A DELTA-CURRENT ADMITTANCE RELAY FOR LINE LOADABILITY ENHANCEMENT

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1. INTRODUCTION

The United States to Manitoba interconnection consists of two 230 and one 500 kV transmission lines and as of 1994 has a total capability of 1875 MWs from Manitoba to the United States. The 500 kV line was constructed in two segments: the North section runs from Manitoba Hydro's Dorsey Substation in Winnipeg to the Forbes Substation in northern Minnesota, the South runs from Forbes to Northern States Power's (NSP) Chisago substation in the Twin Cities. The bulk of Manitoba Hydro's generation is hydro based and has been developed on the Nelson River system feeding into Hudson Bay. A 3850 MW HVdc transmission system delivers the power to the Winnipeg area and to the 500 kV system. A simplified one-line diagram of the 500 kV system is given in Figure 1.0.

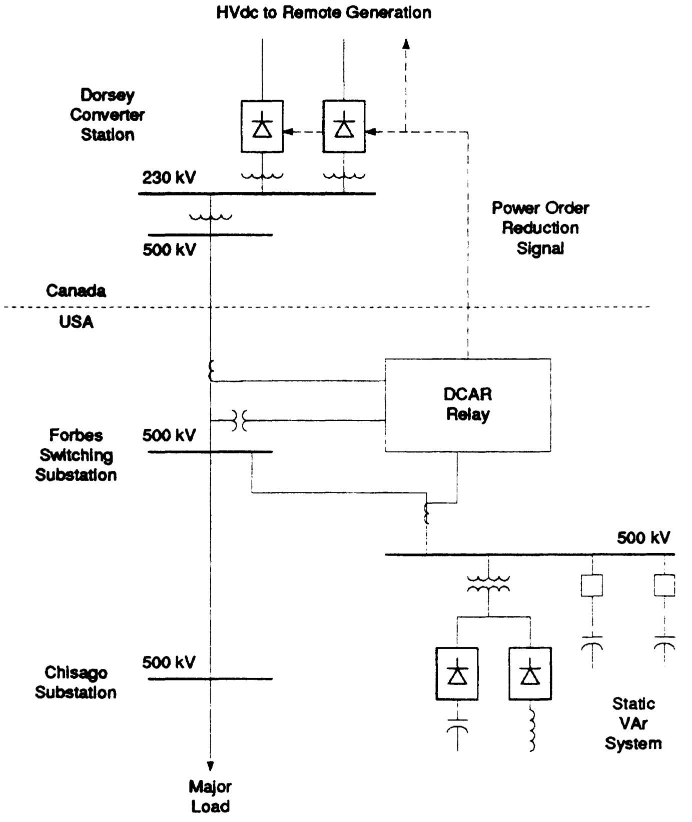

Figure 1.0 - One line diagram of system

In order to enhance the operation of the integrated AC/HVdc transmission system, a fast power order reduction scheme was added to the Dorsey converter system controls which rapidly reduces the HVdc power flow when certain stressed AC power system conditions are realized. Some of the conditions detected are loss of any major Manitoba interconnection or a low AC system voltage at the Dorsey 230 kV bus. In 1991, an impedance measuring out-of-step relay was applied to the North 500 kV line at Forbes for detection of "voltage threatening" power swings or severe system disturbances and initiation of an HVdc reduction order. A transfer trip type transmitter was used for communicating the signal to the Dorsey converter station. The ability of this scheme to rapidly reduce Manitoba to US transfers following severe system disturbances has enhanced the overall southward power transfer capability by several hundred megawatts.

Since 1991, NSP and Manitoba Hydro have further increased the transfer capability of the 500 kV system by adding series capacitors in 1993 and a +400/-450 MVAr static VAr system (SVS) at Forbes (SVS) in 1994, all of which have complicated the application of the Forbes impedance dc reduction relay. Increased flows on the 500 kV have moved the steady state impedance locus within its outer blinder where a setting change (closer to the Z plane origin) would desensitize the relay and make coordination with existing out-of-step tripping relays difficult. Also, with the SVS providing dynamic voltage support at Forbes, an HVdc reduction is no longer required, nor is it desirable, while the SVS is in operation and adequately supporting the voltage. Applying an impedance based reduction relay, which would provide reliability for system voltage protection as well as security against misoperation with the SVS in service, was deemed a difficult if not impossible task.

