Where are the Circuit Breakers?

Nigel Machin and Jurie Dekter
Rectifier Technologies Pacific
24 Harker Street
Burwood, Victoria, 3125
Australia
information@rtp.com.au

Abstract A technique for using relays and a fuse to replace the output circuit breaker on a rectifier module is presented. The technique involves less power loss, less cost, greater compactness, and greater reliability than the traditional circuit breaker.

1 Introduction

The circuit breaker has been used as a combined disconnection device and over-current protection device for the DC output of rectifiers for many years. This double function provided by one component has made the circuit breaker the industry standard and many Telecom specifications require their inclusion in rectifier modules.

The advent of the modular switch mode rectifier (SMR) has created an opportunity for alternative devices, particularly because the SMRs can be disconnected from the DC bus at their connector.

2 Functional Requirements

There are many functions required by the system that can be performed by the circuit breaker.

- Disconnect device for servicing - it is not safe or desirable to perform servicing operations on live equipment so the rectifier must be capable of being disconnected from the AC and DC power systems.

- No surge at plug-in or at any other time - the electrolytic capacitor on the output of each rectifier can pass a high surge current when the rectifier is first connected to the DC bus. For example a 3000uF output capacitor has an ESR of 15mohm. If this capacitor is connected in a discharged state to a 54Vdc bus, then a brief surge of 3600A can occur. This surge could upset the load by setting off under-voltage alarms, or at least make a loud ‘click’ on the telephone network. By closing the output circuit breaker only after this capacitor is charged, the surge is reduced or eliminated.

- Polarity reversal protection - if the polarity of the output of the rectifier is reversed then the system will pass a large uncontrolled current through the internal secondary diode of the rectifier. It is best to open the circuit in this circumstance with an overcurrent protection device such as a circuit breaker.

- SMR isolation from the DC bus in the event of an SMR secondary circuit failure - if an SMR suffers catastrophic failure in its output circuit then the battery and system should be protected - an overcurrent protection device is required.

1 Circuit Breaker Characteristics

The miniature circuit breakers which are frequently used for output protection and disconnection are low-cost, DIN rail mounting, modular types which can be seen in the ‘fuse box’ of any recently wired house. Most AC rated circuit breakers are suitable for breaking DC current at 60V, provided that the line inductance is small (L/R<0.015s for one manufacturer). They will clear fault currents of 6 or 10kA typically though more expensive versions will clear 36 kA. This capability is sufficient for small battery systems, but quickly becomes inadequate in larger systems such as are found in central office exchanges. Clearing time for a 20x overload is between 8 and 20ms for a typical magnetically tripped circuit breaker.

4 Circuit Breaker Installation and Performance

A circuit breaker must be easily accessible for the operator to actuate it and this mostly means mounting on the front panel of the SMR. Connectors for AC and DC are now more commonly mounted at the back of each SMR to allow easy module changeover. Since the correct electrical position for the circuit breaker is as near as possible to the live output terminal, cabling or bussing between the back and the front of the SMR needs to be provided, usually going both ways! This cabling creates a significant power loss (it carries full output current) and tends to block airflow in the SMR. It also acts as an antenna picking up noise as it passes across the ‘hot’ power electronics switching circuits.

The circuit breaker self-heats and should be kept cool (or de-rated accordingly), and so uses up valuable cool-space. The circuit breaker should be mounted vertically in order to please the eye, which means a minimum case height of 3U (132mm) for most types.

When designing for an output circuit breaker in an SMR module there is (in our experience) a considerable overhead of space, especially for smaller modules.

5 The Circuit Breaker in Operation

In the event of a fault the circuit breaker will trip (assuming that the fault current is not excessive) and further damage to the equipment will be prevented - until the operator comes along to investigate the problem. The operator will in many instances test to see if there is a genuine fault or if the breaker has just turned off. The subsequent re-start will create more damage to the module and jeopardise the reliability of the system further. The operator may repeat this process many times before being fully satisfied!

6 Relay and Fuse Characteristics

Semiconductor protection fuses are desirable because in the event of a fault they minimise the damage that occurs by virtue of their fast-blow characteristics. These fuses have high interrupt ratings, being 100 or 200kA which should be adequate for very large installations. The energy let-through is well controlled and a silver element fuse will clear an overload of 20x rated current in 1ms or less - almost an order of magnitude faster than a circuit breaker - resulting in much less damage in the event of a fault.

Relays are suitable for switching their rated current with little or no margin for overload. They mostly will break their rated current at 24Vdc maximum, and will burn out if asked to switch off at 48Vdc! In the event of a sudden overload the contacts of the relay tend to be pulled apart by the mutually repulsive magnetic fields in the conducting parts of the contact, while plasma arcing heats the contact surfaces. After a short time the repulsive force diminishes and contacts re-close, and then (assuming the heating of the contact surfaces has been sufficient) ‘weld shut’! Great care must be taken if we are to use the relay successfully in the output circuit of a rectifier.

