Abstract: A major research project was undertaken to investigate the occurrence of frequent flashovers in 3.3kV, inductively grounded, underground mine power distribution systems. This paper presents the results of field recordings of switching transient overvoltages occurring in mine power systems. The paper also presents the results of computer simulations of switching transients. The research effort resulted in the design of a Resistor-Capacitor snubber that significantly reduces the switching transients consequent to earth fault isolation. The paper presents both computer simulations and field recordings that illustrate the effectiveness of the snubber.

I. INTRODUCTION

In the mid 1990’s a number of underground coal mines in the Central Queensland area experienced several equipment failures in their transportable, 11kV/3.3kV Longwall mining substations due to flashovers and insulation failures. The flashovers that occurred caused damage to neutral earthing reactors, vacuum contactors and in one case a catastrophic failure of the transformer. As a result of these failures a major research project was instigated to investigate the magnitude and nature of the transient overvoltages causing these failures. The research project included undertaking extensive field recordings of the transient overvoltages occurring during the operation of Longwall mining equipment as well as above ground field tests. The project also included using the field recordings as a basis for developing and verifying computer models that were used to investigate and predict the nature and magnitude of switching transients under various operating conditions.

From the field tests that were undertaken it was found that the largest transient overvoltages occurred subsequent to the isolation of single-phase-to-ground faults on the 3.3kV side of the Longwall substations. It is the study of these transients that is the main focus of this paper.

II. CURRENT CHOPPING

It is well documented that vacuum interrupting devices (contactors and circuit breakers) are a contributing factor to high values of transient overvoltages in electrical distribution systems [1,2]. Vacuum interrupters are traditionally associated with a phenomenon referred to as current chopping. Current chopping is defined as an abrupt interruption of the current flowing through a switch before the current waveform reaches its natural power frequency zero crossing [3].

The process of current chopping is best understood by considering the opening of a switching device, that is, a circuit breaker or contactor, to turn off a load. While the switch is closed, load current flows through the switch. When the switch commences opening, an arc is established between the parting contacts. So long as an arc exists between the contacts of the switch, the current continues to flow through the switch. As the contacts of the switch part even further, and the current approaches the zero value, the arc becomes unstable and eventually extinguishes causing the current flowing in the arc to immediately drop to zero. The instantaneous value of the current when the arc extinguishes is known as the Chop Current. Current chopping is particularly prevalent in vacuum interrupters because of their inherent ability to efficiently exinguish arcs that are formed between the opening contacts of the interrupter.

The magnitude of the chop current in a switching device is dependent upon many factors, such as, the type of switching device, the contact material, the contact shape and the peak magnitude of the current that was flowing through the switch prior to interruption [4]. Chop current values as large as 1 to 2 Amps are not uncommon [5].

The consequence of current chopping is that transient overvoltages are produced. The reason for this is that even though the current in the switching device immediately falls to zero following arc interruption, the energy stored in the inductive components of the affected circuit do not immediately fall to zero. The energy stored in the inductive components of the circuit are dissipated by utilising the circuit’s stray capacitances as a return path. The oscillations formed between the inductive and capacitive components of the circuits are in fact transient overvoltages. The magnitude of the transient overvoltages is largely dependent upon the stored energy prior to current interruption.
III. FIELD TESTS

A typical arrangement for a transportable mine substation is as shown in Fig. 1.

![Diagram of transportable substation configuration](image)

Fig.1 Typical transportable substation configuration.

The two most distinctive characteristics of the transportable mine substations in operation in Central Queensland are the use of a 5A Neutral Earthing Reactor (NER) on the transformer secondary and vacuum contactors. The 5A NER’s are used to limit the single-phase-to-ground fault levels. The vacuum contactors are used for controlling power delivery to the connected motors as well as isolating earth faults. Note that the vacuum contactors are not used for isolating phase-to-phase or three-phase faults due to their low interrupting capacity rating. As discussed in Section II above, vacuum switching devices and inductive network elements contribute largely to the incidence of transient overvoltages.

In order to investigate exactly how significant an affect these equipments have on the incidence of transient overvoltages in mine power systems on-site, above ground, transient field test recordings were conducted on the substation configuration shown in Fig.1. A Tektronics TDS 544A high speed digital storage oscilloscope was used to record the line-to-ground voltages on the source side of the vacuum contactors. The voltage across the NER was also recorded.

Recordings of the transients subsequent to the Direct-On-Line (DOL) starting of the motor were taken, as were the transients subsequent to stopping the motor. In addition, single-phase-to-ground faults were instigated at the terminals of the motor and the transients subsequent to their isolation, via operation of the vacuum contactors, were also recorded.

As a result of the recordings that were undertaken it was found that significant prestriking transients occurred during the starting of the motor. Prestriking transient overvoltages as large as 8kV (line-to-ground) were recorded. Conversely, it was found that no transients occur during the turning off of a motor under normal balanced conditions. However, if was found that significant transient overvoltages occurred during the isolation of a motor consequent to an earth fault on the load side of the vacuum contactors. On one occasion a phase voltage of 20kV (line-to-ground) was recorded on the 3.3kV (line-to-line) side of the substation.

