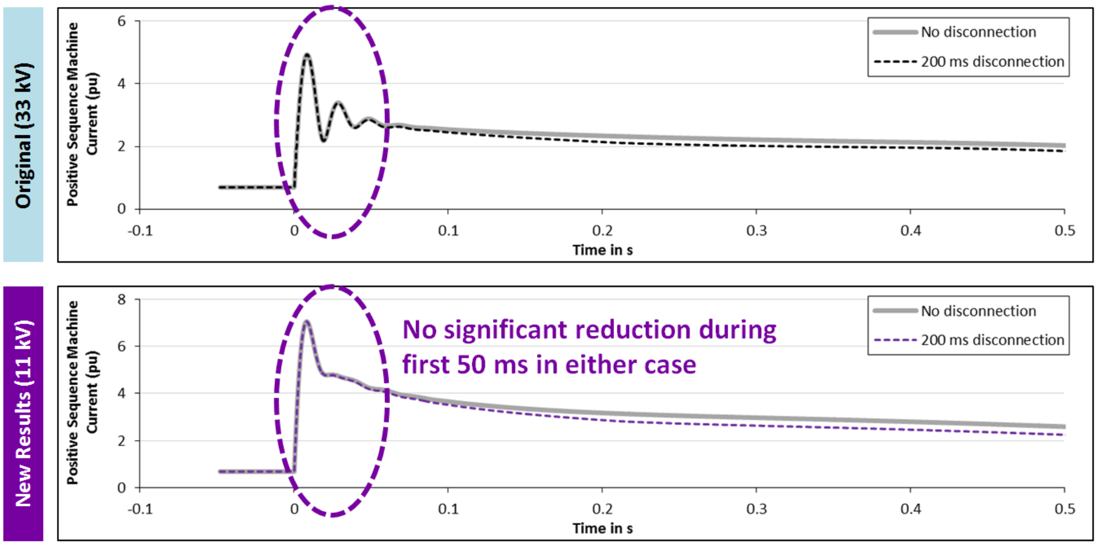


Figure 4-13: Generator positive sequence current with excitation disconnection for original network and reconfigured with fault on 11 kV bus, 0–500 ms.

The results from these simulations on the reconfigured network have demonstrated the validity and applicability of the previous conclusions about passive flux discharge to conditions caused by faults in different parts of the network.

4.3 Active Flux Discharge

Active flux discharge has been modelled using the reconfigured 11 kV fault network and using a three phase fault at the bus located in the middle of one of the 11 kV lines (as shown in Figure 4-11). As previously discussed in Section 3.4.1, it is not possible to model active flux discharge using conventional (commercial) power system analysis software as the required parameters and inputs are not available to access (let alone change during simulations).

To overcome this, the network model has been developed in the Matlab/Simulink environment which allows more flexibility. The generator model is of fifth order (compared to the detailed eighth order model used in DIgSILENT PowerFactory) and does not display the fast dynamics (electromagnetic transients associated with stator windings) which are typically seen at the instant of fault occurrence. Nevertheless, the model is of sufficient detail to model the effects of active flux discharge as these effects would take place typically after several tens of miliseconds. It should also be noted that the model uses a positive sequence *direct-quadrature-zero* (*dq0*) axis machine representation, i.e., typical Park's model of synchronous machien (individual phases are not modelled and negative and zero sequences are neglected). In the plots shown within this section, phase currents are derived from the positive sequence current using the *dq0→abc* transformation.

4.3.1 Model Validation

As discussed above, a new model is used for these studies and so the first requirement is to validate the new model against the results previously obtained with the detailed DIgSILENT PowerFactory model.

Figure 4-14 shows the generator currents following the stated fault for both the detailed and simplified models. The results overlay each other almost perfectly – the only discrepancies being some initial fast dynamics at the instant of the fault occurrence (first 20-30 ms). It can be concluded that the simplified model is suitable for comparison with the previously obtained results.

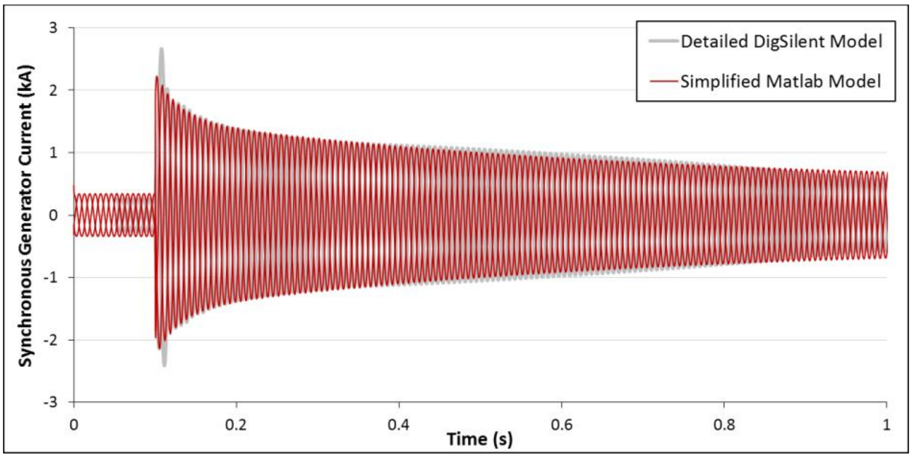


Figure 4-14: Validation of simplified Matlab generator model against detailed DIgSILENT model.

4.3.2 Simulation Results

The results obtained from the simulations are shown in Figure 4-15 to Figure 4-19. In all cases the advanced voltage regulation is engaged for 200 ms, starting 10 ms after the fault occurrence. Note that in these simulations the fault occurs at a time of 0.1 s (not 0 s as previously) and so the labelled points at 0.3 s correspond to 200 ms after the fault occurs (as before).

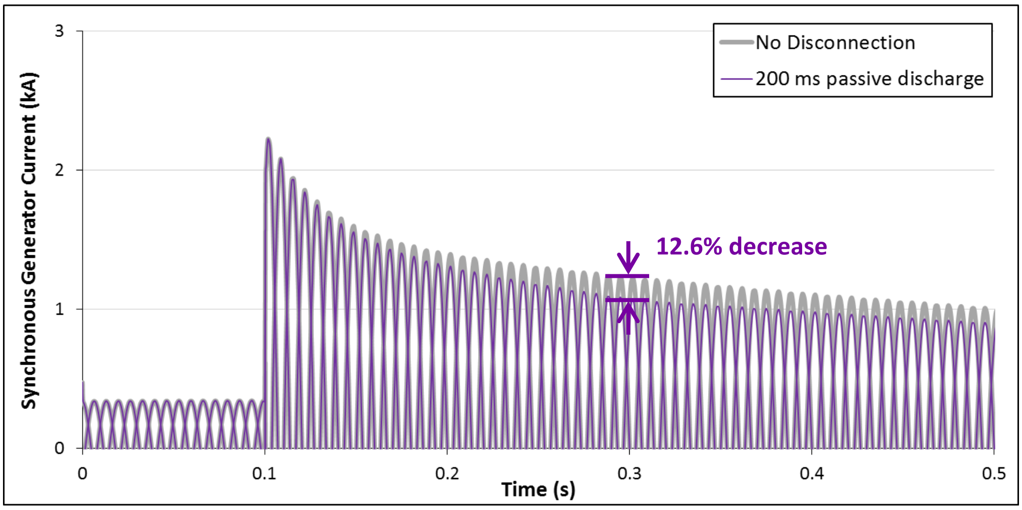


Figure 4-15: Simplified generator model - passive flux discharge.

Figure 4-15 displays the results of passive flux discharge using the new model which results in slightly higher reductions than seen previously using the more detailed model. It is important (when looking at Figure 4-16 to Figure 4-19) to note the relative improvement that *active* discharge can have compared to this *passive* result.

In Figure 4-16 to Figure 4-19, the results are displayed with reference to the previously defined k factor – see (3.1) in Section 3.4.1. It is clear that as the k factor increases, the decay in fault contribution becomes very large – in one case reducing the fault current to pre-fault levels after 200 ms. However, it is evident that it is still not possible to affect the fault contribution in the first moments after the fault occurrence. The fault current may decay rapidly, but the peak values remain the same.

