SELECTION OF DISTANCE RELAYING SCHEMES WHEN PROTECTING DUAL CIRCUIT LINES

Darren Spoor* and Joe Zhu**

*Transmission Development
TransGrid

** School of Electrical Engineering
University of Technology, Sydney

ABSTRACT

The difficulties associated with the distance protection of dual circuit transmission lines is well known and appropriate schemes have been implemented worldwide that enable reliable protection of these assets. However, the application of these schemes usually fail to consider the more extraordinary fault occurrences that can plague transmission systems.

This paper considers the application of various faults to a simulated dual circuit transmission line. The observations have shown that inter-circuit faults may be undetectable in the instantaneous zone of protection when lines incorporate some of the presently used distance schemes. These faults can present impedances to both line terminals that are larger than those required for Zone 1 operation. Such an event has the potential to lead to a loss of major loads, mal-operation of single pole tripping schemes and even system instabilities based on the critical clearance requirements.

1. INTRODUCTION

Mutual coupling and the possibility of multi-circuit faults are the main difficulties when protecting dual circuit lines.

Coupling can produce severe underreaching and overeaching errors for distance relays, whereby the network topology, and zero sequence source impedances are both important factors in determining the magnitude of such errors. In some cases, distance relays may see less than 50% or far more than 100% of the line, depending on the infeed and coupling conditions experienced. [4]

The operation of the transmission network can result in large variations in these errors. The status of the parallel circuit produces the most noticeable effect on a simple dual circuit line, as having the circuit in service will cause overreach. However, underreach will be experienced if the line is out of service and earthed at either end. [4]

Consequently, the relay zone reaches are affected, as the distance elements must observe all faults on the lines irrespective of the network configuration.

The inherent line arrangements also make them prone to multi-circuit faults, of which the earthed cross-country fault is the most common. However, unearthed inter-circuit faults create unusual problems for the protection engineer as zero sequence currents are present in the circuits themselves, but these do not extend beyond the busbars. [1]

Inter-circuit faults are known to result in relay underreach for the phase elements [1]. This occurs as the faults change their appearance from double phase to earth to single phase faults as the position along the line is varied. This transition can push past the boundaries of the impedance characteristics required for successful operation of many protection schemes. [7]

It is also known that there can be a loss of phase selectivity for single-pole tripping schemes under these conditions [2]. This can be a serious concern on important dual circuit lines such as network interconnectors.

The probability of experiencing an Inter-circuit fault is significantly high [1], as they can result from bushfire activity, line galloping or broken conductors. It is generally understood that some faults require different solutions for the protection engineer, but when designing dual circuit protection schemes, the consequences of inter-circuit faults are often not considered in conventional design philosophies

This paper presents an analysis of different faults on a simulated dual circuit transmission line with assumed zone distance reaches, and outlines the need for the design philosophy to include an analysis of complex faults such as inter-circuit faults.

2. DISTANCE PROTECTION

2.1 Line Impedance Parameters

For a short dual circuit line, the transverse voltages and line currents present can be defined by the transmission line impedance matrix.

$$\begin{bmatrix} V_A \\ V_B \\ V_C \\ V_X \\ V_Y \\ V_Z \end{bmatrix} = \begin{bmatrix} Z_A & Z_{AB} & Z_{AC} & Z_{AX} & Z_{AY} & Z_{AZ} \\ Z_{BA} & Z_B & Z_{BC} & Z_{BX} & Z_{BY} & Z_{BZ} \\ Z_{CA} & Z_{CB} & Z_C & Z_{CX} & Z_{CY} & Z_{CZ} \\ Z_{XA} & Z_{XB} & Z_{XC} & Z_X & Z_{XY} & Z_{XZ} \\ Z_{YA} & Z_{YB} & Z_{YC} & Z_{YX} & Z_Y & Z_{YZ} \\ Z_{ZA} & Z_{ZB} & Z_{ZC} & Z_{ZX} & Z_{ZY} & Z_Z \end{bmatrix} \begin{bmatrix} I_A \\ I_B \\ I_C \\ I_X \\ I_Y \\ I_Z \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} I_A \\ I_B \\ I_C \\ I_X \\ I_Y \\ I_Z \end{bmatrix}$$

Equation 1 – Transmission line impedance matrix

As is the case for a single circuit under balanced conditions, the matrix is diagonally symmetrical (all the self-impedances and coupling impedances are identical). Similarly, for an unbalanced circuit the impedance matrix will remain diagonally symmetrical although the self and mutual impedance terms differ.