7 Proposed Circuit

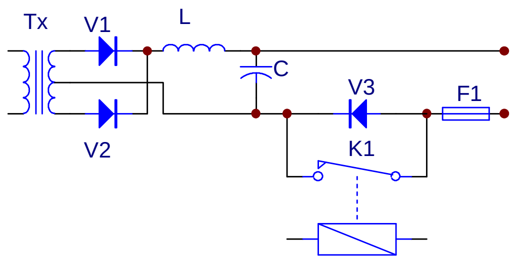

Fig 1. Proposed power circuit.

The circuit in Fig 1 shows our proposal applied to the output of a rectifier.

Fuse F1 provides protection for the battery and bus in the event of catastrophic failure in the output circuit or polarity reversal. It is internally mounted in the SMR, so if it has cause to open, the operator is unable to ‘try it again’ and must replace the SMR.

Relay K1 isolates output capacitor C from the DC bus initially and closes only when the voltage on C is equal to the bus voltage, eliminating output current surges. Importantly the action of closing the relay is performed by the circuit and not the operator (as is circuit breaker closure) and therefore happens correctly every time. Once it closes it remains closed under all circumstances except when mains power fails. During mains power failure there is no output current, therefore the relay opens under no-load conditions and so should be reliable.

Diode V3 bypasses the contacts of K1 in the event of a high current surge as occurs during a short circuit test. V3 limits the voltage developed across the arcing contacts of K1 and thereby reducing the contact heating and preventing them ‘welding shut’.

The output connector functions as the disconnect device. The SMR is designed to fit into a magazine with rear mounted blind-mating connectors. The act of removing the SMR from the magazine performs a complete and unambiguous disconnect function.

Power loss is reduced because the relay and fuse are positioned near the output connector. Although the fuse and circuit breakers have comparable loss, the reduction in length of high current cabling means that the overall loss is less.

Cost of component parts is about the same for each solution, however the relay/fuse solution results in a smaller SMR case size, and consequently greater power density. This decreases the number of racks required in large systems, and in small systems increases the number of SMRs in a subrack/magazine. System costs are thus reduced in both small and large systems.

Reliability is enhanced on a system level because startup sequencing is automated and because fault clearing is adequate and final (no try-it-again possible after the fuse blows). There is less chance of a fire or damage to the exchange because of the large fault clearing capability of the fuse.

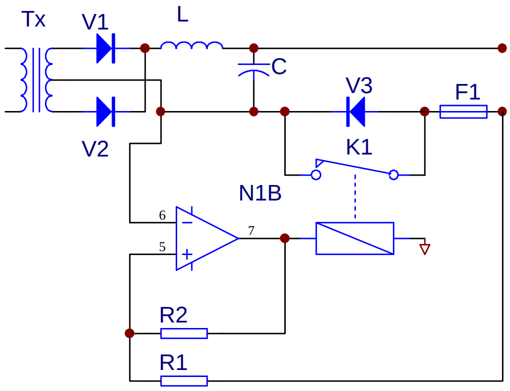

Fig 2. Simplified control circuit.

A simple comparator with a moderate hysteresis provides control of K1 as shown in Fig 2. K1 is a normally open relay (so that its contacts will be open when there is no power applied to its coil). When mains power is first applied K1 is initially open, and the comparator holds it open until the voltage on C and the output voltage are the same. When K1 closes the circuit is effectively latched since the voltage across the contacts of K1 cannot rise to overcome the hysteresis around the comparator. Note that if there is no battery (just a resistive load perhaps) then K1 will close almost immediately because both C and the output will be at zero volts initially.

Diode V3 can be inexpensive since it only handles occasional surges. A 1N5404 type was found to be sufficient to handle a fault current of 7000A, corresponding to 6000uF of output capacitance. Hundreds of discharge tests proved the diode reliable in this service.

One interesting possibility that this circuit allows is hot-pluggability. If a connector is used whose contacts can break the full load current, then an SMR can be removed and inserted into a live DC and AC bus. Soft start and inrush limiting must be provided on the AC input of the SMR of course.

8 Parallel Relays

In applications where the output current exceeds the rating of the largest sized commodity type relay, the temptation is to use multiple relays in parallel.