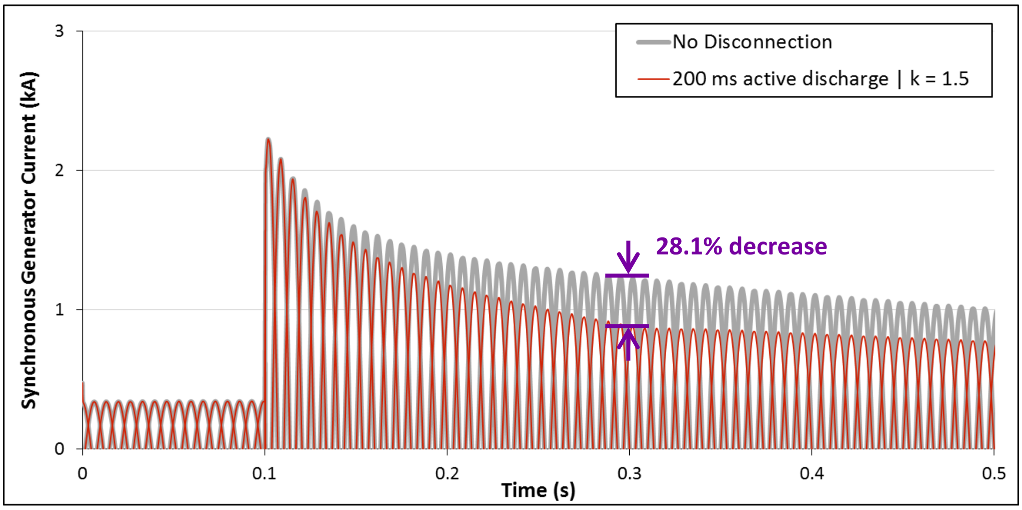


Figure 4-16: Simplified generator model – active flux discharge, k = 1.5.

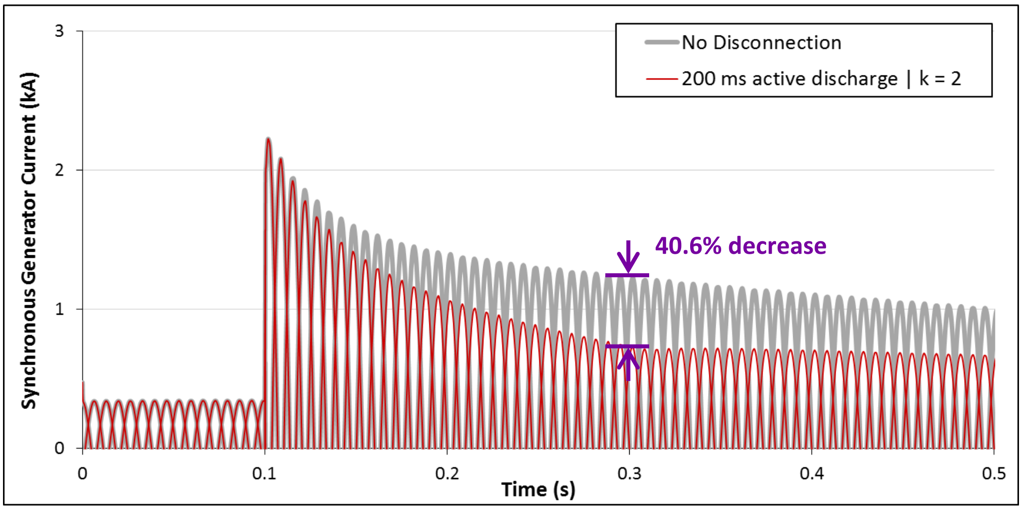


Figure 4-17: Simplified generator model – active flux discharge, k = 2.

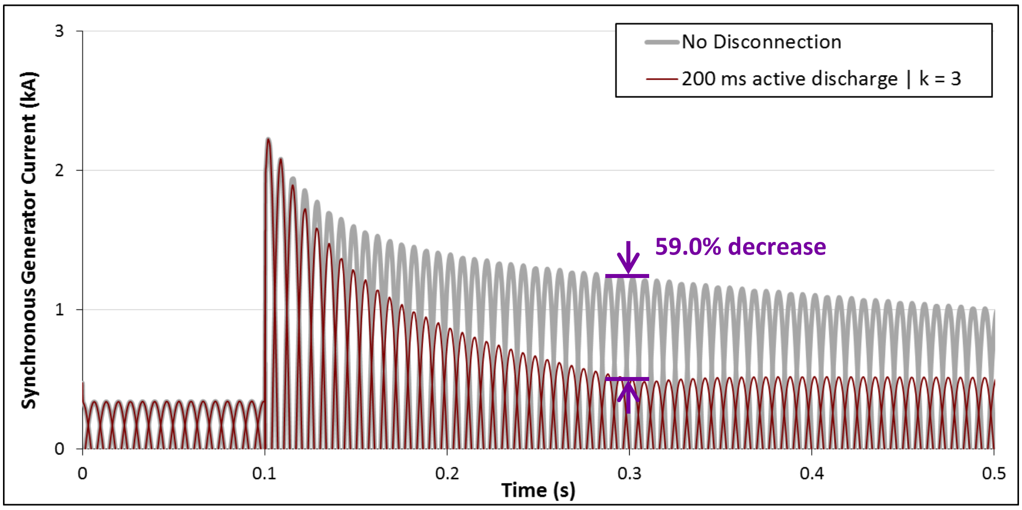


Figure 4-18: Simplified generator model – active flux discharge, k = 3.

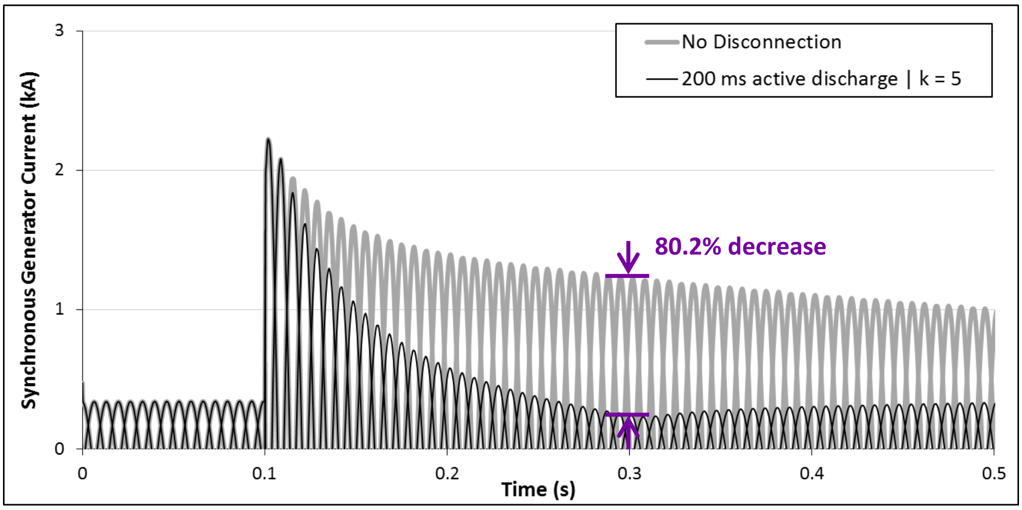


Figure 4-19: Simplified generator model – active flux discharge, k = 5.

It should also be acknowledged that (although not modelled here) the use of high k factors results in overvoltages across the field winding at the instant that the additional external resistance is *switched in. As field windings are voltage-limited, any attempt to practically implement a scheme like this would require careful analysis to ensure that voltage limits are not exceeded otherwise generator damage may occur.*

4.3.3 Active Flux Discharge Summary

Active flux discharge has been shown to be a very effective method of rapidly reducing the fault current contribution of synchronous generators during faults. It is possible to make very large reductions of up to 80% (compared to no advanced voltage regulation) within a 200 ms period. However, it is still not possible to reduce the fault contribution in the first moments after the fault occurs – the magnitude of the first peaks will remain the same.

4.4 Comparing Synchronous Machines and Induction Machines

This section presents the results of comparison of the fault contribution of synchronous machines with that of induction machines. In order to complete this study, the test network has been modified slightly.