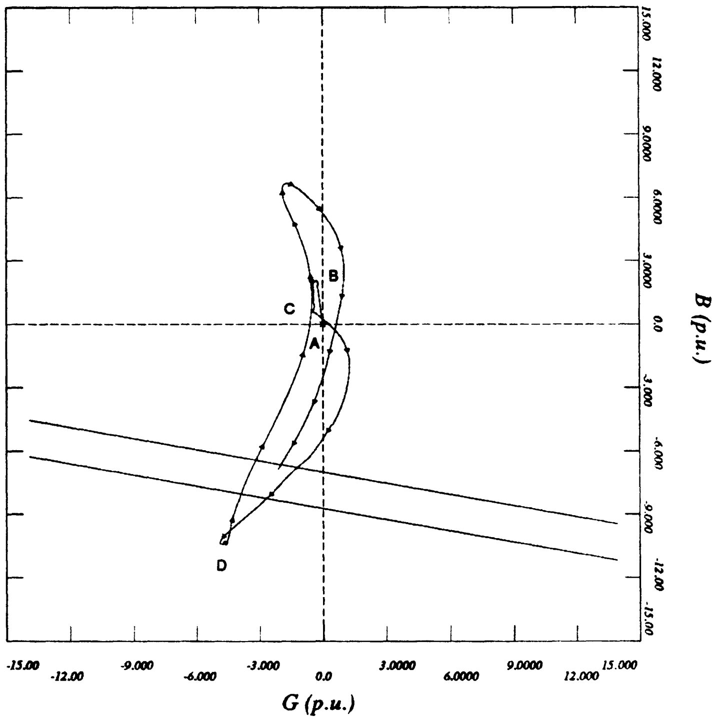

Figure 2.1 - Delta admittance plane swing trajectory

2. PRELIMINARY DEVELOPMENT

Faced with the above difficulties, the development of a novel relay application for HVdc reduction, using 500 kV current and potential as inputs, was pursued. In order to provide adaptability for varying line flow conditions and still maintain required sensitivity, the incorporation of a delta or washout function into an impedance or admittance algorithm was envisioned. A delta current admittance relay (DCAR) function, where:

$$\Delta Y = \Delta I_{line} \ / \ V_{line}$$

This was selected because its amplitude would tend to approach zero during steady state conditions making it "adaptive" to system conditions. During dynamic events the function would develop an amplitude and phase dependent on the severity of the swing and the amount of voltage depression. The details of the washout function are discussed in Section 3 of this paper.

The performance of the relay algorithm was then tested by incorporating it into the MAPP stability model and running numerous simulations looking at various faults and pool disturbances. Figure 2.1 shows a typical admittance plane plot of the DCAR locus observed for a severe generator outlet stuck breaker fault, and illustrates some of the prominent characteristics of the delta current admittance plane. In this plane, movement on the vertical axis corresponds to reactive power or current changes whereas horizontal movement represents changes in real power. The initial movement (point A to B), which is due to the fault itself, is along the vertical axis indicating that the fault current is predominantly reactive, a well established fact. The movement upwards (increasing imaginary admittance) indicates that the fault is "behind" the relay. After fault clearing (point C) the swing trajectory moves down along the vertical axis or in the negative reactive power direction. This correlates with the nature of severe MAPP disturbances observed at Forbes where heavy VAr flow from Manitoba to the US is typically seen in the first half swing cycle. Point D corresponds to the minimum voltage point of the first half swing cycle. Also shown in Figure 2.1 are the straight line blinder characteristics which are used for swing detection and HVdc reduction initiation. Timing logic is applied to discriminate between faults and swings, similar to standard out-of-step relays. In the case of the DCAR, a timer is started when the locus crosses the blinder closest to the origin; a reduction order occurs when the timer expires and the second blinder is crossed.

For comparison, a Z plane apparent impedance locus for the same disturbance is shown in Figure 2.2. The relay characteristics shown here are those of the original impedance reduction relay.

