Earth Leakage Current in an Isolated Power System with Power Electronic Converters

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Abstract - **Power electronic drives are increasingly used in offshore power systems. Earth leakage current is one of the undesirable effects caused by the switching action of semiconductor devices. This paper illustrates the signatures of the earth leakage current produced by a thyristor DC drive, a PWM AC drive and an AC drive with a PWM rectifier. The mechanism is explained in each case and the leakage current path is outlined. This study may provide useful information on developing counter measures to attenuate the earth leakage current. Laboratory measurements and computer simulation are used to illustrate the effects of the system design and operational arrangement in practice.**

Keywords: Transient, Earth Leakage Current, Drives, Offshore System, Modelling, Test.

I. INTRODUCTION

Power electronic drives are increasingly used in industry. Their interface with the utility supply is of concern to power system engineers. The interaction between the drive system and the supply includes both steady state characteristics such as voltage regulation and harmonics, as well as fast transients. This paper is concerned with one possible side effect of operating power electronic drives in an offshore system for oil/gas production: the fast transient earth leakage current.

Offshore electrical systems are often characterised by local generation, large constant and variable speed motor drives, as well as long cable runs. The operation of power electronic drives causes significant earth leakage current, which may disturb the control and protection devices in the system. On an offshore installation, earth leakage current when flowing across joints of the metallic platform structure is always a potential source of electrical ignition. The chemical corrosion process of some platform structures may also be accelerated [1]. The earth leakage current is excited by the switching of power semiconductor devices. Such phenomena can not be predicted using conventional power system models. The purpose of this paper is to investigate the mechanism of earth leakage currents produced by different variable speed drives.

Thyristor controlled DC drives are widely used for drilling on offshore platforms. Considerable low order harmonics, particularly the 5^{th} and 7^{th}, are injected into the supply system [2]. In order to make use of the robustness of the induction motor, large AC drives are increasingly used to power various pumps and gas compressors [3]. Such drives usually have a diode or thyristor input rectifier. A PWM (pulse width modulation) inverter is used to supply the induction motor, which provides soft starting as well as variable speed control for the motor. To limit the harmonic currents generated by the input rectifier, the 12-pulse or higher rectifier circuits may be used. Alternatively AC drives with a PWM rectifier have been proposed, which can also absorb some harmonics produced by other loads. This paper will consider these three types of variable speed drives and investigate how the earth leakage current is produced by their power electronic stages.

Based on the evidence from laboratory experiments, an analytical study is performed for a PWM AC drive supplying a down-hole pump. This is one of the drive systems that have experienced frequent nuisance tripping in practice due to the high earth leakage current. The system natural frequencies can be estimated using simplified models including the long cable between the inverter and motor [4]. The switching frequency of the PWM inverter should be set away from the natural frequency in the design to avoid resonance during switching transients.

II. EXPERIMENTAL SYSTEM SET-UP

The drilling drives can be supplied from low voltage generators whose neutral point is solidly earthed to the platform structure [1]. To qualitatively, but physically, model the offshore system, a test rig was established as shown in Figure 1. The synchronous generator supplies the power electronic drive via a 10 metre screened cable. The converted power from the drive is fed to the motor terminals using another 20 metre cable. The motor frame and the drive case are consecutively earthed to the neutral of the generator. The earth path is explicitly defined using the earth conductor and cable screen. This provides a means of measuring the earth leakage current flowing in the earth path. The experimental system is arranged so that the chance of another leakage path, for instance via the stray capacitance between components, is minimised [5]. In practice, the drives and machines are usually earthed directly to the platform structure, the path of the leakage current is consequently more complicated. The above test arrangement is however adequate to study the fundamental phenomenon of earth leakage current.

The practical details of the power electronic converters and motor in Figure 1 will be specified with the presentation of each drive system. The generator voltage is regulated to 420V, 50Hz. The drive is loaded up to about 3kW by means of a DC generator which is not further earthed. The earth leakage current measured for each drive is described next.