4.4.1 Network Modifications

A smaller synchronous generator is added to the network to replace the original 4.9 MVA unit. This smaller generator has the following properties:

- Rotor Type — Salient pole
- S_{rated} — 0.525 MVA
- R_{stator} — 0 pu
- $X_{leakage}$ — 0.06 pu
- X_d — 2.2 pu
- X_q — 1.45 pu
- $X_d{}'$ — 0.13 pu
- $X_d{}''$ — 0.09 pu
- $X_q{}''$ — 0.11 pu
- $T_d{}'$ — 1.56 s
- $T_d{}''$ — 0.033 s
- $T_q{}''$ — 0.033 s
- H (rated to S_{rated}) — 0.19 s

4.4.2 Simulation Results

The machine outputs following the original three phase fault on the bus in the middle of the 33 kV line are shown in Figure 4-20 and Figure 4-21. The results are presented in per unit (on the machine base) for more direct comparison. The synchronous machine is operated using standard constant excitation with no advanced voltage regulation scheme. It is clearly evident from both the three phase and positive sequence representations that the fault contribution from the induction machine is not as large, and decays very rapidly compared to the synchronous machine. After approximately 150 ms from the instant of fault occurrence, the induction machine current output has reduced to roughly nominal rated levels.

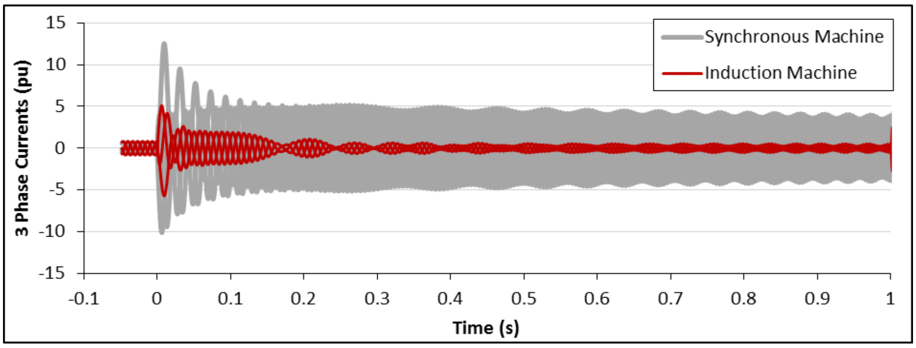


Figure 4-20: Comparing synchronous and induction machines – three phase currents.

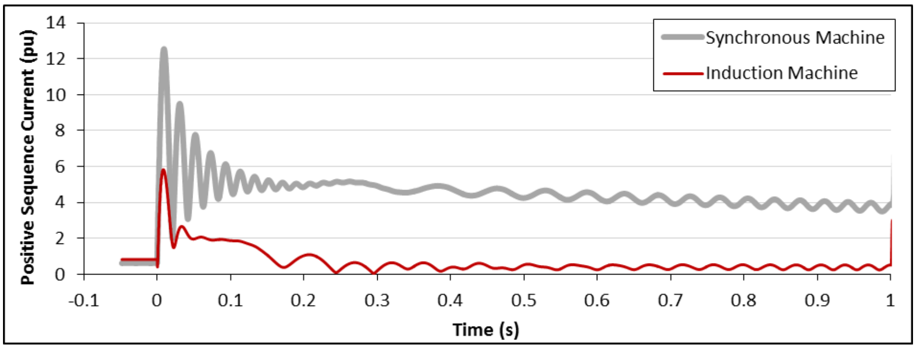


Figure 4-21: Comparing synchronous and induction machines – positive sequence currents.

The reason for the rapid decay in fault contribution from induction machines is revealed by Figure 4-22 in which the machine flux linkage (in pu) is shown. It can be seen that the flux in the induction machine very quickly decays during the fault whereas the decay within the synchronous machine is much slower. This vast difference means that it is synchronous machines which pose the greatest issue with respect to fault level contribution.

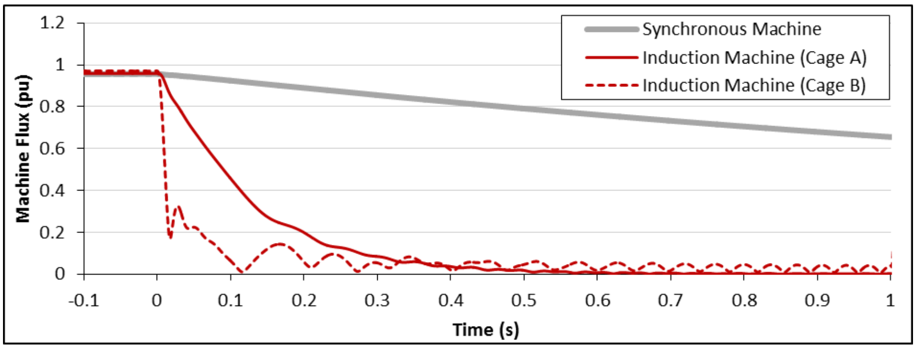


Figure 4-22: Comparing synchronous and induction machines – machine flux.

4.5 Machine Disconnection

A brief study investigating the effect of disconnecting the entire synchronous machine during fault conditions has been also completed. With the network in its original form (as described in Chapter 2 and shown in Figure 2-1) the synchronous machine is disconnected from the network 50 ms after the fault begins and is connected to a braking load (to ensure it does not over-speed).

Figure 4-23 and Figure 4-24 show the short circuit current at the faulted bus in the network during these studies. In the zoomed plot (Figure 4-24) it is clear that the disconnection of the machine results in the removal of the fault contribution by this machine (as expected).

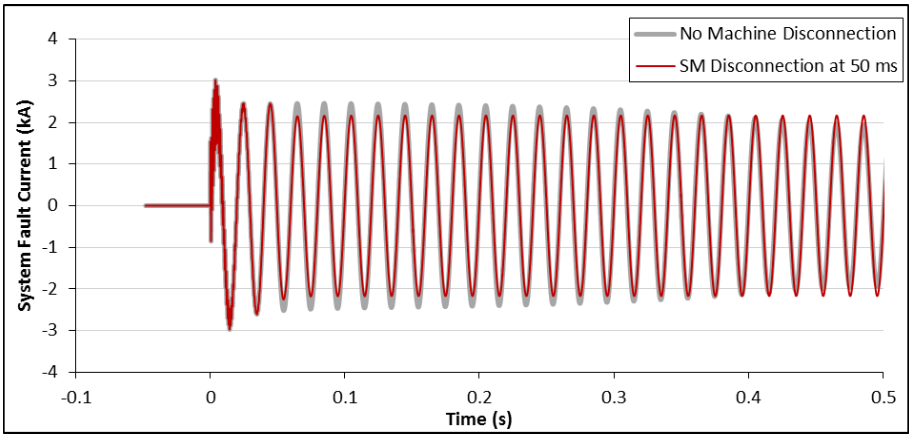


Figure 4-23: Synchronous machine disconnection – current at fault location.

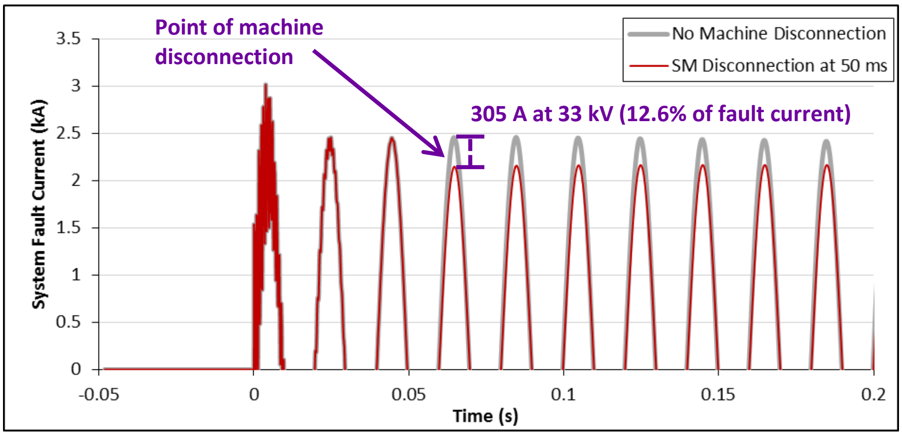


Figure 4-24: Synchronous machine disconnection – current at fault location (zoomed plot).