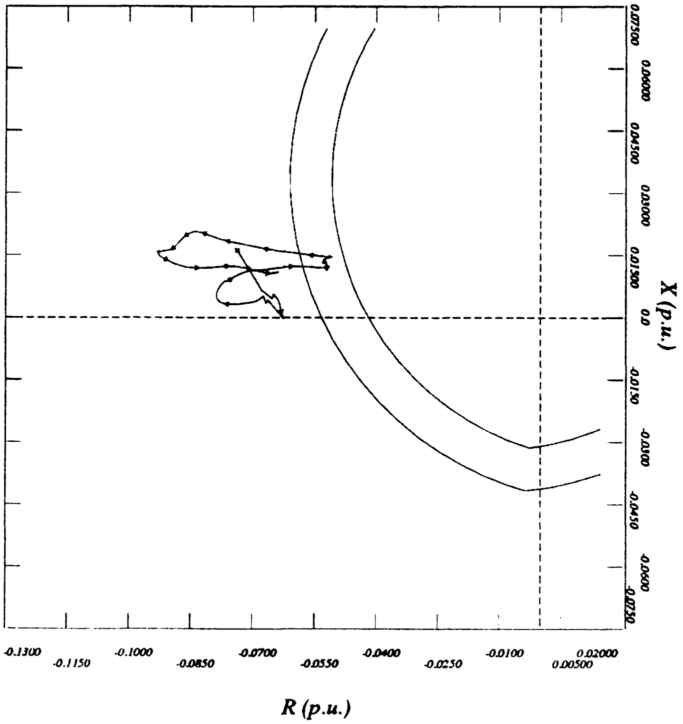

Figure 2.2 - Z plane swing trajectory

In order to prevent relay operation during normal SVS operation , a current compensation feature was added to the algorithm that adds the delta SVS current to the delta line current as shown below:

$$\Delta Y = (\Delta I_{line} + \Delta I_{svs}) / V_{line}$$

During severe disturbances the polarity of SVS current applied to the relay is opposite that of the line current which effectively reduces the total delta current contribution to the DCAR function. In the DCAR plane, this has the effect of moving the trajectory away from the tripping characteristics. Figure 2.3 shows the DCAR response for the same stuck breaker fault with the addition of the SVS and current compensation.

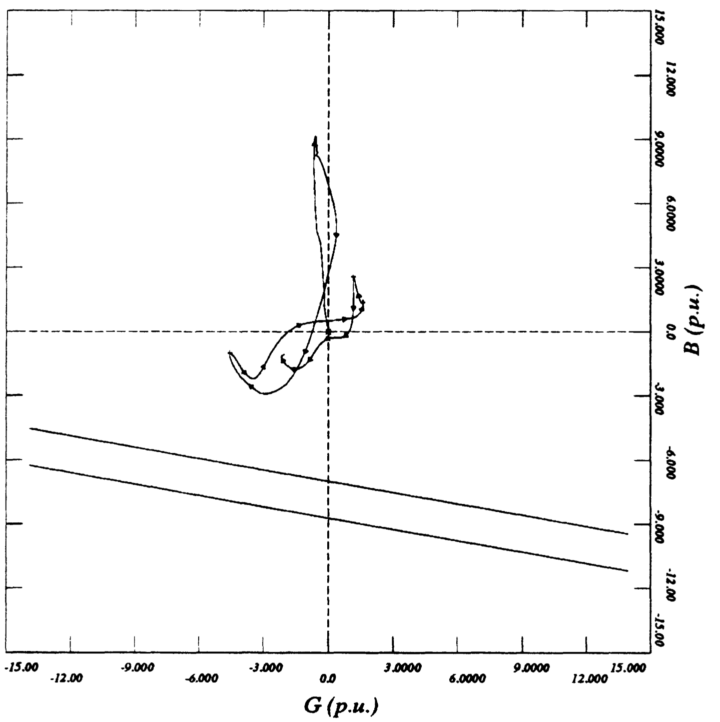

Figure 2.3 - DCAR swing trajectory with SVS compensation

From these results it was concluded that the DCAR was a viable concept and would meet the requirements established for an HVdc reduction relay at the Forbes Substation. It would provide adaptability through the use of the delta or washout function and sensitivity to initiate reductions for severe disturbances with the SVS out of service or failed. The SVS current compensation would prevent operation with the SVS in service.

The next phase of development was that of hardware implementation and prototype testing. Since the hardware platform was already established, this task primarily involved software implementation of the DCAR algorithm. Prototype testing was performed both at the factory and on a digital TNA, but is not discussed in this paper due to size limitations.

3. THEORY

Consider the elementary two machine system model of Figure 3.1.

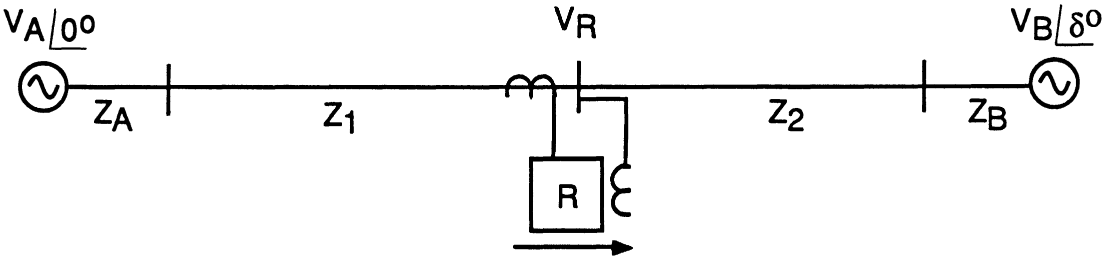

Figure 3.1 - Simple two machine system for swing study.