IV. POWER SYSTEM COMPUTER MODEL

Following the collection of the field recordings the task of developing a computer model to simulate the switching transient overvoltages was undertaken. The computer model was developed in the popular Alternative Transient Program (ATP) power system simulation package.

The single line diagram shown in Fig.2 is a representation of the base system model that was developed.

![Single line representation of the base computer model](image)

Fig.2 Single line representation of the base computer model.
The computer model explicitly models each of the phases, hence, all interactions that occur between the phases can be observed. It can be noted that the 11kV and 3.3kV circuit breakers shown in Fig.1 have been omitted from the computer model shown in Fig.2. The reason for this is that all of the switching studies investigated involved the operation of the 3.3kV vacuum contactors only. Hence, there was no need to include the 11kV and 3.3kV circuit breakers in the computer model.

The model used for the source consisted of three single-phase, ideal, balanced, sinusoidal voltage sources in series with an equivalent Thevenin source impedance branch. A more detailed representation of the 11kV network was undertaken in the initial stages of the project, however, it was found the inclusion of this did not have any influence on the outcome of the transient simulations. In fact, it is interesting to note that no perceptible transients were seen on the 11kV side of the transformer following switching operations on the 3.3kV side of the transformer.

The model used for the transformer consisted of the interconnection of three of the standard ATP single-phase transformer models. The single-phase transformers were interconnected to give a phase shift corresponding to the Dyn11 vector group.

Following the initial computer simulations that were undertaken it was found that it was necessary to include the core loss resistance of the NER as this was largely responsible for damping the transients consequent to the isolation of earth faults.

It was found that the transformer stray capacitance, although small, was an essential part of the computer model. The stray capacitance dictates the frequency of oscillations associated with earth fault isolation. The value of the stray capacitance was calculated using (1)

$$f = \frac{1}{2\pi \sqrt{L \cdot C}}$$

Where, $f$ is the oscillation frequency, $L$ is the inductance of the NER and $C$ is the stray capacitance on the 3.3kV side of the transformer.

Although not required for the earth fault simulations, it was found that the inclusion of a reactance representative of the transportable substation's 3.3kV bus bar was required when simulating motor starting prestriking transients.

Two different vacuum contactor representations were used in the computer simulations. For the earth fault isolation simulations the simple "Time-Controlled" switch provided by ATP was used. For the modelling of prestriking transients, the more sophisticated programmable "TACS-Controlled" switch was used.

A simple pi model was used for the trailing cable. Numerous simulations were performed for various sizes and lengths of Type 241.3 trailing cables.

The simple static IEEE motor model was used for motor starting and earth fault isolation simulations by appropriately interconnecting resistive and inductive branches. For motor stop studies the more complex motor model developed by Ghani [6] that models a motor's dynamics was used. Static and dynamic models for 150kW, 275kW and 450kW motors were developed.

V. COMPUTER MODEL VALIDATION RESULTS

The computer models that were developed were validated against actual voltage recordings taken from the field. The models were validated against single-phase-to-ground fault isolations, motor starting (including prestriking transients) and motor stopping transient recordings.

The waveforms shown in Fig.3 are field test recordings that were taken during the isolation of a Phase-A-to-ground fault located at the terminals of a 150kW motor.

![Fig.3 Field recording voltage waveforms during the isolation of a single-phase-to-ground fault.](image_url)
The corresponding waveforms produced by the computer model (earth fault located on Phase A of "Bus5") are shown in Fig.4.

Fig.4 Computer simulation voltage waveforms during the isolation of a single-phase-to-ground fault.

By a process of trial and error the opening sequence of the three phases of the vacuum contactor were determined. Unfortunately during the field recordings no means were available to measure the vacuum contactor current. As a result of this, the chop current used in the computer model was gradually increased until the magnitude of the field and computer simulation voltage waveforms correlated with each other. For the computer simulation transients shown in Fig.4 a vacuum contactor chop current of 1.25A was used.

It was initially thought that the magnitude of the transient overvoltages subsequent to the isolation of earth faults were directly proportional to the magnitude of the chop current. However, by inspection of the currents flowing through the various branches of the computer model it was found that the overvoltage magnitudes were in fact proportional to the current flowing in the NER at the time of fault isolation. For the simulation presented in Fig.4 the NER current at the instant of fault isolation was 1.29A. In this instance the difference between the chop current and NER current is only small, however, under certain conditions, such as the isolation of high impedance earth faults it was found that the difference between the chop current and NER current could be significant. Hence, it was found that under certain conditions large overvoltages could occur even if the chop currents is relatively small.

VI. TRANSIENT OVERVOLTAGE REDUCTION

Following the validation of the computer model against field recordings a large number of studies were performed to ascertain the worst case overvoltages that could be expected, both during the isolation of earth faults and the energisation of motors. Studies involving different length trailing cables, different size trailing cables, different size motors and different switching instances were investigated.