4.5.1 Machine Disconnection Summary

Disconnection of a synchronous machine will certainly remove any fault contribution. However, this requires circuit breakers in order to disconnect the machines, whereas flux discharge can be achieved using power electronics and advanced voltage regulation. This approach would be limited by the speed of disconnection and as before, will not be able to reduce the fault contribution at the first instant of the fault (when it is at its most severe). It also requires excellent protection coordination in order to connect the machine to the braking impedance.

4.6 Synchronous Motor Operation

Simulations have demonstrated that operating the synchronous machine as a motor (rather than as a generator) reduces the fault current contribution under otherwise identical conditions. This is shown in Figure 4-25 where this reduction is clearly visible. The disconnection of the excitation voltage in order to achieve passive flux discharge has a similar effect (in terms of proportional current reduction) as previously demonstrated in Section 4.2.

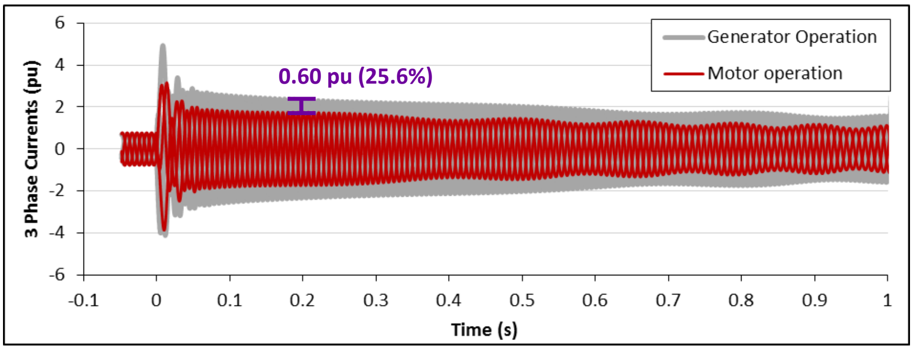


Figure 4-25: Synchronous machine operated as a motor – machine currents.

4.7 Protection Considerations (G59)

At the request of ENW, Engineering Recommendation G59 has been briefly reviewed in order to assess whether there are issues relating to the possible implementation of the advanced generator control schemes simulated within this project. The full title of the document is *Recommendations for the Connection of Generating Plant to the Distribution Systems of Licensed Distribution Network Operators*. Please note that Issue 3 (dated September 2013) was used.

Broadly, G59 does not appear to restrict the application of *machine* or *machine excitation* disconnection during fault conditions. It does, however, stipulate certain conditions when the machines should continue to operate in parallel (Section 9.3). Specifically, generating machines should continue to operate in parallel during over- and under-frequency conditions. If the machine is to be disconnected during a fault, it will need to be reconnected to the network *extremely promptly* following the fault clearance in order to avoid negatively affecting system performance.

Note that generating units will also be equipped with *Loss of Mains* protection which may potentially be exploited to disconnected and isolate machines.

4.8 Summary

- Two advanced voltage regulation schemes (passive and active flux discharge) have been simulated and tested to establish the extent to which they can reduce the fault current contribution from synchronous machines.
- It has been demonstrated that both schemes result in a decay of the machine fault current. However, neither scheme is able to reduce the fault current in the first instances following the fault occurrence (when the machine fault contribution is greatest).
- Active flux discharge results in much greater decay of the fault current contribution than the passive scheme. If the additional resistance is large enough, the fault current can reduce to below nominal rated current. However, the use of high additional resistance can potentially result in overvoltages on the filed windings which must be carefully considered and avoided.

- The fault contribution between synchronous and induction machines has been compared and contrasted. Induction machines contribute far less fault level and their contribution decays within 150-200 ms due to the fast decay of the machine flux.
- The effects of machine disconnection have been simulated, displaying the reduction in fault current that results. However, practical implementation of such a scheme is not trivial and will require excellent protection coordination.
- Engineering Recommendation G59 has been briefly reviewed in order to assess its implications for the application of advanced voltage regulation or machine disconnection. It does not appear to restrict application of the simulated approaches, however, it does stipulate conditions under which the machines should remain connected to the network.

5

Conclusions & Further Work

5.1 Conclusions

The study into investigation of fault level contribution and management of AC machines using representative generic distribution network started by providing a description of the way in which the fault current contribution from a synchronous machine is affected by the excitation system and how it can be manipulated by modifying the excitation system.

The initial studies focused on assessing the effect of excitation disconnection on fault current contribution by synchronous machine. It has been demonstrated that though this is a feasible method of reducing fault current contribution of synchronous machines a very small reductions (up to approximately 8.5% of *base case* values) can be obtained for individual phases, with greater reductions seen the longer the excitation system is disconnected. No improvement is made to the first peak of fault current and only very small reductions are made within the first 50 ms (the most severe fault period).

The alterations of the excitation system required to enable active flux discharge have been described at a high level, however precise details relating to the practical implementation of such a scheme has not been given as it was outside the scope of this project. The study provided details relating to the modelling of the different excitation schemes and how software limitations have been overcome through additional model development to facilitate simulation of active excitation flux discharge.

Active flux discharge has been shown to be a very effective method of rapidly reducing the fault current contribution of synchronous generators during faults. It is possible to make very large reductions of up to 80% (compared to no advanced voltage regulation) within a 200 ms period. However, it is still not possible to reduce the fault contribution in the first moments after the fault occurs – the magnitude of the first peaks will remain the same.

Though it has been demonstrated that both schemes result in a decay of the machine fault current, neither scheme is able to reduce the fault current in the first instances following the fault occurrence (when the machine fault contribution is greatest). Whichever excitation scheme (conventional, passive, or the recently proposed active flux discharge) is used, it will not affect the steady state flux linkage within the machine and therefore will not affect the fault contribution at the instant of fault occurrence. This flux linkage is dependent on the machine parameters and the operating point at the time of fault occurrence. Even though the active flux discharge results in much greater decay of the fault current contribution than the passive scheme (i.e., if the additional resistance is large enough, the fault current can reduce to below nominal rated current), the use of high additional resistance can potentially result in overvoltages on the field windings which must be carefully considered and avoided.

The effects of machine fast disconnection following the fault have been analysed as well. The fault current contribution by the machine in this case is also reduced; however, practical implementation of such a scheme is not trivial and will require excellent protection coordination.

The study also compared fault current contribution between synchronous and induction machines. It has been confirmed that Induction machines contribute far less to fault currents and their contribution decays within 150-200 ms due to the fast decay of the machine flux. If the synchronous machine is operated as a synchronous motor (rather than as a generator) its fault current contribution will be less than in case of operation as a generator. The disconnection of the excitation voltage in order to achieve passive flux discharge in this case has a similar effect (in terms of proportional current reduction) as in the case of operation as a generator.

Finally the study also briefly reviewed Engineering Recommendation G59 in order to assess its implications for the application of advanced voltage regulation or machine disconnection. It has been found that G59 does not appear to restrict application of the investigated approaches; however, it does stipulate conditions under which the machines should remain connected to the network.

5.2 Extensions & Further Work

The following areas of further work have been identified as potentially viable to facilitate active fault current management in distribution networks:

- Detailed study into potential reduction in fault current contribution for a subset of critical generators/machines in the distribution network including detailed modelling of machines and associated excitation systems. Machine disconnection and modification of excitation system should be considered in these studies including relevant protection coordination.

- Study of fault level contribution by rotating plant (synchronous and induction machines) in the network and optimal management of fault levels on network or part of the network basis. This would involve development of methodology for identification of fault current contribution by individual rotating plant, ranking of rotating plant based on fault level contribution and application of relevant mitigation devices/actions at optimal locations in the network to manage fault levels at pre-defined values.