This matrix can be divided into four sub-matrices, as shown above. *A* and *D* contain the self and mutual impedance terms for the two circuits. However, the parameters within *C* and *D* describe the inter-circuit coupling between the lines.

Generally the line sequence impedances can be obtained from the self and coupling parameters of the circuit. However as most lines are not symmetrical, the actual impedances observed at a particular location will also depend marginally on the combination of faulted conductors and the geometry of the line.

$$Z_0 = Z_S + 2Z_M \qquad Z_S = \frac{1}{3}(Z_R + Z_W + Z_B)$$
$$Z_1 = Z_2 = Z_S - Z_M \qquad Z_M = \frac{1}{6}(Z_{RW} + Z_{RB} + Z_{WB} + Z_{WR} + Z_{BR} + Z_{BW})$$

Equation 2 – Symmetrical Impedances

2.2 Phase-to-Phase Fault Detection

To measure the distance to all faults involving more than one phase, a simple distance relay compares the voltage between the two faulted phases with the difference between the phase currents.

$$Z_{RY} = (V_R - V_Y)/(I_R - I_Y)$$
$$Z_{YB} = (V_Y - V_B)/(I_Y - I_B)$$
$$Z_{BR} = (V_B - V_R)/(I_B - I_R)$$

Equation 3 – Phase element operation

Therefore it is often necessary to implement a number of phase elements to correctly measure the fault type. Other techniques exist, such as the use of a polyphase distance element, but these can have serious deficiencies under certain system conditions. [6]

2.3 Phase-to-Earth Fault Detection

It is also necessary to measure the positive sequence line impedance between the relay and any earth faults. Consequently, relays also contain earth elements which incorporate the faulted phase voltage and current.

However, earth faults incorporate zero and positive sequence currents. As the positive and zero sequence impedance is usually different in overhead lines, some calculations are needed to equate the observed phase impedance to that of the positive sequence line impedance. This is achieved with the Residual Compensation Factor K_0.

$$Z_R = V_R/(I_R + I_0 K_0)$$
$$Z_W = V_W/(I_W + I_0 K_0)$$
$$Z_B = V_B/(I_B + I_0 K_0)$$
$$K_0 = (Z_0/Z_1 - 1)$$

Equation 4 – Earth element operation

2.4 Relay Impedance Characteristics

Over the years many different characteristics have been proposed by universities and utilities around the world. Some of the most commonly utilised impedance 'shapes' include the mho, offset mho, quadrilateral, peanut and lens. Selection of these characteristics often depends on the required sensitivity to load, resistance and source impedance.

Today most manufacturers offer a choice of quad or mho characteristics. Although others are still available for situations where high load currents are experienced.

Generally mho characteristics provide very reliable and adequate responses when used in most protection applications. However, quadrilateral characteristics can provide increased resistive reach in situations where load currents will not constrain the characteristic. These benefits are limited as the resistive reach is restricted to approximately 3.5 times the reactance value for zones set to 80% of the line impedance. Thus quadrilaterals are mostly employed for the earth elements on short lines without earth wires; non-effectively earthed systems and feeders with high footing resistance. Conversely, phase elements should incorporate a mho characteristic as fault asymmetry can further increase an angular displacement between a relay and the fault current. [3]

2.5 Protective Zones of Operation

The three-zone mho relay has been developed to allow adequate discrimination when protecting transmission lines with distance protection. Each element is used in conjunction with timers dividing the system into different zones with different tripping times.

The first zone is instantaneous and extends from the relaying point to a location just short of the remote busbar. This is commonly set to 80% to allow for transducer, relay and line parameter errors.