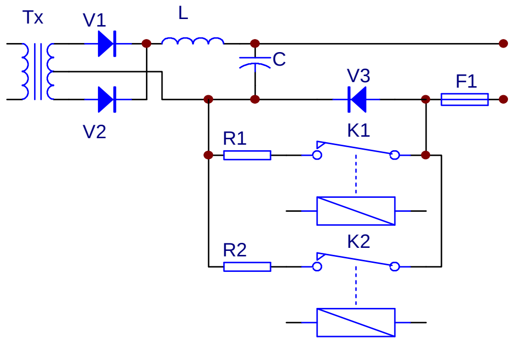

Fig 3. Arrangement for paralleling relays.

The relays must acceptably share current in the medium to long term or lifetime reduction will occur. This can best be achieved by using resistors in series with each relay's contact and then parallelled as shown in Fig 3.

A suitable value for the series sharing resistors is about the same value as the relay's contact resistance. In our 100A output SMR, four sharing resistors for 30A relays were made from 15cm lengths of 2.5mmSQ PVC insulated wire.

9 Failure Detection for Parallel Relays

If one relay in a parallelled array is not taking its fair share then the SMR is at risk. It is easy to monitor the relative voltages across the sharing resistors (R1 and R2 in Fig 3) in order to detect a problem.

An interesting phenomenon occurs when the relays first close. Sharing is initially poor, settling only after some minutes at medium to high currents. The effect appears to be related to the contact material. It also appears that the contact resistance of silver alloy contacts decreases with time, and while this may not have much effect when a single relay is used, it causes up to 5:1 current imbalances in parallelled contacts. In order to be able to detect a true imbalance, our monitoring circuit ignores imbalances for several minutes to allow the contacts to establish themselves.

10 Implementation

Fig 4 shows a 25A SMR module with no circuit breakers or individual controls. This module is hot-pluggable and has internal AC fuses for fault protection in case no upstream circuit breaker is used. A separate bank of circuit breakers can used for AC distribution to each SMR, which function as on/off switches as well as providing overcurrent protection if desired. By installing these breakers outside the SMR the AC wiring and AC input connector of the SMR are protected. In its output circuit each SMR uses a single 30A relay, a BS88 style HRC semiconductor protection fuse, and a

1N5404 relay bypass diode. The fuse is oversized in order to minimise power loss.

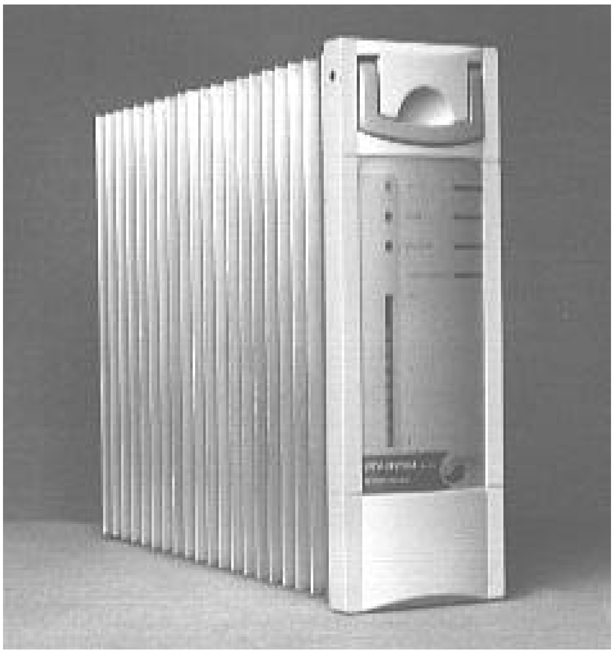

Fig 4. 25A SMR showing no circuit breakers.

Fig 5 shows five of the 25A modules side-by-side in a 19 inch rack. The absence of circuit breakers has allowed us to make a more compact and ‘clean’ system than would otherwise be possible. The simple approach has been extended to include a ‘plug and play’ approach where the operator has no adjustments to make when an SMR is replaced.

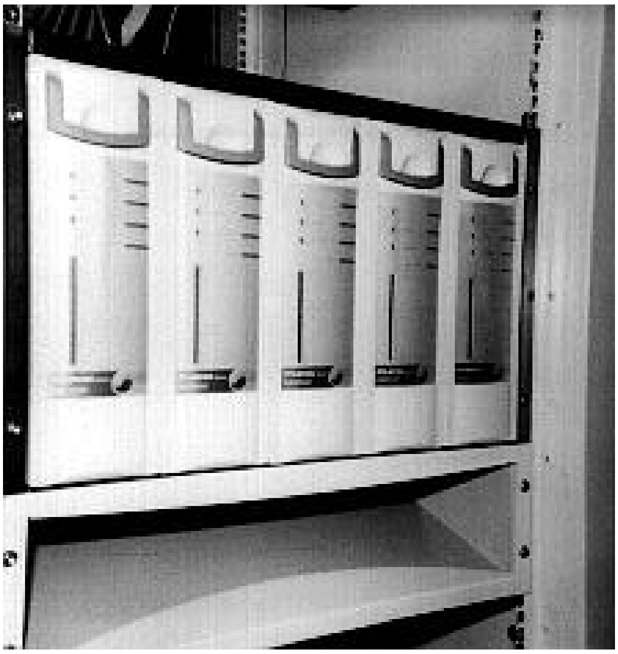

Fig 5. Magazine of 25A SMRs in a 19 inch rack.