6

Appendix

6.1 Comments on “Fault Level Management Query Document” (24 March 2014)

Electricity North West Limited is exploring methods of active fault level management as part of a Second Tier LCN Fund project for 2014/15.Our interest lies with synchronous generators connected at 11kV or 6.6kV in the distribution network, in the range 1-5MW, such as those utilised in Combined Heat & Power applications eg district heating. Ways of reducing earlier the generator’s fault contribution are being explored. We are interested in comparing the fault contribution of the generator with the excitation field de-energised, against the fault contribution with no intervention.

Query 1:

We wish to know the type of generator and its excitation in the range of interest. Please can you tell us of your understanding with regard to the existing population of generators and future generators.

JVM

I cannot comment on this. This information should be provided by manufactures and it would be very useful to get as much information as possible to facilitate “more realistic” simulation studies.

Query 2:

We suggest that it may be possible to stop quickly the fault current contribution of the generator by switching off the generator field current. It is expected that the field current would circulate through the rotating rectifier and decay over a short period. Please can you tell us of your understanding of the switching off of the DC field current of the existing population of generators.

JVM:

This would be unusual practice to say the least. Loss of excitation (LOE) is one of standard protections applied to synchronous machines. This is standard practice for large generators and that I am not sure whether similar practice, and if so to what extent, has been followed for generators rated below 5 MW, but I would think so. Generally, there are two types of excitation systems, rotating and static. Rotating system uses dc or ac generator as the sources and static system applies the rectifiers as sources which are directly fed from the generator terminals via a step-down transformer. Today, most excitation systems are ac or static types because of the fast response ability.

When a generator loses its excitation, the rotor current gradually decreases and the field voltage decays by the field time constant as well. In this case, the generator operates as an induction generator and draws reactive power from the power system instead of generating reactive power. (*Note:* When the generator reactive power output exceeds under exctitation limit (UEL) the alarm element will pick up after about 0.5s time delay. When the operating point falls into the operating region, loss of excitation (LOE) protection element will pick up and sent a trip signal after 0.75s time delay. If the operating point exceeds the UEL but stays outside the protection zone, the tripping signal will be initiated by UEL after long time delay, e.g. 1 minute; meanwhile an undervoltage element will be implemented to accelerate the tripping process, if the voltage reduction exceeds the relay setting. The typical UEL characteristic is a straight line in P-Q plane and setting criteria is limited by generator steady state stability limit and generator under excited capability limit (normally 80%-85% of generator leading reactive power capability in generator capability curve.) However, when the generator is equipped with AVR and PSS, the AVR stability limit is far beyond the leading reactive power capability which should not be the limit of UEL. In this case, the UEL is set in parallel with P axis in P-Q plane and starts from the p.f. 0.95 leading point in armature limit line.)

The loss of excitation will result in reverse reactive power (Q) flow and increase of currents in the stator to maintain P (for grid connected SG). Additionally generator may pole-slip or even start to operate as a motor but this would be followed by large transients in currents and electromagnetic torque. (*Note:* Pole slip means that the generator rotor will suddenly turn as much as one complete revolution faster than it should be spinning, depending on the number of magnetic poles, and then come violently to a stop again as it tries to magnetically link up again with the stator magnetic field(s). This causes catastrophic failure of the coupling between the prime mover and the generator, and sometimes worse.)

If somehow the generator doesn't slip a pole when excitation is significantly decreasing the other undesirable thing that can happen is that the synchronous generator will become an induction generator, which cause the rotor to get very hot very quickly (high currents are induced in to the rotor teeth and wedges), leading to insulation damage, high vibration, rotor striking stator--in general, none of these things are desirable. Under heavy load condition, the generator, especially salient pole generator, may suffer from severe mechanical stress because of the power swing after loss of excitation. In case of loss of excitation the generator will start to take 2-4 times of its rated reactive power to magnetise the rotor. During this period grid will face the major loss of voltage reduction and instability. More importantly, while running as an induction generator, stator current will be 2-3 times of its rated value based on the slip. Such a huge current could also damage the stator winding. However the real power (MW output) delivered by the induction generator will remain almost the same, as this is controlled by the prime mover. The loss of generator's reactive power in the system may cause instability to the system. Short interruption and re-synchronisation would certainly induce large transient currents and torques and the torque/current spike following resynchronisation could be of the same order of magnitude as the initial fault current. Faulty re-synchronisation of synchronous machines is often more detrimental to machine then behaviour during/ exposure to faults. Figures below illustrate some of the typical transients following loss of excitation.

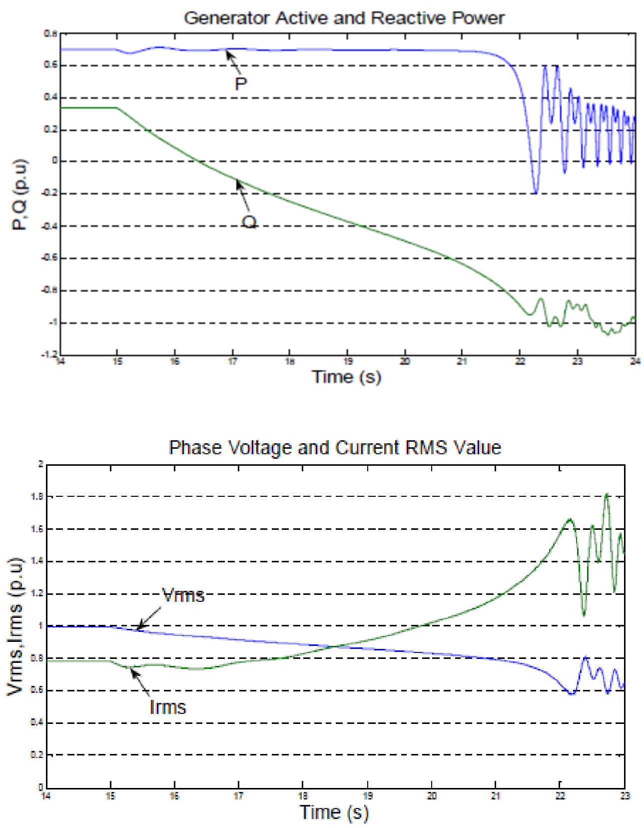


Figure 6-1: Real and reactive power and voltage and current of generator following loss of excitation.

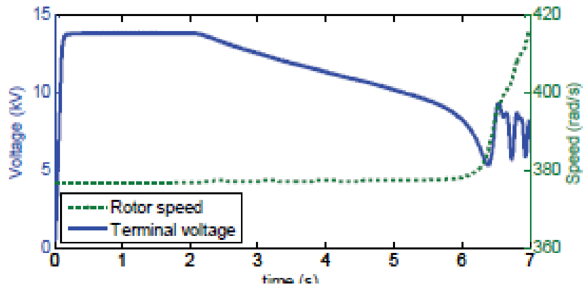


Figure 6-2: Rotor speed and terminal voltage of generator following loss of excitation.

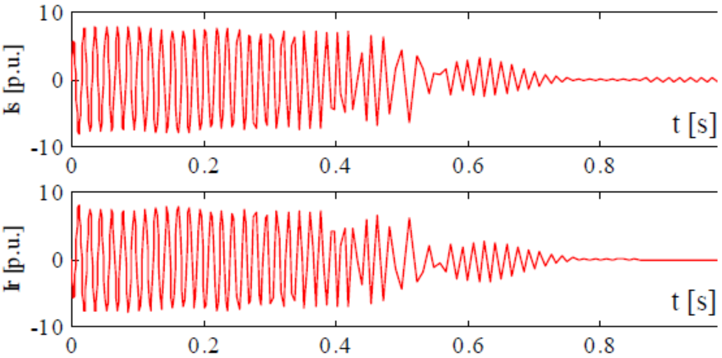


Figure 6-3: Stator and rotor current of IM during acceleration from stand still

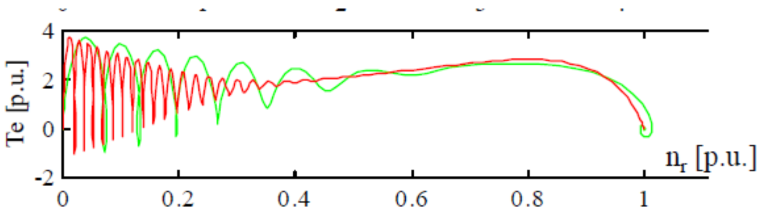


Figure 6-4: Electromagnetic torque of IM during acceleration from stand still with different inertia constants (green H=0.2, red H=07)