Zone 2 is graded to provide remote backup protection for the next zone in the power system, which is commonly the remote busbar. Hence a reach of 120% of the line impedance is usually applied with a timer setting close to 0.4 seconds for transmission circuits.

The third zone is configured for backup protection of equipment further embedded in the system.

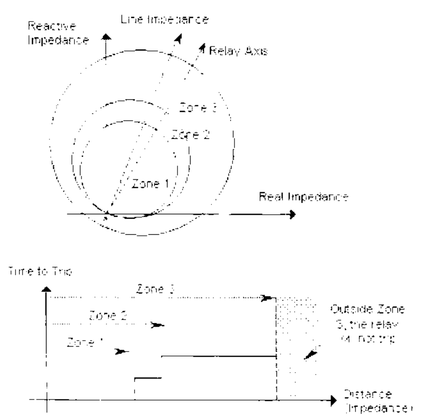


Figure 1 – Protection zone grading of mho distance elements

3. DISTANCE PROTECTION SCHEMES

Without a suitable protection signalling scheme, faults near one end of a circuit will result in a Zone 2 operation at one of the relaying locations. Consequently, a total clearance time of around 27 cycles is possible for some faults. However this is often unacceptable due to system stability and load sensitivity constraints.

Distance schemes incorporate communication between the relaying locations, which enables a reduction in the total tripping time for the fault. Some of the more common schemes include:

3.1 Permissive Underreach (PUR)

Generally, these schemes will trip a line instantaneously if the fault is seen:

- By both ends in Zone 1
- By one end in Zone 1 and the other end in Zone 2

Where both relays see a Zone 2 fault, the Zone 2 timer (typically 400ms) will delay breaker operation. Consequently, to protect the line, all faults must be observed by at least one relay within the Zone 1 impedance characteristic.

3.2 Permissive Overreach (POR)

Similarly permissive overreach schemes will trip instantaneously if the fault is observed:

- By both ends in Zone 1
- By one relay in Zone 1 and the remote relay in Zone 2
- By both relays in Zone 2

Permissive Overreach schemes will trip for faults where the apparent impedance at both relays is quite large. However, the Zone 2 setting must be configured to grade over all the possible impedance values observed at the relays, produced by faults on the line.

3.3 Blocking Schemes (B)

Blocking schemes are slightly different in their Zone arrangements and protection signalling logic. However, they will also trip a line instantly when a fault is seen:

- By both ends in Zone 1
- By one relay in Zone 1, and where the other relay observes the fault in the high impedance region of the Zone 2 characteristic.
- By both ends in Zone 2, as long as the apparent impedance is greater than that observed by the smaller Zone 3 forward reach.

With correctly set zone reaches (especially Zone 3), blocking schemes are similar to permissive overreach schemes in terms of the Zone 2 setting requirements. Blocking schemes are often applied in conjunction with overreaching schemes in situations where the reliability of the protection signalling channel cannot be assured.

3.4 Current Differential (CD)

Current differential schemes do not rely on distance techniques but are often used in conjunction with distance schemes. These incorporate the measurement of current at each end of a feeder, on a per-phase basis. This information is then transferred between the relays, creating a trip signal if the difference in current is adequately large.

4. COMPARATIVE FAULT ANALYSIS

To assess the adequacy of such protection schemes on a dual circuit line, a base scenario was chosen. The model included a 330kV source voltage, as well as equal positive and zero sequence source impedances of 41.9∠82.4°Ω and 23.4∠83.4°Ω.

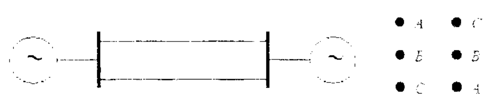


Figure 2 – Simple dual circuit line topology with low reactance phasing

The dual transmission circuits themselves were 172km in length, assuming a low reactance construction. This also applied to the geometry of the conductors and sizes, resulting in positive sequence line impedances of 58.9∠84.9°Ω. Similarly the zero sequence line impedance obtained was 165.5∠74.8°Ω, resulting in a residual compensation value of 0.735∠-15.6°.

This scenario was then analysed using the Alternate Transients Program using a distributed parameter line model for the transmission lines, and a sequence component equivalent of the source impedances.