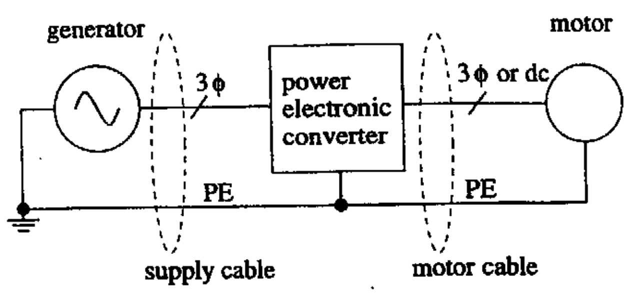

Figure 1 General Experiment Set-Up

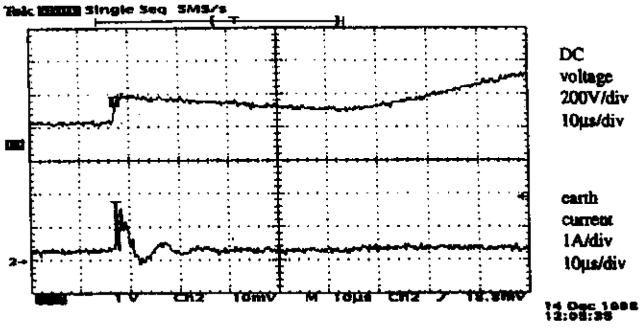

Figure 2 Generator Earth Current for DC Drive

III. THYRISTOR CONTROLLED DC DRIVE

The AC side of a three phase thyristor bridge is generally considered as a three-wire connection which does not permit a zero sequence current. However Figure 2 which shows the generator earth current indicates that current spikes have been produced in the neutral line. This spike corresponds to a commutation in the thyristor rectifier. The current path is formed by the stray capacitance distributed in different parts of the system. For instance, for the test DC motor the stray capacitance between the armature winding and the frame is about 6nF. Stray capacitance also exists between the thyristor modules and the heat sink which is mounted firmly to the earthed drive case.

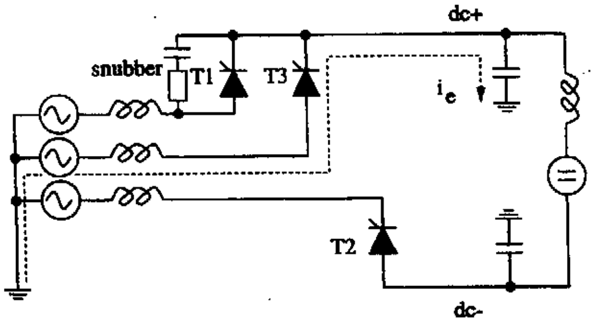

Figure 3 Explanation of Earth Leakage Current

Figure 3 shows how the thyristor commutation within the rectifier can excite the earth current spike. At the beginning of commutation, thyristor T3 is gated on and causes a step increase in the potential of the positive DC bus with respect to the neutral point. The capacitance and inductance distributed in the system form a resonant circuit which can be excited by the voltage step change. Another change of voltage is seen at the end of commutation when thyristor T1 turns off. Due to the effect of the snubber associated with thyristor T1, the change of voltage will be slower at the end of commutation than at the beginning. As a result the earth leakage current, which is partially due to the dv/dt, is also lower at the end of commutation.

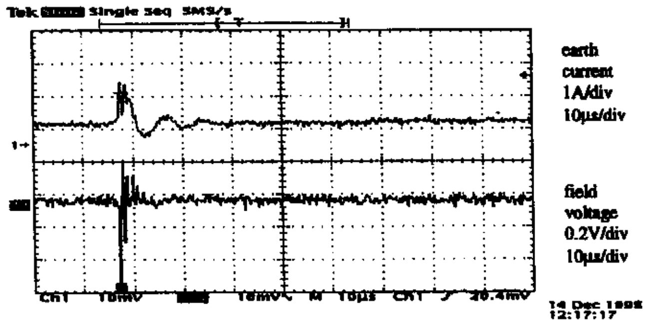

Figure 4 Field Winding Voltage during Commutation

Figure 4 shows the field winding voltage of the generator during the commutation. It is clear that the switching transient on the stator is coupled to the rotor circuits across the air-gap. This implies that if an analytical model is to be developed for the generator, the rotor windings have to be considered. The coupling between the stator and rotor depends on the rotor position which can be determined using the firing angle of the rectifier and the fundamental power level of the generator.