The corresponding Z-plane diagram is shown in Figure 3.2 along with constant-δ curves for end-to-end swing angles of 70, 80 and 90 degrees.

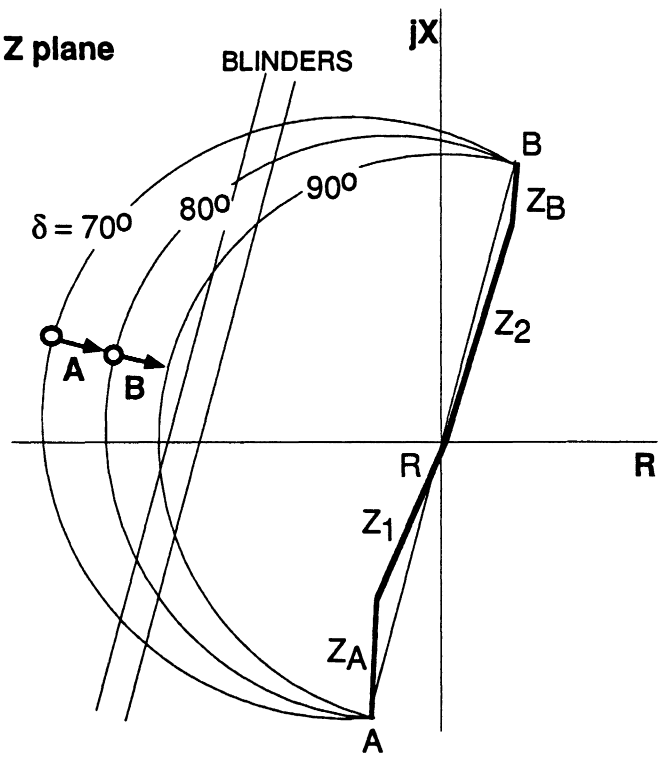

Figure 3.2 - Z plane plot of the system, with three particular lines of constant swing angle shown. Two swings are shown: A: from 70° to 80°, and B: from 80° to 90°.

The case "A" shown is meant to imply a swing that started with δ=70° steady state, swung to a maximum of δ=80° and then swung back to a new steady state condition, not shown. Similarly, for case "B", the swing started at δ=80° and swung to a maximum of δ=90° before swinging back to a new steady state value

The logic for swing detection consists of a timer that is started when the swing locus crosses the outer blinder , and stopped when it crosses the inner blinder. If the time exceeds a certain minimum, then the relay "knows" that this is not a fault condition and initiates a "trip" or HVdc reduction signal.

Principle of the Delta-Current Admittance Relay (DCAR)

The first concept of the DCAR is that if an admittance plane rather than an impedance plane is used, then the no-load condition is at the origin rather than at infinity; in other words, the no-load point is visible on a plot of finite magnitude.

The second concept of the DCAR is that it is not the absolute value of the maximum swing angle that is important, but rather the excursion in angle away from a given starting point.

Figure 3.3 illustrates these two concepts. Note that the trajectories labelled "A" and "B" are not drawn arbitrarily; they are carefully calculated from the two trajectories of Figure 3.2.

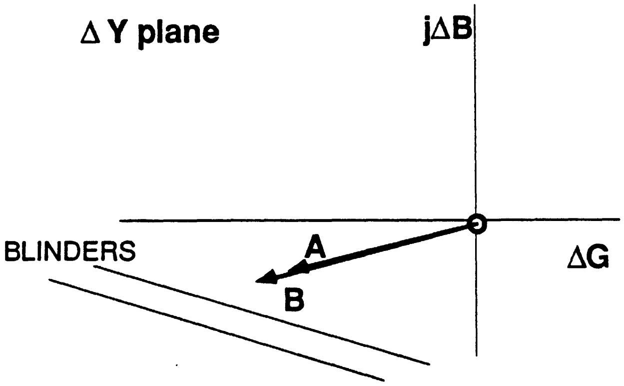

Figure 3.3 - Swings "A" and "B" corresponding to those of Figure 3.2.

The algorithm is designed such that the steady-state is always represented by the origin of the admittance plane. If the admittance is changing, the locus moves away from the origin, but when a new steady-state is reached, the locus "decays" back to the origin. The decay time constant is T_w.