The asymmetrical nature of the lines resulted in a small disagreement between the actual impedances observed by each relaying element for a bolted fault at the remote busbar. This means that a fault on one busbar will result in observed impedances that vary between 55.8Ω and 64.4Ω, where the two vertical phases closest to the earth obtain the lowest loop impedance. The upper phase conductors have slightly increased impedances, while the lower and upper conductors have elevated impedance values due to the reduced mutual coupling between the phases.

Relay Element	Observed Impedance
R-B	64.38∠85.2°Ω
R-W	55.87∠84.8°Ω
W-B	56.59∠84.7°Ω

Table 1 – Phase impedances for the line

4.1 Selection of Zone Settings

Generally, the zone boundaries of the protective relays are chosen so that any credible fault on the line for all system configurations will be observable. This generally means that the Zone 1 and Zone 2 reaches are reduced and increased respectively in accordance with a set of system studies. This guarantees the correct operation of the relay under all system operation conditions.

An alternative approach is to use a residual compensation value that eliminates the mutual coupling effect for any setting, if the parallel line is grounded and there is no infeed from the remote end [2]. Although this eliminates the overreaching errors, there is a corresponding increase in the underreaching errors. However, a system study approach has been adopted in this analysis.

In this situation, a solution was obtained using an asymmetrical line model. This approach required the use of the original ATP distributed parameter model to determine the impedances seen by each individual element for a fault on the remote busbar. Here each combination of phase, earth and double phase to earth fault was applied while noting the impedances observed by each relay element.

	ELEMENT					
	B-R	R-W	W-B	R-E	W-E	B-E
3 Ph	59.7Ω	55.4Ω	55.8Ω	55.4Ω	57.6Ω	57.8Ω
R-B	59.6Ω					
R-W		55.3Ω				
W-B			56.0Ω			
R-E				61.3Ω		
W-E					67.0Ω	
B-E						66.1Ω
R-W-E		54.7Ω		59.0Ω	64.4Ω	
R-B-E	60.4Ω			61.0Ω		65.9Ω
B-W-E			55.9Ω		65.5Ω	61.6Ω

Table 2 – Both lines in service

	B-R	R-W	W-B	R-E	W-E	B-E
3 Ph	64.5Ω	56.0Ω	56.2Ω	58.2Ω	55.9Ω	62.0Ω
R-B	64.4Ω					
R-W		55.9Ω				
W-B			56.6Ω			
R-E				52.8Ω		
W-E					55.4Ω	
B-E						59.2Ω
R-W-E		55.5Ω		54.0Ω	55.2Ω	
R-B-E	64.9Ω			53.1Ω		62.6Ω
B-W-E			56.4Ω		57.6Ω	56.8Ω

Table 3 – One line out of service

	B-R	R-W	W-B	R-E	W-E	B-E
3 Ph	64.1Ω	55.8Ω	56.1Ω	57.0Ω	56.8Ω	61.5Ω
R-B	64.0Ω					
R-W		55.7Ω				
W-B			56.5Ω			
R-E				47.5Ω		
W-E					48.6Ω	
B-E						51.2Ω
R-W-E		55.5Ω		52.3Ω	47.4Ω	
R-B-E	64.4Ω			47.0Ω		57.1Ω
B-W-E			56.3Ω		54.1Ω	49.1Ω

Table 4 – One line out of service and earthed

The Zone 1 reach should observe as much of the circuit as practically possible whilst never reaching the remote busbar. Applying an 80% Zone 1 reach to the worst-case minimum line impedance results in a Zone 1 setting of 37.9Ω; or 73% of the positive sequence impedance.

Conversely, the Zone 2 reach must always observe the full line impedance, even in the worst case. Hence, a setting of 80.4Ω, or 136% of the positive sequence line impedance, is required when a margin of 120% is employed using the ATP loop impedances. However, no fault on the circuit should result in an observed impedance within this 120% margin

4.2 Detection of Faults

The analysis incorporated the application of faults on the transmission line at 75% of the line length. This location is significant as it may require Zone 2 operation by one terminal relay.