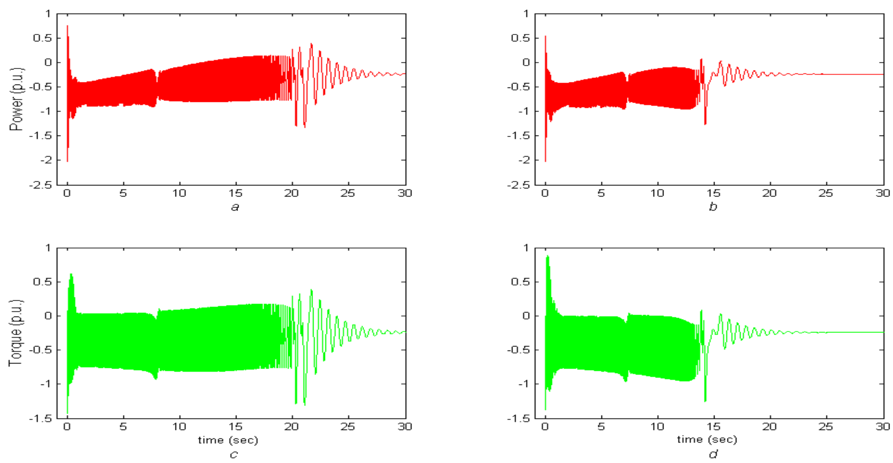


Figure 6-5: Power and torque traces for direct on line acceleration of SG:
i) With additional rotor resistance a) Power c) Torque; ii) Without additional rotor resistance b) Power d) Torque (excitation connected at 20 sec and 13 sec respectively)

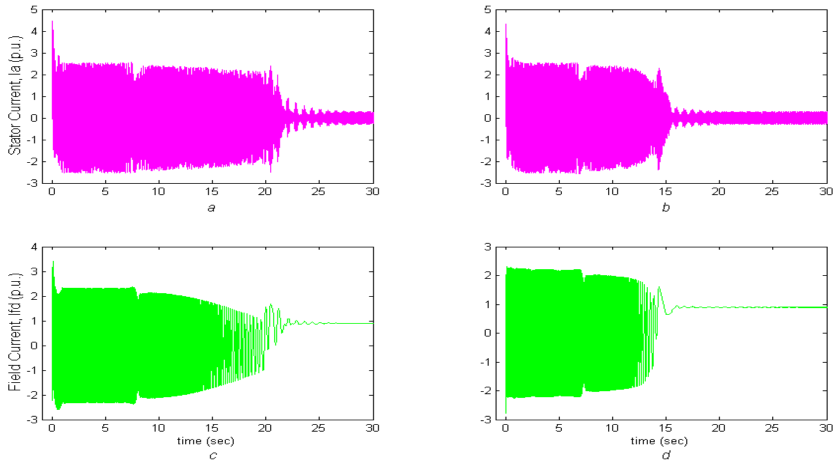


Figure 6-6: Stator and rotor current for direct on line acceleration of SG:
i) With additional rotor resistance a) Stator c) Rotor; ii) Without additional rotor resistance b) Stator d) Rotor (excitation connected at 20 sec and 13 sec respectively)

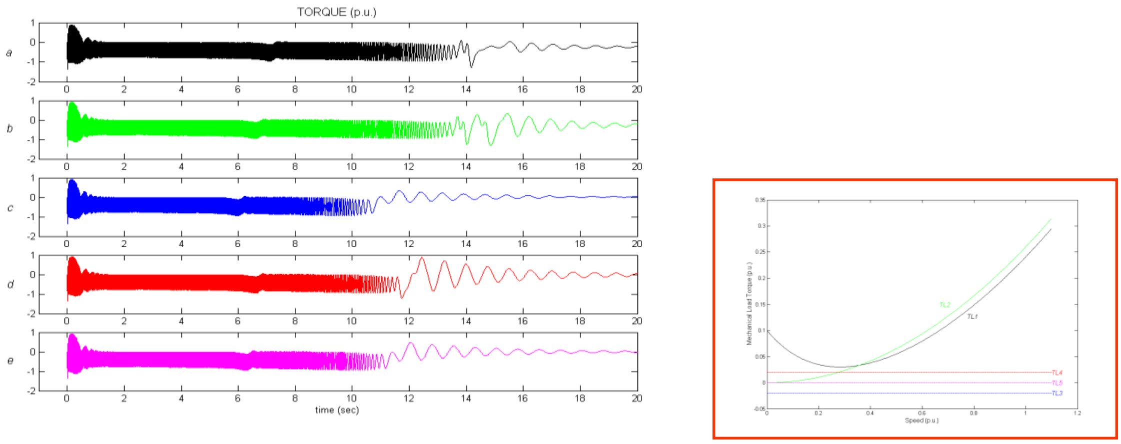


Figure 6-7: Acceleration of SG with different load torque

When the excitation is lost, SG starts to work as IM and draws reactive power (Q) from the grid in an effort to maintain the magnetic field in the air gap. If the grid can supply required Q overloading of rotor and stator can occur, if not terminal voltage will drop. Machine basically becomes underexcited, rotor angle may increase and machine will lose synchronism. If the SG was partially loaded before the disturbance (roughly less than 30%) the consequential over speed (speed increase) may be only very small 0.1-0.2%. If a generator is operating at full load when it loses excitation, it will reach a speed of 2% to 5% above normal. Due to reduced voltage, stator current increases to deliver the same real power (P). Voltage over current ratio becomes smaller and the SG positive sequence impedance reduces, so underexcitation limiter will react.

The Reverse Power Relay monitors the amount of P that is flowing from the generator, it is there to ensure that a loss of fuel, steam, water, etc. does not cause the generator to run as a motor. The exact behaviour of the SG depends on many variables, including the state of the grid and operating point of the machine just prior to the loss of excitation. A lightly loaded machine will have a much less severe reaction than a fully loaded one. Similarly if the grid is at light load and there is plenty of Q capacity available elsewhere, the consequence of loss of excitation is less severe. The real danger is to a fully loaded machine under high demand conditions. Here there is a very real probability of machine slipping poles (losing synchronism) with the grid, not because it overspeeds (it shouldn't unless there are governor and/or control valve problems), but because as the field decays the magnetic field in the air gap will ultimately become too weak to couple the power from the prime mover to the grid. (*Note:* Loss of excitation is roughly analogous to climbing a hill in manual transmission car and pushing on the clutch, or putting automatic transmission into neutral, or a loss of hydraulic fluid in automatic transmission/torque converter, there will be no coupling of power from the engine to the transmission/drive wheels. The car will slow down, and if the foot is not removed from the throttle, the car engine will speed up. The resulting mismatch in speeds is equivalent to the pullout condition, and will cause great damage if the clutch plate speed is not matched to the engine speed before re-engaging.) If SG does slip poles then the reverse power relay might act as the grid tries to pull the rotor back into synchronization, but if the field has weakened significantly, or completely lost, then there won't be any 'poles’ for the air gap flux to align with.

If the generator is a significant portion of the overall load (which will not be the case for SG smaller than 10 MW) then there may be a system transient stability problem. If the SG is lightly loaded then it might continue operating until the operator notices that the field current is too low, there is no power being produced, there are a lot of VARs/current flowing into the machine, the power factor meter is reading much too low, the fuel flow is lower than expected, etc., or any combination of them. Some of this will depend on the type of governor and the mode that it is in, so over speeding, though unlikely, cannot be ruled out.

An example of damage caused by loss of excitation: Exciter control circuit was accidently opened such removing excitation from a synchronized and loaded 3 MW horizontal direct drive hydro-turbine. The error was spotted and the control circuit was closed. This caused the generator rotor and stator to mechanically rub, throwing the turbine-generator out of alignment with the tremendous torque due to the generator not being in synchronism. (This was happening during an end-of year start-up rush and the generator stator and bearing pedestals had not been doweled yet.)