To accomplish this, the current used in the calculation of admittance is processed through a "washout" function, as illustrated in Figure 3.4. To clarify this terminology:

$$\text{Admittance} = Y = G + jB = I/V$$
$$\text{Delta Admittance} = \Delta Y = \Delta G + j\Delta B = \Delta I/V$$

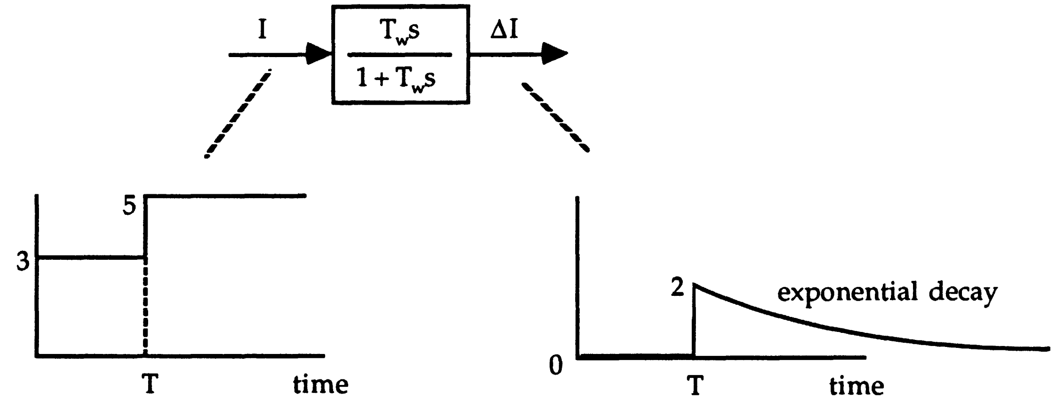

Figure 3.4 - The WASHOUT function
Note: The "washout function is applied to the real and imaginary parts of the current separately

4. IMPLEMENTATION

Software

A block diagram showing the final version of the algorithm is shown in Figure 4.1. A gain function, shown by the Ks block, allows the amount of SVS current compensation to be adjusted.

Additional blocks were included to subtract the synthesized or calculated mechanically switched capacitor (MSC) current from the total SVS current. This would allow the algorithm to only take into account the reactive current being supplied by the fast thyristor switched SVS elements and is accomplished through the switch status inputs C1S and C2S of the figure. The two summing junctions show where the capacitor current is subtracted from the measured total SVS current.

Hardware

Refer to Figure 4.2. Because of the complexity of the software, a powerful computing platform was necessary. The one used is capable of this, and in addition can perform many other functions simultaneously, such as:

- Fault recording
- PT fuse failure detection
- Remote access to recordings, settings, and software algorithms
- "Standard" out-of-step detection
- Subharmonic current detection