The current spike consists of components at different frequencies and damping factors. The effects of such earth leakage current include the electromagnetic interference to the control and protection systems, and the RF condition monitoring system installed on the generators [6]. The amplitude of the leakage current increases with firing delay angle. The worse case therefore corresponds to the low speed operation of the drive and during start up.

IV. PWM AC DRIVE

The power electronic stage of a PWM drive includes a diode rectifier supplying a capacitively smoothed DC link. The diode rectifier operates with zero degree firing angle and as a consequence the earth leakage current spike produced by the commutation process in the rectifier is small. Large earth leakage current spikes can be excited by the switching of the IGBT devices in the PWM inverter.

Figure 5 shows the measured generator terminal voltage and the earth leakage current flowing back into the generator neutral. It is shown that the generator terminal voltage has a flattened top and the PWM drive behaves like a voltage type of harmonic source to the supply [7]. Within a single fundamental cycle, a large number of leakage current spikes are produced in the generator earth corresponding to the switching events of the IGBT devices in the PWM inverter. Figure 6 shows on a fast time base the earth leakage current corresponding to a step change in the inverter output voltage. It is clear that the maximum peak to peak current is over 3A.

The mechanism generating the earth leakage current spike can be explained using Figure 7. The positive and negative buses of the dc link are connected to one of the input phases. The DC link voltage can be considered as constant due to the large value of the capacitance. During the transient of an IGBT switching, the output side of the switched phase will see a change of voltage with respect to the generator neutral. The amplitude of the change is equal to the DC link voltage. As the DC link capacitance appears to be a short circuit for high frequency leakage current spikes, an equivalent circuit of the inverter has been derived as shown In Figure 7. The exciting voltage source can be calculated as below.

$$v_{sw}(t) = \frac{1}{3}[v_{aout}(t) + v_{bout}(t) + v_{cout}(t)] \qquad (1)$$

where $v_{aout}(t)$, $v_{bout}(t)$ and $v_{cout}(t)$ are modulated instantaneous output voltages of the three phases of the inverter. The line-line output voltages consist of trains of pulses with variable width. It is clear that corresponding to each switching in the inverter, a voltage step which equals to 1/3 of the DC link voltage is produced in the equivalent circuit. The dv/dt associated with the switching excites a transient in the lightly damped resonant circuit formed by the inductance and capacitance of the cables, motor and generator. The earth leakage current spike is produced as a consequence.

It is possible to block, to some extent, the flow of the earth leakage current. For instance, in large PWM drives, it is common to insert a series inductance in the DC link on the rectifier side. Figure 8 shows the earth leakage current measured in this case. It is shown that the amplitude of the leakage is slightly reduced due to the series inductance. However, as the earth leakage current can still flow freely via another DC rail, which does not have the series inductance, the earth leakage current is not fully blocked. The effect of the series inductance is that only one phase of the supply, i.e. the generator, is now directly connected to the return path of the earth leakage current. The other two supply phases affect the phenomena only by mutual coupling. The top-flattened characteristic of the voltage waveform is also attenuated. The principle advantage of adding the series inductance is to reduce the total harmonic distortion of the steady state current drawn from the supply.