When the excitation is lost and the generator remains connected to the grid and prime mover continues to supply power, the generator starts acting as "Induction generator" with reverse Q flow (from grid to machine). It draws excitation current from the grid and runs at some "slip". The control room will notice rise in speed of this SG (others running at synchronous speed). The slip value depends on various parameters of the generator (various reactances etc.) and the amount of load delivered by this set. The stator current would exceed its rated value (assuming that SG was supplying rated load at the time of loss of excitation) as it would be the vectorial sum of load current and the excitation current drawn from the grid. As the generator is not running at synchronous speed, the rotor direct axis and quadrature axis would be cutting stator field axis. As the two axes reactances are different, the currents and the reactance drop would fluctuate at slip frequency. This in turn will make fluctuation in the terminal voltage of the generator. The final value of this fluctuation will depend on the grid strength and its parameters. The size of generator (compared to grid capacity) will decide the amount of fluctuation in grid voltage. If allowed to run as induction generator, the generator will be damaged due to excessive stator current. The power station auxiliary components (various motors etc.) may trip due to fluctuation in grid voltage.

In any case loss of excitation (LOE) is an abnormal operating condition that must be avoided to prevent major damage to the generator. The Loss of Excitation, Out of Step, and Reverse Power relays and others are typically used to prevent this from happening. There are five LOE protection schemes used today: 1) R-X scheme with single and double relay scheme (based on generator terminal impedance measurement). 2) R-X with directional element scheme (-do-). (Note: In normal operation condition, the SG generates P and Q to the system which means both 'R' and 'X' are positive and the terminal impedance is located in the first quadrant in R-X plane. When the excitation is lost, the SG starts to draw Q from the system and 'X' becomes negative from the LOE relay point of view. As a result, the terminal impedance loci in R-X plane moves to the forth quadrant and the endpoint of terminal impedance ranges between the subtransient reactance and synchronous direst axis reactance. To limit system voltage, the SG may have to operate under excited and absorb Q from the power system. It is important that it is able to do so within its capabilities as defined by the generator capability curve. The generator Under Excitation Limiter (UEL) must be set to maintain operation within the capability curve. The loss of field relay must be set to allow the Generator to operate within its Under Excited Capability.) 3) G-B Scheme (Based on generator terminal admittance measurement). 4) P-Q Scheme (Based on generator active and reactive power output). 5) U-I Scheme (Based on the measurement of phase angle difference between phase voltage and current). R-X scheme is widely used in the industry, while P-Q scheme has not been used in the industry yet. Comparison of different protection schemes for different scenarios is given in Table 6-1.

Table 6-1: Speed of operation of different protection schemes.

Case		RX	RX directional	GB	PQ	UI	Out of step
Case 1: 80% load	Alarm signal	5.81s	2.9s	4.76s	4.03s	3.97s	7.13 s
	Trip signal	6.31s	5.42s	6.72s	4.73s	5.47s	
Case 1: 40% load	Alarm signal	7.89s	2.1s	9.73s	4.8s	6.43s	18.08 s
	Trip signal	8.39s	7.93s	10.73s	8.05s	7.93s	
Case 2: 80% load	Alarm signal	8.57s	4.19s	7.03s	5.68s	5.74s	10.43 s
	Trip signal	9.07s	7.12s	9.38s	6. 35s	7.24s	
Case 2: 40% load	Alarm signal	33.78s	3.35s	55.01s	11.8s	21.6s	-
	Trip signal	34.28s	24.5s	56.01s	30.63s	23.1s	
Case 3: Condenser	Alarm signal	11.38s	3.05s	-	2.94s	-	-
	Trip signal	11.88s	11.42s	-	9.2s	-	

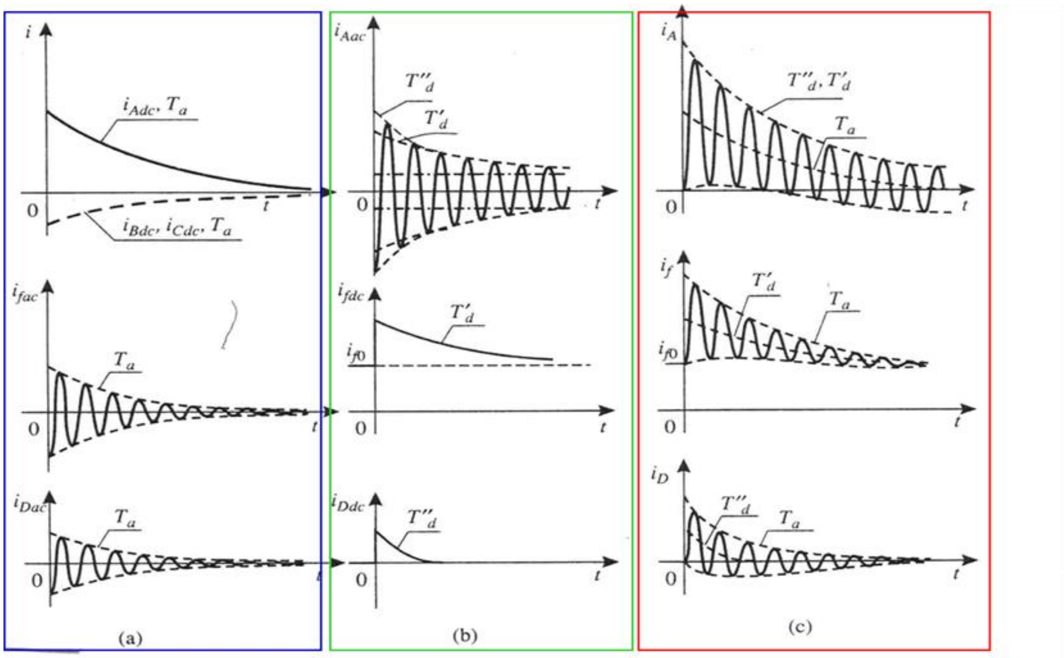
Query 3:

If possible, please provide a graph of the generator fault contribution against time following receipt of a signal to the excitation system to switch the field current for a typical generator in the range of interest. Otherwise could you provide a mathematical formula to describe the fault current decay or an approximate decay time constant for the field current?

JVM:

The fault contribution of SG following loss of synchronization cannot be produced at this stage without simulation studies. Some general description of fault contribution and fault current decay is given below.

A three-phase fault causes the flow of short-circuit armature currents that have both an ac and dc component. The resulting ac armature mmf rotates with Rotor and induces additional dc currents in rotor, while dc armature mmf is stationary with respect to rotor and therefore induces additional ac currents in rotor.



Short-circuit currents in the generator: (a) dc component of the phase current and the corresponding ac component of the field and damper winding current; (b) ac component of the current in phase A and the corresponding dc component of the field and damper winding current; (c) the resulting current in phase A, the field and the damper winding as the sum of the currents shown in (a) and (b)

Figure 6-8: Induced currents in different windings of SG following short circuit while generator was operating at no load.

X_d (X_s), X_d', X_d'' – synchronous, transient and subtransient reactance, respectively

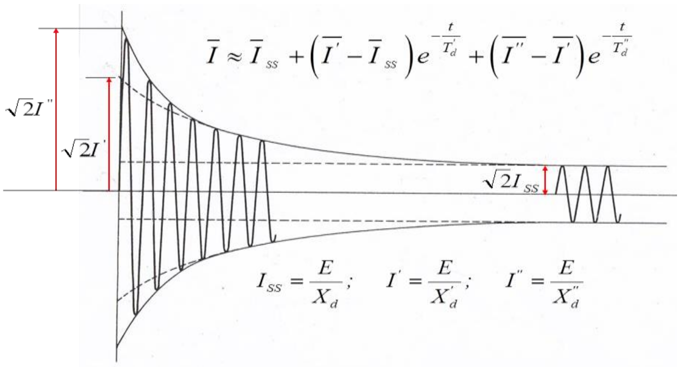


Figure 6-9: Symmetrical fault current induced in one phase of generator (no dc-offset)