Applying a low impedance three-phase, phase-to-earth, phase-to-phase, a double-phase-to-earth, or an earthed cross-country fault, results in apparent impedances which will be observed in Zones 1 and 2 at the respective relaying locations. This results in the correct operation for all the protective schemes described previously.

However, care must be taken when implementing single pole tripping schemes as both the phase and earth elements may pick up for cross-country faults, resulting in a three-pole operation on both feeders where only single pole tripping is required. This is also a concern for phase to earth faults close to a busbar as the phase elements can observe an impedance that is within their operating characteristic.

4.2.1 Observation of Inter-Circuit Faults

Alternatively, unearthed inter-circuit faults appear to be a serious concern for dual circuit lines. In this analysis an observed impedance of 125% of the line was detected, and the observation of the fault would only have been possible as a result of the 120% margin previously applied to the Zone 2 settings.

The resulting phase and earth element impedances at either end of the line can be seen in Figure 3. However, Figure 4 indicates the effects of increasing the busbar source impedance ratio to a value of 2:1.

The effects on the phase element impedance can be observed by varying the fault position along the line. Here the maximum under-reach is obtained for faults occurring 60%-80% of the line length.

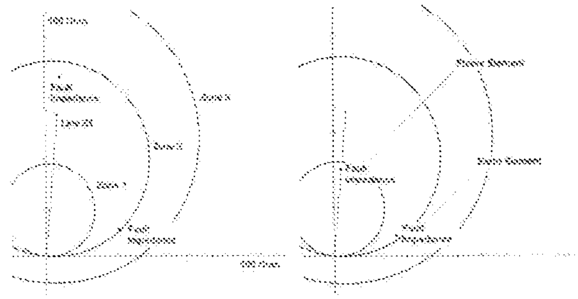


Figure 3 – Inter-circuit fault impedances seen by phase elements at either terminal (1:1 SIR, fault at 75%)

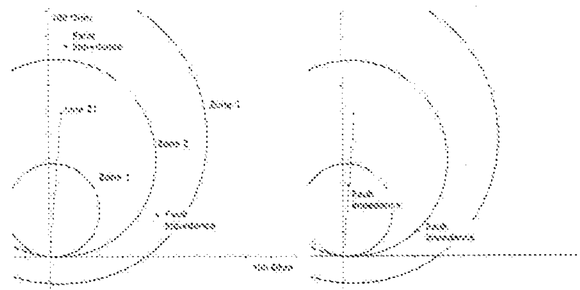


Figure 4 – Inter-circuit fault impedances seen by phase elements at either terminal (2:1 SIR, fault at 75%)

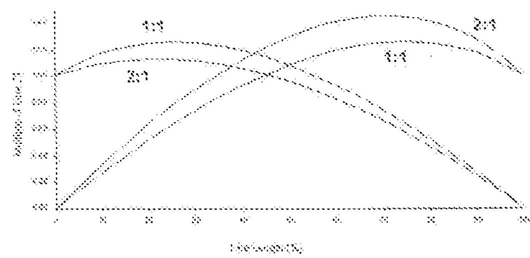


Figure 5 – Impedances observed by phase element s for two source impedance ratios

4.2.2 Selection of Protection Scheme

Detection of these faults using a permissive underreaching scheme would require both relay impedance plots to exist below the Zone 1 limit of 73% at all locations.

Similarly, neither of the curves could extend beyond the Zone 2 boundary of 136% for permissive overreaching or blocking schemes to protect the lines.

Consequently, permissive underreaching schemes will not observe inter-circuit faults at any location. Permissive overreaching or blocking schemes would have detected this event for a line with equal source impedances, despite the acute loss of the 120% Zone 2 margin below the forward reach. However, a source impedance ratio above 1:1 can result in only Zone 3 detection of such faults, making the scheme incapable of protecting the circuit.