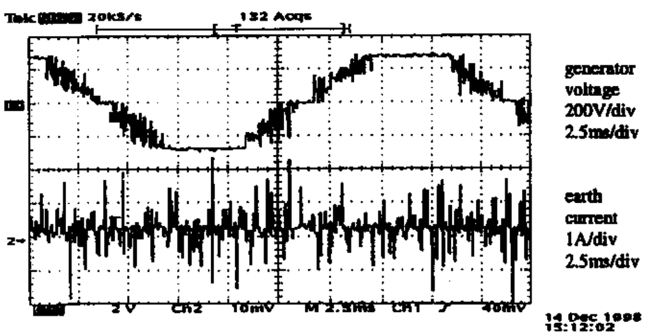

Figure 5 Generator Voltage and Earth Current

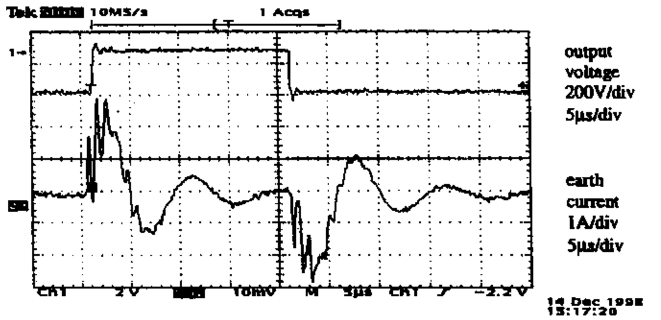

Figure 6 Inverter Voltage and Generator Earth Current

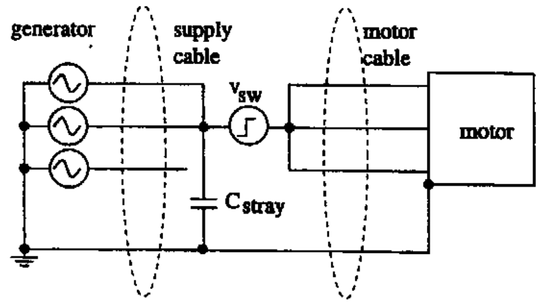

Figure 7 Equivalent Circuit for PWM AC Drive

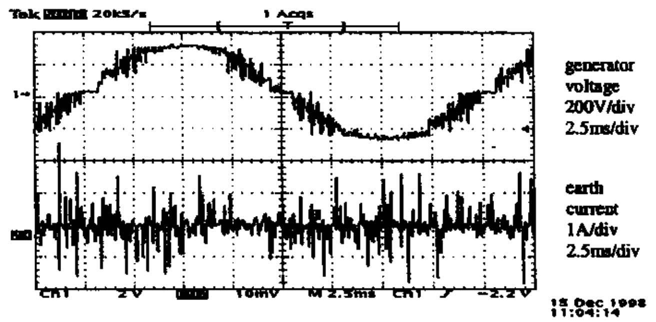

Figure 8 Measurement with Series Inductor

V. AC DRIVE WITH PWM RECTIFIER

This drive system is similar to the last one on the inverter side but has a three phase PWM rectifier at the input side instead of a diode bridge. An inductance of 6.2mH (measured at 100Hz) is connected in series in each phase to balance out the switching harmonics produced by the rectifier. The switching frequency of both the inverter and rectifier is set to 4kHz. Figure 9 shows the generator terminal voltage (line to line) and line current. The two waveforms are phase displaced by 30 degrees, corresponding to unity power factor operation. The ripple in the waveforms suggests that the input series inductance does not fully suppress the switching harmonics, i.e. the supply impedance is large.

Figure 10 shows the switched AC voltages of both the rectifier and inverter, together with generator earth leakage current. Switching in either converter will produce an earth leakage current spike. It is assumed that the switching speed of the semiconductor devices used in the rectifier and inverter are the same. The difference in the leakage current is partially due to the stray capacitance between the IGBT modules and their heat sink. This is illustrated in the equivalent circuit shown in Figure 11. At any instant, every input or output phase is connected to either the positive or negative DC bus through a conducting device. The large DC link capacitance again provides a short circuit to the high frequency current. Therefore, as far as the earth leakage current spikes are concerned, the input (output) phases are in parallel. The exciting voltage sources in Figure 11 can be derived as before reflecting the switching actions in the rectifier and inverter.