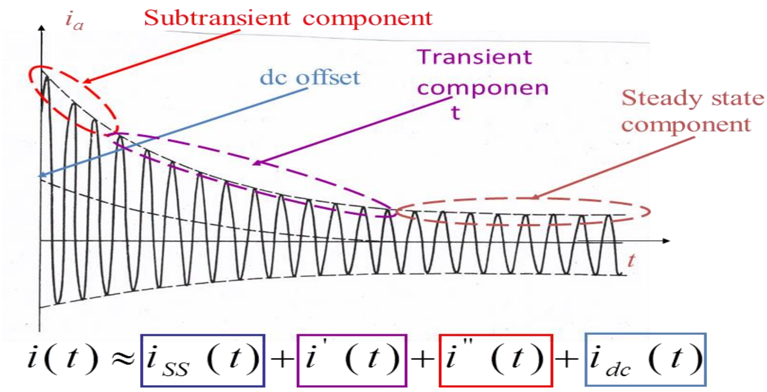


Figure 6-10: Asymmetrical fault current induced in one phase of generator – with different current components

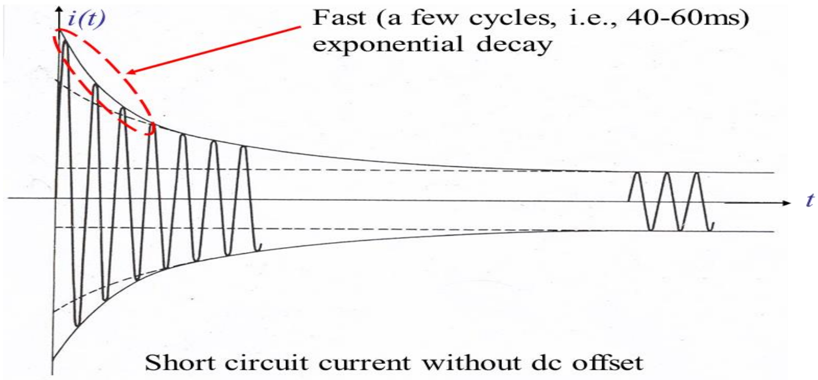


Figure 6-11: Duration of subtransient current induced in one phase of generator (no dc-offset)

Query 4:

Please can you comment on whether it would be feasible to interrupt the excitation current in these generators using a circuit breaker.

JVM:

The interruption of excitation is not advisable as discussed at length above. Some further simulation studies would be useful to illustrate potential drawbacks, and benefits if those drawbacks are to be neglected. The discussion on the issue, though, as applied to different excitation systems, by PB is appropriate.

Query 5:

Please can you comment on whether mitigating measures are required to interrupt the excitation current in these generators; for example depressing an induced a voltage spike.

JVM:

The interruption of excitation is not advisable as discussed at length above. Some further simulation studies would be useful to illustrate potential drawbacks, and benefits if those drawbacks are to be neglected. These studies could inform further discussions regarding potential mitigation measures.

Query 6:

Please can you provide a graph of generator short circuit current versus time with the rotor current interrupted vs no intervention?

JVM:

This would need to be simulated first in order to establish possible influence. Some indication of the effect is illustrated in Figure 6-2 above. I am not aware of existence of other relevant graphs, though I obviously have not seen all the graphs produced on this subject in books and research papers.

Query 7:

Please can you provide the above information based on using the static exciter as an inverter to reverse the DC voltage applied to the rotor winding.

JVM:

This would need to be simulated first in order to establish possible influence.

6.2 Fault current contribution by rotating plant (24 March 2014)

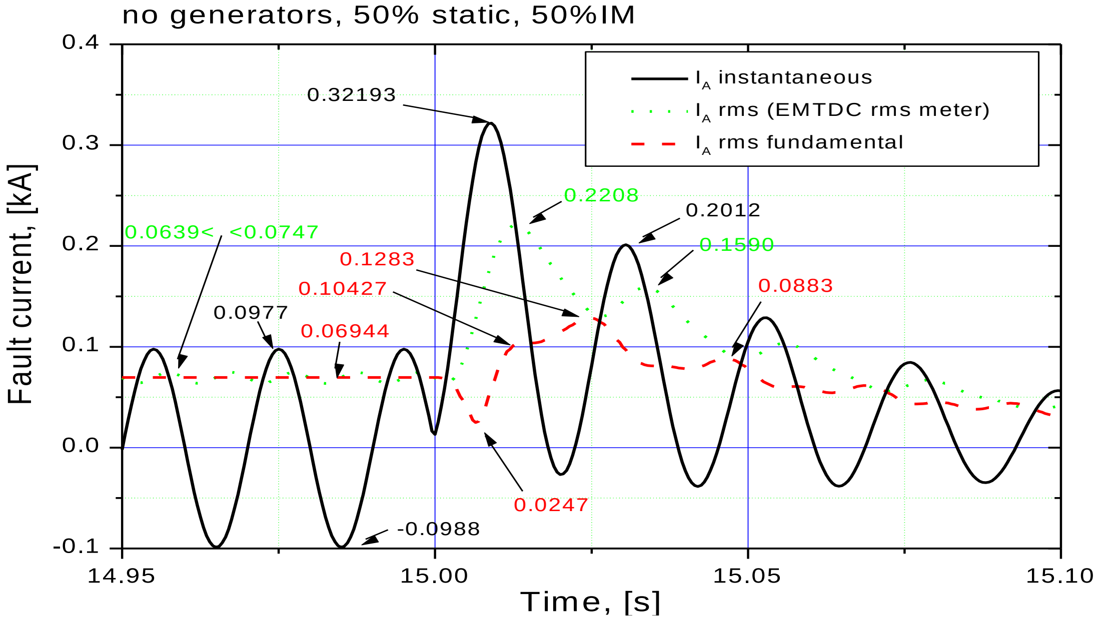


Figure 6-12: Fault current contribution by aggregate load without generators considering different estimation methods

The contribution of the aggregate rotating plant to the fault levels can be calculated with a reasonable accuracy based on small naturally occurring disturbances in the network. The presence of local generation influences the power flows in the network. Depending on generator's power factor and the size of IM load the real and/or reactive power at the monitoring point may not always flow in the same direction. The sensitivity coefficients, in particular the reactive power related coefficients, i.e., $\partial Q/\partial \theta$ and $\partial Q/\partial V$, get influenced by this change in power flows and as a consequence the formulae based on these coefficients would not give accurate prediction of the fault level contributions. There is a very strong dependence of the results of calculation on estimated sensitivity coefficients and therefore it is essential to estimate the coefficients as accurately as possible.

The major problem in estimating these coefficients is the assessment (measurement) of the relevant real and reactive power drop following the disturbance. In the case when the generators are present in the network there is initial (positive) jump in the reactive power following the change in voltage phase angle. This makes it difficult to assess initial change in the reactive power and makes the estimation of the corresponding sensitivity coefficient very difficult. If the initial drop in the real and reactive power is calculated using the rms values of the first harmonic of voltages and currents, smooth and free of excessive oscillations responses are obtained. If these responses are used for the estimation of the fault level contribution however, the calculated fault level contributions are significantly lower than those obtained using IPSA (10 ms asymmetrical rms values) simulations. (The calculated values are roughly 40%-50% lower.) On the other hand, if the initial drop in the real and reactive power is calculated using one of the following approaches:

using the instantaneous values of phase currents and voltages, using the averaged rms values of phase voltages and currents, using d-q components of phase voltages and currents; the calculated fault level contribution would be closer to those obtained using IPSA (10 ms asymmetrical rms values) simulations but still significantly higher. If the estimated fault level contributions (based on one of these two methods) are compared with those obtained in IPSA simulations using 0 ms asymmetrical rms values, a good agreement can be observed. The differences are within ±15%.

For practical application of the methodology it would be necessary to conduct field measurements at distribution bus of interest in order to determine the sensitivity coefficients specific to that bus prior to calculating the fault level contribution by the aggregate rotating plant using proposed formulae.

The other very important, if not the most important issue is the instant in time at which the fault level contribution is calculated. The differences in the results may be very big if the fault levels are calculated at different times following the disturbance due to the rapid decay in the fault current. One possible approach in this respect would be the extrapolation of the real and reactive power curve obtained using rms values of the first harmonic of voltage and current to desired instant of time (e.g., 10ms, 20ms, etc.)