The computer simulations that were undertaken found that for a chop current of 2A, overvoltages as large as 26kV (line-to-ground) could occur during the isolation of earth faults. The motor starting simulations found that prestriking overvoltages up to 9kV (line-to-ground) could be expected. It was also found that the closer the poles of the vacuum contactors closed in unison typically resulted in smaller prestriking transients during motor energisation.

Because the computer simulations showed that large overvoltages could occur in mine power systems, particularly during the isolation of earth faults, the focus of the research shifted to identifying ways of reducing the magnitude of the overvoltages.

The 5A NER and the inherent current chopping ability of the vacuum contactors had been identified as the two factors that contributed most to the overvoltages. Given that the vacuum contactors are an integral part of the substation design it was decided that efforts to reduce the transient overvoltages would be restricted to investigating alternate grounding schemes.

The design criteria imposed for any alternate grounding scheme was that it should be small, generate little heat and restrict earth fault currents to 5A.

Computer simulations showed that the use of a 5A neutral earthing resistor was very effective at reducing the overvoltages consequent to the isolation of an earth fault. It was however, rejected as a practical solution, due mainly to space restrictions within the existing transportable substations.

The simple concept of connecting a Resistor-Capacitor snubber in parallel with the 5A NER was simulated. It was immediately obvious that the addition of an R-C snubber
was very effective at reducing the transients consequent to earth fault isolation. After performing a number of simulations it was found that a 1kΩ resistor in series with a 0.5μF capacitor provided the best overall attenuation of transient overvoltages for various circuit configurations. Computer simulations showing just how effective the 5A NER/R-C snubber earthing system is at reducing overvoltages consequent to earth fault isolation is illustrated in Fig.5. For this simulation a chop current of 1.0A was used.

![Graphs showing computer simulation results](image1)

**Fig.5** Computer simulation of earth fault isolation when a 5A NER + R-C snubber grounding is used.

Due to the high impedance of the R-C snubber (under all likely frequency conditions) the physical size of the resistor was not a concern. Furthermore the heat generation would be minimal and the effective impedance of the parallel combination of the 5A NER and the R-C snuber is almost the same as the impedance of the 5A NER by itself.

The results of the R-C snubber computer simulations were made available to a number of coal mine personnel and the Queensland Government’s Department of Mines and Energy. As a consequence of this, a decision was made to manufacture an R-C snubber and conduct further field tests to confirm the effectiveness of the R-C snubber in practice. The snubber was manufactured in Australia by MM Mining, a manufacturer of various types of mining equipment ranging from transportable substations to overload protection relays to trailing cables. The fully encapsulated R-C snubber constructed by MM Mining was named the RC-2000.

![Field recording graphs](image2)

**Fig.6** Field recording of earth fault isolation when a 5A NER + R-C snubber grounding is used.

It is obvious from Fig.6 that the addition of an R-C snubber to the earthing system of the transportable substations virtually eliminates overvoltages subsequent to earth fault isolation. The computer simulations and subsequent field recordings also showed that the addition of the R-C snubber marginally reduces the transients associated with motor starting. The ability of the R-C snubber to reduce motor starting transients is illustrated in Fig.7.
Fig. 7 Field recording of Phase “A” motor starting prestriking transients.

Fig.7(a) is a field recording of the Phase “A” prestriking transients when system grounding consists of a 5A NER only. Fig.7(b) is a field recording of the Phase “A” prestriking transients when system grounding consists of a 5A NER in parallel with an RC-2000.

A comparison of Fig.7(a) with Fig.7(b) shows that following the complete closure of the vacuum contactors, at approximately the 3ms mark, all disturbances quickly disappear when the R-C snubber is installed.

VII. RC-2000 SERVICE EXPERIENCE

Since the RC-2000 was first field tested, there have been ten (10) installed in 11kV/3.3kV transportable Longwall mining substations at five different mines. To date there have been no reported failures of the RC-2000. Moreover, there has been no reported NER, vacuum contactor, or transformer failures of any kind in the transportable substations that have been fitted with an RC-2000.

Given that single-phase-to-ground faults are a reasonably common occurrence in underground mining operations, the RC-2000 has undoubtedly minimised the exposure of the 11kV/3.3kV substations to the harmful effects of large transient overvoltages.

VIII. CONCLUSIONS

The results of an extensive research project into the study, field measurement and computer simulation of transient overvoltages in inductively grounded mine power systems has been presented. The research project found that transient overvoltages in excess of 20kV (line-to-ground) can occur in 3.3kV (line-to-line) power systems grounded through 5A neutral earthing reactors during the isolation of earth faults. The results of computer simulations and subsequent field measurements following the addition of an R-C snubber in parallel with a 5A NER were also presented. These results showed that the transient overvoltages consequent to the isolation of earth faults are virtually eliminated.

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X. REFERENCES