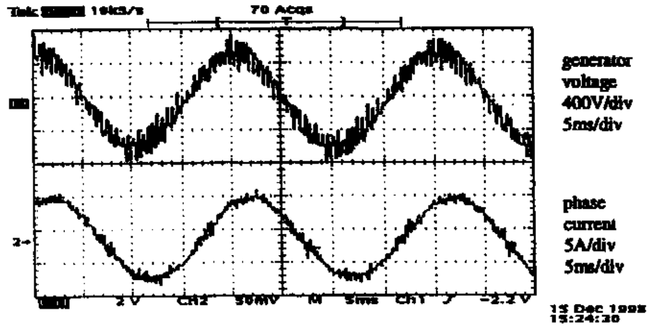

Figure 9 Generator Voltage and Current

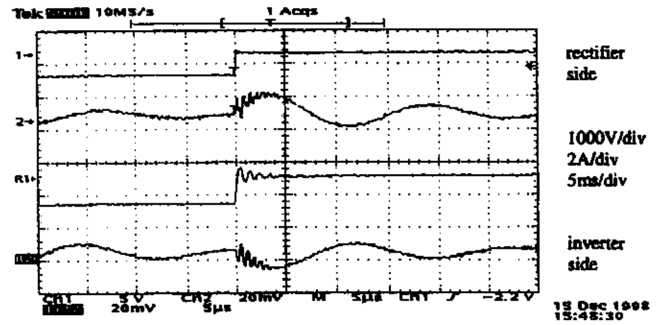

Figure 10 Switched Voltages and Generator Earth Current

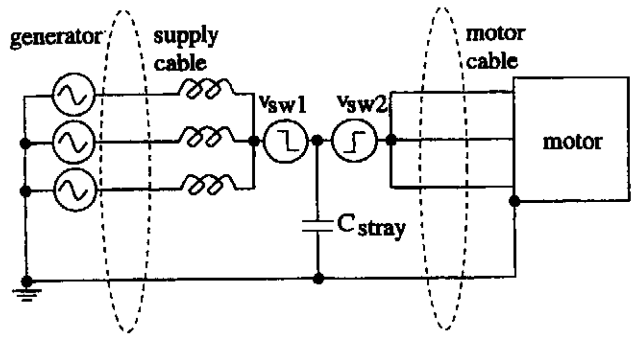

Figure 11 Equivalent Circuit for AC Drive with PWM Rectifier

The measurements shown in Figures 8 and 10 indicate that series inductance on either the AC or DC side will not fully suppress the earth leakage current. Although this could be because of the finite inductance value which has been used, in practice any realistic inductor will demonstrate a stray capacitance between its two terminals. This provides a path for high frequency current.

VI. SIMULATION OF A DOWN-HOLE PUMP DRIVE

PWM AC drives have been used to provide down-hole pumps which are nowadays frequently used for artificial lift. Between the PWM inverter and the down-hole induction motor, which drives the pump, there is a long cable running from the top of the well to the bottom. In this case the natural frequency of the system can be lowered to be closer to the switching frequency of the power semiconductor devices leading to a resonance. It is important to calculate the earth leakage current phenomena for such a system so that the worst case can be avoided. It is necessary to develop the simulation models for the components included in the equivalent circuit of Figure 7.

On the output side, the mutual capacitance between the phases can be ignored. This is because all three phases are in parallel when considering the earth leakage current. The distributed characteristics of the cable and induction motor however need to be considered. In the time domain, both the cable and the motor can be represented using the multi-section equivalent circuit shown in Figure 12. For the cable, the parameters are calculated as follows.

$$L_{sec} = (\frac{1}{3}L_1 + L_e)/n_{sec} \tag{2}$$

$$C_{sec} = 3C_{1e}/n_{sec} \tag{3}$$

where L_1 is total inductance of each cable phase, L_e is the earth path inductance and C_{1e} is the capacitance between the phase and earth. n_{sec} is the number of sections connected in series. For the delta connected motor, the above parameters are modified as below.

$$L_{sec} = \frac{1}{6}L_{ls}/n_{sec} \tag{4}$$

$$C_{sec} = 3C_{se}/n_{sec} \tag{5}$$

where L_{ls} is the leakage inductance of one phase of stator winding and C_{se} is the total capacitance between one phase of the stator winding and the motor frame. Resistance will be added in series with the capacitance to represent the frequency dependent damping effects.

The distributed characteristics of the supply cable and generator also need to be appropriately represented. The above equivalent circuit can be used for the supply cable. A full high frequency model similar to that proposed in [8] is adopted for the generator.

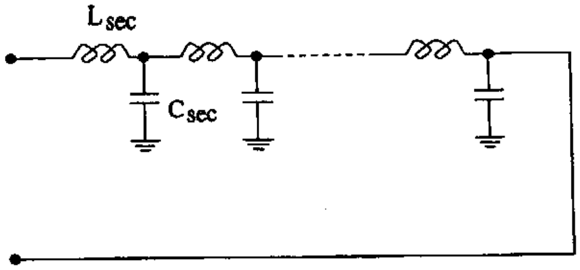

Figure 12 Distributed Circuit Model for Cable and Motor

It is has been observed in Figure 4 that corresponding to an earth leakage current spike, a transient response is also induced on the rotor side. This is because the earth current does not equally divide between the hree stator phases. As a result, the generator model is further developed as shown in Figure 13, with the magnetic coupling between the stator and rotor circuits included. The stray capacitance between the stator winding and the generator frame is also represented. Such a complex model is not necessary for the induction motor. Parameters of simulation models are listed in the Appendix.