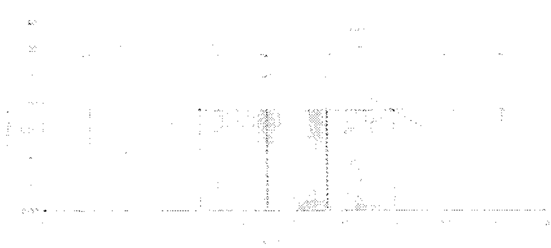


Figure 6 – PUR blind section, and loss of 120% margin for POR and B schemes, with equal SIR.

Current differential schemes appear to be the only reliable approach to detecting inter-circuit faults when compared to conventional mho based protective techniques. Nevertheless, it may be possible to detect inter-circuit faults when the Zone 2 reaches are increased in permissive overreaching or blocking schemes. Similarly, setting the mho angle at 20° below the line angle, for certain source impedance ratios, can assist in detection of the earth elements.

A quadrilateral characteristic could also aid in fault detection due to the extended resistive reach, enabling observation of the earth element impedance at the location furthest from the fault. Although, the expected load impedance locus should be considered carefully in such situations.

Shorter dual transmission circuits will extend the apparent earth fault impedance away from the origin of the impedance plot. However, as quadrilateral characteristics are commonly used on short lines, the resistive reach of the quadrilateral characteristic may be set to compensate.

Nevertheless, the use of earth elements for detection of inter-circuit faults should only be considered as part of a system study that considers the impacts of inter-circuit faults in critical locations. It should be noted that the required zone reaches depend heavily on the source impedances and other system parameters. Consequently the impact of these faults should consider these parameters in a sequence, ATP or other similar model.

5. CONCLUSION

Conventional philosophies directing the use of protection schemes for dual circuit lines may not enable the detection of unearthed inter-circuit faults in the instantaneous zone of operation. This is an essential requirement in many cases, including network interconnectors or lines carrying heavy or sensitive loads.

To permissively detect inter-circuit faults, at least one overreaching or blocking scheme is required with a Zone 2 setting large enough to cover the apparent impedances observed from each busbar.

In cases of single pole tripping, an inter-circuit fault will trip the three poles from both circuits as a result of the phase element impedances. This can be overcome by using at least one current differential scheme in conjunction with logic that will trip the faulted phases only. Otherwise, all six voltage and current signals should be analysed by a single relay to determine the fault condition.

As a result of this analysis, there is an identifiable need to adopt different protection design philosophies based on the potential implications of inter-circuit faults.

6. REFERENCES

[1] Agrasar, M., et al "A useful methodology for analysing distance relays performance during simple and inter-circuit faults in multi-circuit lines". IEEE Transactions on Power Delivery, Vol 12, No 4, July 1997.

[2] Agrasar, M., et al "Evaluation of uncertainties in double lines distance relaying. A global sight". IEEE Transactions on Power Delivery, Vol 12, No 4, July 1998