Fig 6 shows a rack of twenty 100A SMRs previously described with no internal circuit breakers [1]. A bank of twenty circuit breakers can be seen at the top of the rack for AC distribution (discussed above). Each module is 2U (88mm) high which permits a standard 45U high rack to deliver 2000A. The inclusion of circuit breakers would have increased the module height to 3U (132mm) and only 1300A would have been available per rack.

Each SMR is programmable from its front panel and has an LCD display to show output current, status, and various settings. There is a low current on/off switch which turns the control circuit on or off. An alternative to this control arrangement would be the simple set-up of the 25A SMR. Each SMR has four 30A relays with four current sharing resistors (lengths of wire), a single BS88 style fuse, and two parallelled 1N5404 relay bypass diodes. A quad op amp is used to detect sharing imbalances and the micro-controller provides the long time delay required for the relay contacts to settle.

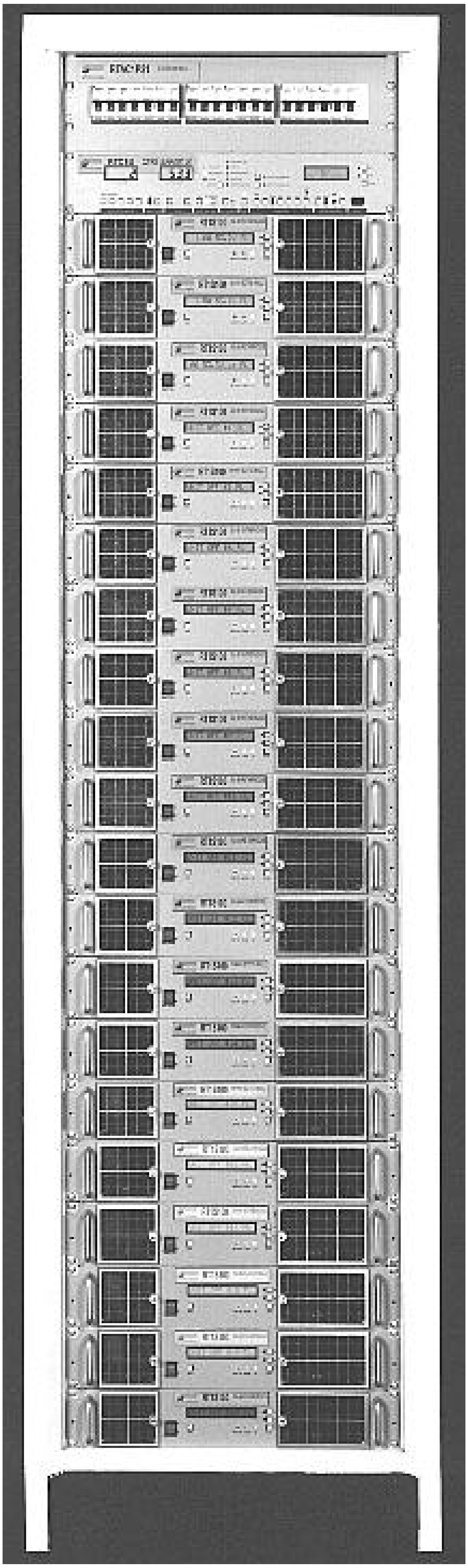

Fig 6. 2000A rack made possible by 2U high 100A SMR modules.

11 Conclusion

An alternative to the output circuit breaker has been proposed which reduces power loss, reduces system cost, enhances system reliability, and results in smaller SMR modules than are otherwise possible. The alternative uses a series combined relay and fuse. The fuse is a superior protection device, and the disadvantages of the relay are overcome by the techniques described. Examples of SMRs incorporating the new technique are described showing the superior power density and simplified front panel layout possible. The 25A SMR can be hot-plugged as a result of this new technique. So next time someone asks 'Where are the circuit breakers?' you have an answer!

References

[1] N. Machin & T. Vescovi, "*Important System Design Concepts for a Modular DC Rack Power System featuring a Single Phase 100A, 48V Switch Mode Rectifier*", INTELEC Proceedings 1995.