In the generator model, the stator winding are divided into sections. For simplicity, the rotor windings are modelled as lumped circuits. The dampers are short circuited while the DC supply to the field winding is represented using a Thévenin model with a constant EMF and impedance. The mutual coupling between the stator and rotor windings are equally divided between the sections on the stator side. This is only a simplistic description of the synchronous generator which combines the performance at both high frequencies and fundamental frequency together. More accurate models will be developed in future studies to improve the quality of the simulation [9].

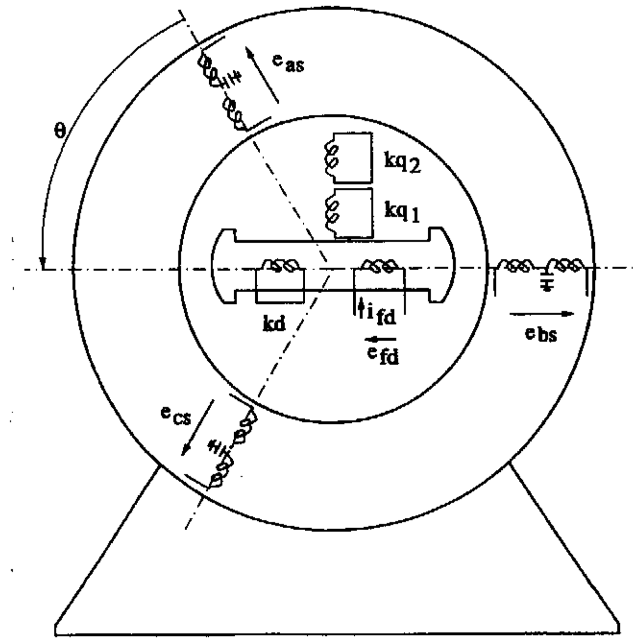

Figure 13 Generator Model

The simulated waveform of the earth leakage current is shown in Figure 14. It is shown that the simulation model reproduces the major features of the measured earth leakage current spike. The oscillation frequency and amplitude show reasonable agreement. Using the simulation model, calculations are performed for different motor cable lengths. The results are shown in Figures 15. It is reasonable to expect that as the cable length increases, the natural frequency of the system is reduced. When the cable length approaches 2000 metres, the natural frequency is very close to the switching frequency of the IGBT devices in the PWM inverter (5kHz for the test drive). Resonance will therefore result. This is a condition system designers must try to avoid. In general, resonance is more likely to happen when the switching frequency is low and the cable is long.

Although the operating parameters of a practical down-hole pump drive may be significantly different from the test system simulated, the general phenomenon shown above remains the same. The leakage current has frequently caused nuisance tripping of such down-hole pumps in practice. After proper calibration, particularly concerning the actual damping existing in practical systems, the model described in this paper can be used predict the system response during fast switching transients.