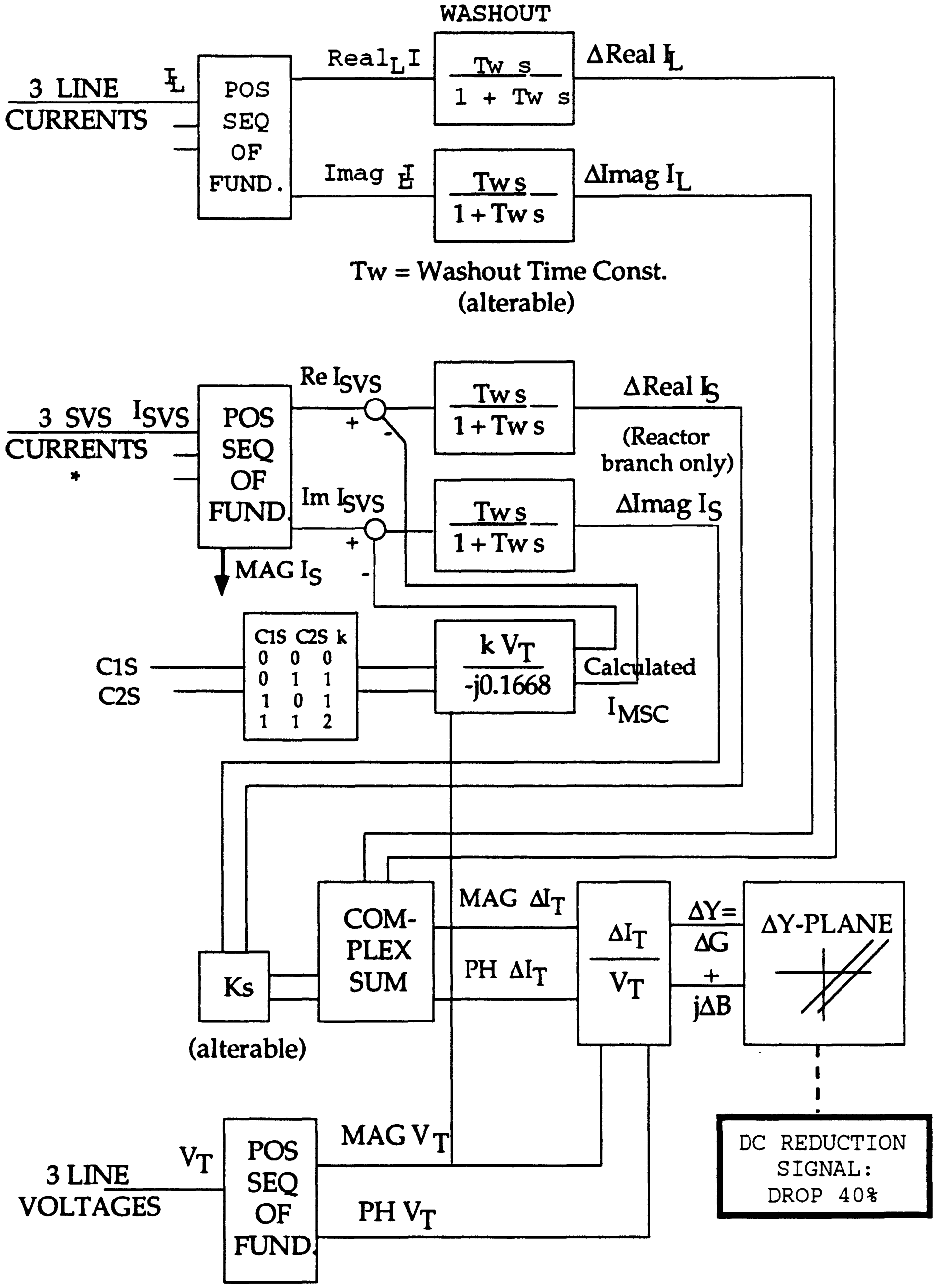

Figure 4.1 - Block diagram for the DCAR algorithm

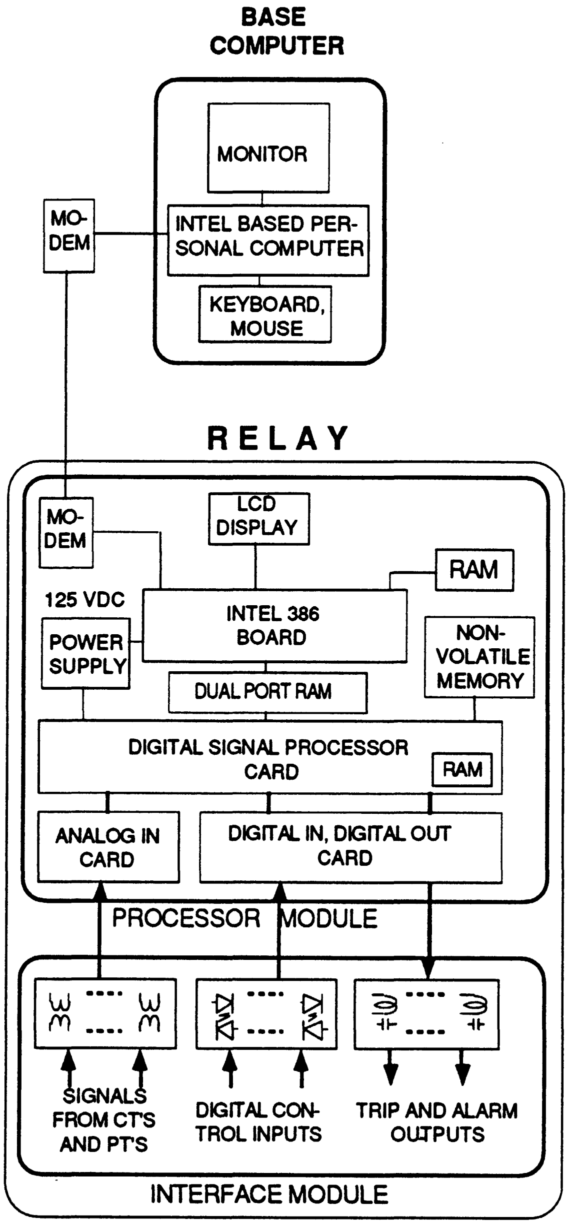

Figure 4.2 - Hardware configuration

5. PERFORMANCE ON THE SYSTEM

Two DCAR relays were installed at the Forbes 500 kV substation in April 1994. The commissioning tests included both steady-state load checks and dynamic switching events. The load checks were performed by using the DCAR's built in test and display functions which display all real time signals as well as admittance and impedance plane locus plots. This was a final verification of the polarity of the current and voltage inputs to the relay. Dynamic switching events included small variations in SVS outputs as well as capacitor bank switching. Data was captured and displayed using the "swing" recorder capability of the DCAR relay.

Figure 5.1 shows the actual delta Y plane trajectory for opening of one of the 300 MVAr capacitor banks. This is seen as an instantaneous movement in the negative dB direction corresponding to a reduction in injected VARs to the system. The locus then settles back to the origin both due to SVS compensation and washout timer effect.