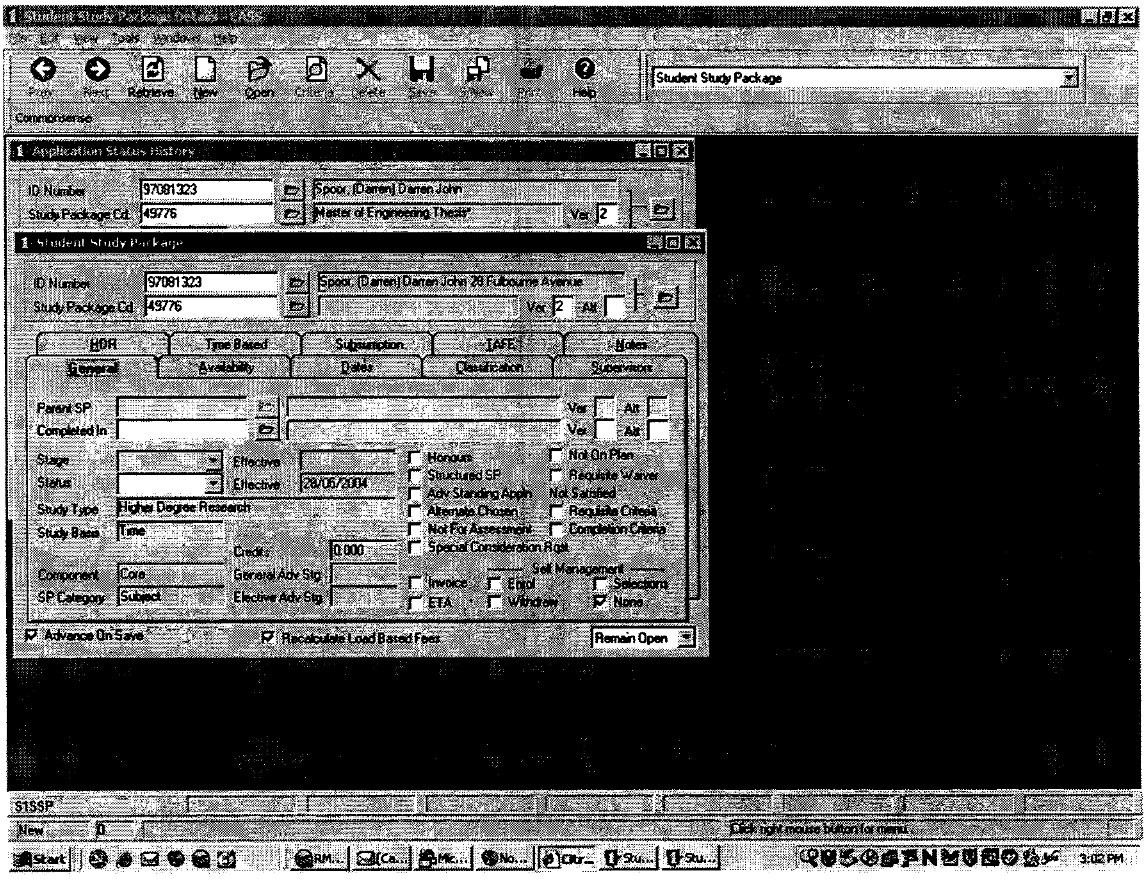
[3] Domzalski, M.J., Nickerson, K.P., Rosen, P.R. "Application of Mho and Quadrilateral distance characteristics in power systems" Developments in Power system Protection, Conference Publication No479, IEE 2001.

[4] Jongepier, A.G., et al. "Adaptive Distance Protection of a Double-Circuit Line". IEEE Transactions on Power Delivery, Vol 9, No 3, July 1994.

[5] McLaren, P.G., et al "Enhanced Double Circuit Line Protection". IEEE Transactions on Power Delivery, Vol 12, No 3, July 1997.

[6] Martilla, R.J., et al "Effect of Transmission Line Loading on the performance characteristics of polyphase distance relay elements" IEEE Transactions on Power Delivery, Vol 3, No 4, Oct 1988

[7] Turner, S., et al "An application in relay-to-relay logic communications for single pole tripping" Proceedings of the 4th international conference on advances in power system control, operation and management, APSCOM-97, Hong Kong, November 1997.


Student Study Package Details - CASS
Prior
Next
Retrieve
New
Open
Criteria
Delete
Save
S/New
Print
Help
Student Study Package
Commonsense
Application Status History
ID Number
97081323
Spoor, (Darren) Darren John
Study Package Cd.
49776
Master of Engineering Thesis
Ver
2
Student Study Package
Spoor, (Darren) Darren John 28 Fulbourne Avenue
Alt
HDR
Time Based
Subsumption
TAFE
Notes
General
Availability
Dates
Classification
Supervisors
Parent SP
Completed In
Stage
Status
Effective
28/06/2004
Study Type
Higher Degree Research
Study Basis
Time
Credits
0.000
Component
Core
General Adv Stg
SP Category
Subject
Elective Adv Stg
Honours
Structured SP
Adv Standing Appln
Alternate Chosen
Not For Assessment
Special Consideration Rqst
Not On Plan
Requisite Waiver
Not Satisfied
Requisite Criteria
Completion Criteria
Self Management
Invoice
Enrol
Selections
ETA
Withdraw
None
Advance On Save
Recalculate Load Based Fees
Remain Open
S1SSP
New
Click right mouse button for menu
Start
3:02 PM