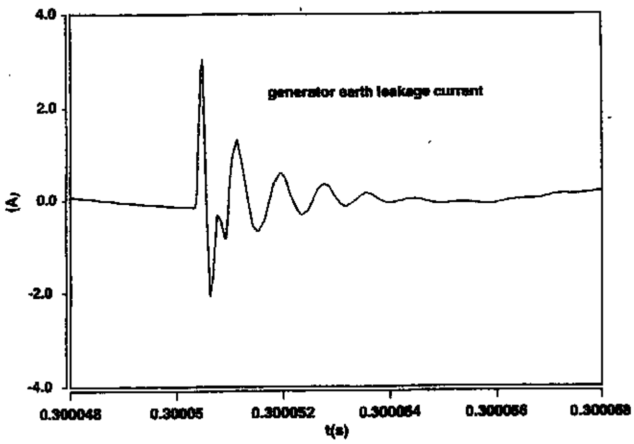

Figure 14 Simulated Generator Earth Leakage Current

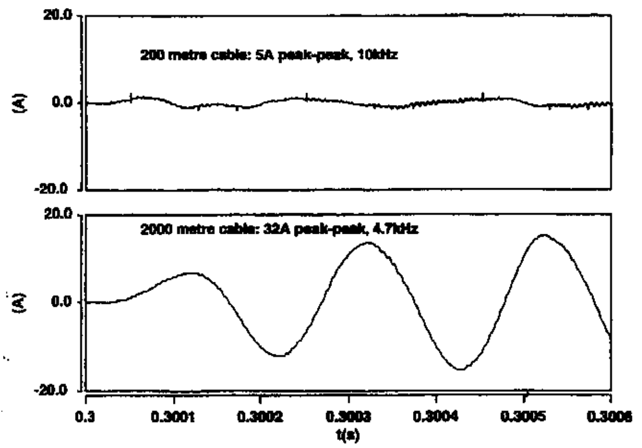

Figure 15 Simulation for Different Cable Lengths

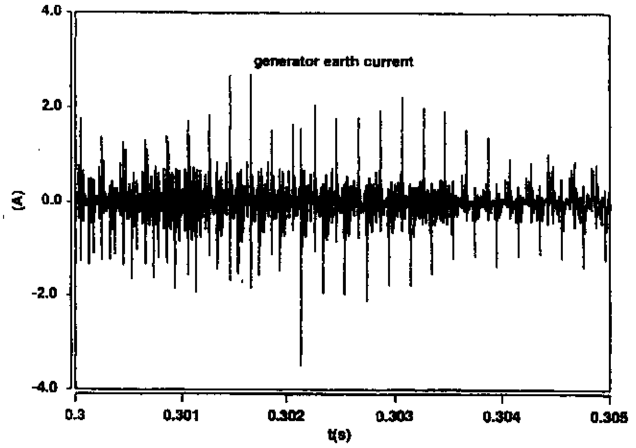

Figure 16 Effect of Rotor Position

Figure 16 shows the simulated earth leakage current of the generator over an extended period of time. It is observed the amplitude of the current spikes is somewhat varied within a fundamental cycle. This could be due to the change of the rotor position when a IGBT switching occurs. Similar signature was observed in the measurement shown previously in Figure 5.

VII. CONCLUSIONS

This paper presents a series of measurements to illustrate the earth leakage current phenomena in an isolated power system with power electronic drives. Three types of variable speed drives are considered and the mechanism of earth leakage current production is explained for each case. An analytical study is performed for an AC PWM drive, which shows that depending on the system conditions large earth leakage current can flow when the switching frequency of the power semiconductor devices is close to the resonant modes of the system. Since more power electronic drives will be used in offshore power systems, the earth leakage current should be considered in future designs. The simulation model developed in this paper can be further improved to carry out engineering studies.

VIII. ACKNOWLEDGEMENTS

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X. APPENDIX: SYSTEM PARAMETERS

Generator
Rating: 415V, 50Hz, 16kVA, 4 pole

$l_{ls} = 0.06 p.u.$	$r_s = 0.021 p.u.$
$l_{lkq} = 0.144 p.u.$	$r_{kq} = 0.0466 p.u.$
$l_{lkd} = 0.0218 p.u.$	$r_{kd} = 0.028 p.u.$
$l_{lfd} = 0.0187 p.u.$	$r_{fd} = 0.0121 p.u.$
$l_{md} = 1.51 p.u.$	$l_{mq} = 0.72 p.u.$

Total stray capacitance between winding and frame: 6nF

Cable
$L_{10} = 0.4 \mu H / m$ (phase and earth conductors)
$r_{10} = 0.019 \Omega / m$
$L_{e0} = 0.2 \mu H / m$ (cable screen)
$r_{10} = 0.043 \Omega / m$
$C_{120} = 20 pF / m$ (between conductors)
$C_{1e0} = 115 pF / m$ (between conductor and screen)

Motor (delta connected)
Rating: 415V, 50Hz, 7.5kW
Stator leakage inductance: 13.3mH/phase
Total stray capacitance between winding and frame: 4.5nF

PWM Drive
Rating: 415V, 7.5kW
Output frequency: 40Hz
Switching frequency of IGBT: 5kHz