The circle represents the relay's trigger threshold for data capture and triggers a 20 second recording with a 10 second prefault period.

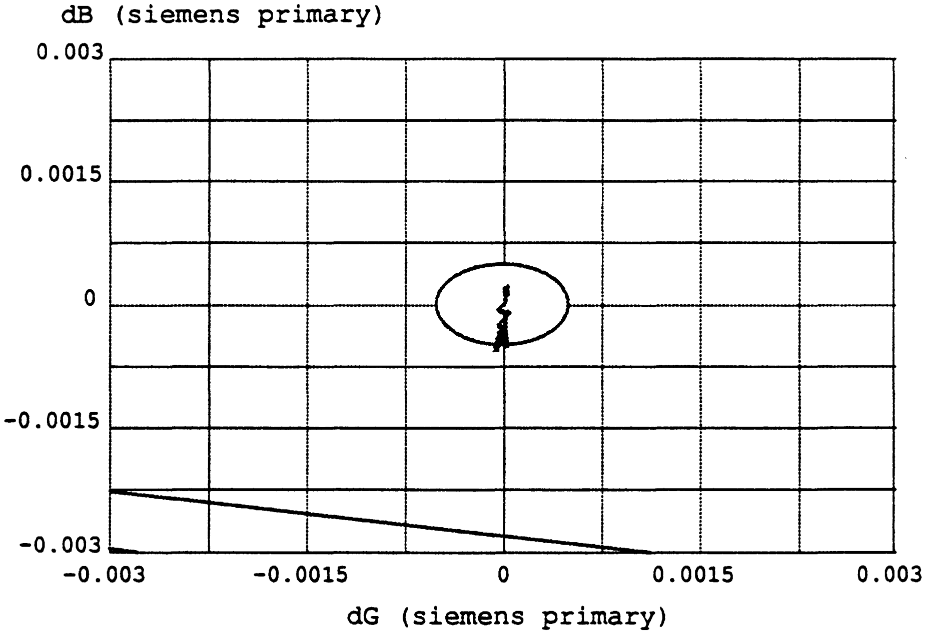

Figure 5.1 - DCAR response to MSC switching

Since the relays were placed in commercial operation, they have been subjected to various system faults and disturbances and have performed "as expected". Figure 5.2 shows the relay response to a fault on the 230 kV system connected to Forbes which was effectively "behind" the relay. Here, instantaneous movement is seen in the positive dB direction.

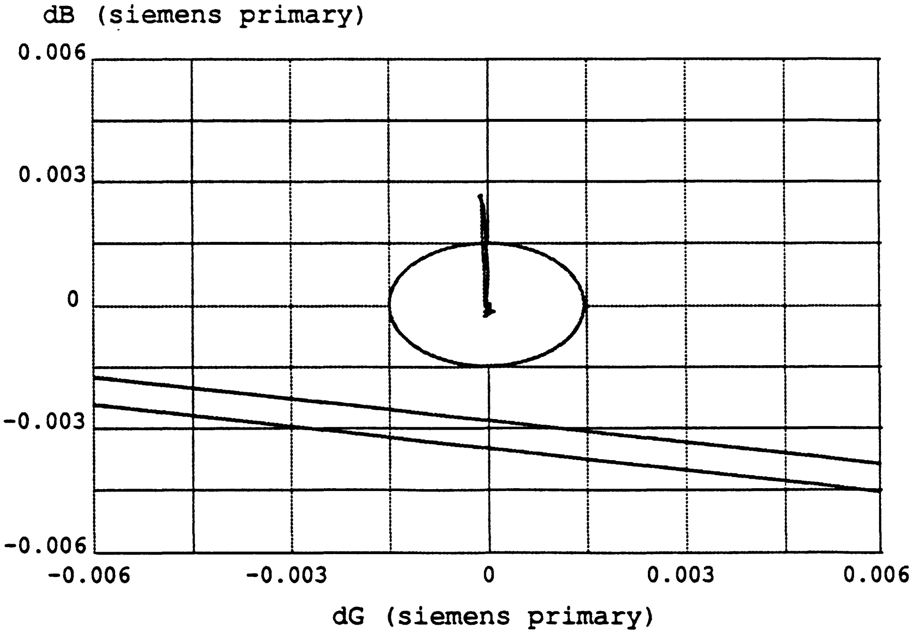

Figure 5.2 - DCAR response to fault on system

Figures 5.3 and 5.4 show the delta admittance and power system response to a Manitoba HVdc fast power order change. Figure 5.4 shows the time response of the 500 kV line real (P) and reactive (Q) power flows as well as the total SVS reactive power injection (Qs). It can be seen that the line power is rapidly reduced from 1300 to 500 MW. The SVS reactive power corresponds to the voltage regulators response to the load rejection and reduces its MVAr output accordingly. As viewed in the delta Y plane (Figure 5.3), the power change or decrease is seen as movement in the positive dG direction. The change in SVS reactive power moves in the negative dB direction followed by washout settling towards the origin.

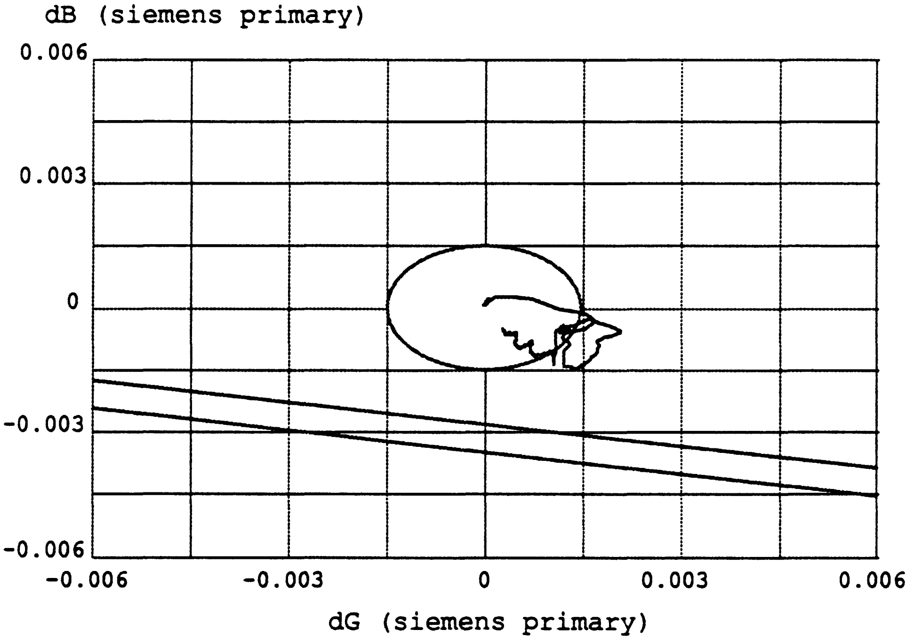

Figure 5.3 - DCAR response to HVdc power order reduction

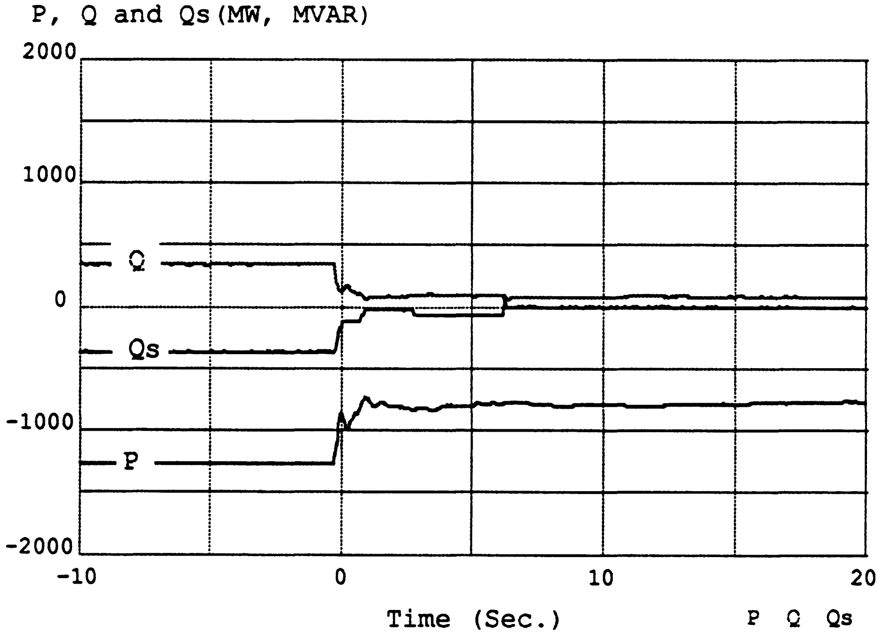

Figure 5.4 - Power system quantities for HVdc power order reduction

6. CONCLUSIONS

A delta-current admittance relay has been successfully applied at the Forbes 500 kV switching substation for detection of severe power system disturbances and for initiation of a fast power order reduction signal to Manitoba Hydro's Nelson River HVdc transmission system. Preliminary development was accomplished using power system stability analysis and demonstrated the feasability of the concept. Real time testing and actual power system operation have verified the DCAR algorithm as well as its hardware implementation.