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QUANTITATIVE FEEDBACK THEORY DESIGN OF LINE CURRENT COMMUTATED HVDC CONTROL SYSTEMS

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Abstract: Line Current Commutated (LCC) HVDC systems consists of uncertain plants. These uncertainties are result of changes/disturbances in the ac networks or in the LCC HVDC system itself. Further uncertainties can be introduced due to simplified system modelling techniques. Quantitative Feedback Theory is a frequency-domain technique that utilises the Nichols chart to achieve a robust design over a specified region of uncertainty. The Quantitative Feedback Theory design philosophy was applied to design the LCC HVDC control system parameters. The stable start-up and step responses of the LCC HVDC system, for varying ac system conditions, conclusively validate the Quantitative Feedback Theory design method of the LCC HVDC control system parameters.

Keywords: HVDC, control system, uncertainty, Quantitative Feedback Theory

1. INTRODUCTION

Line Current Commutated (LCC) HVDC systems consists of uncertain plants. These uncertainties are result of changes/disturbances in the ac networks or in the LCC HVDC system itself. Further uncertainties can be introduced due to simplified system modelling techniques. Feedback control systems reduce the effects of uncertainty which may appear in different forms as disturbances or as other imperfections in the models used to design the feedback law [1]. Feedback also has the property of increasing linearity of the control system [1]. Therefore, negative feedback control is used to limit the effect of these uncertainties in the LCC HVDC system operation. However, feedback control systems have the inherent risk of instability [1].

Erikson et. al [3]. stated that there is a distinct need for quantitative methods for stability analysis of HVDC control systems. Based on a computer program developed by Persson [2] that calculated the rectifier current control transfer function of the uncompensated control loop, Erikkson [3] et. al. used Nyquist plots to analyse the stability of the LCC HVDC rectifier current control loop. Erikson et. al. [3] also used Bode plots and Nyquist plots to design a PI controller for a certain parametric rectifier current control plant. Freris et. al. [4] used Nyquist plot to analyze the stability of the compensated certain parametric rectifier current control loop of a dc transmission system connected between a rectifier with short circuit ratio 3.75 and inverter with an infinite short circuit ratio. Jovcic et. al. [5] used root locus diagrams to analyse the effect of phase locked loop gains on the stability of a certain parametric rectifier current control plant. Jovcic et. al. [6] also used root locus diagrams to analyse the difference of the direct current feedback control loop and the fast power feedback control loop for a certain parametric HVDC system.

Aten et. al. [7] states that little has been published by the industry on how classical control theory can be used to design HVDC control systems. Aten et. al [7] states that classical control theory can assist in determining stability margins and robustness of HVDC control system. Aten et. al. [7] used Bode plots to determine phase and gain margins for various rectifier and inverter short circuit ratios. Rahim et. al. [8] used modern control theory to design a robust damping controller for an HVDC link within a power system. Bode plots were used as the design tool for shaping of the loop transfer function. From the literature review, it is evident that although classical control theory has been superficially investigated to design LCC HVDC control systems, parametric plant uncertainty has not been investigated. Therefore this paper designs robust LCC HVDC control systems using Quantitative Feedback Theory, so as to accommodate parametric plant uncertainty.

2. QUANTITATIVE FEEDBACK THEORY

Quantitative feedback theory (QFT) was developed by Horowitz [11], to provide an effective approach for the design of control systems for uncertain plants and/or disturbances. QFT is a frequency-domain technique that utilises the Nichols chart to achieve a robust design over a specified region of uncertainty. The QFT design philosophy was applied to design the LCC HVDC control system parameters since LCC HVDC systems are naturally uncertain. The reasons for the uncertain nature of LCC HVDC systems are as follows:

1. AC systems' effective short circuit ratios are variable in nature.

2. The LCC HVDC plant transfer functions were developed from simulations thus introducing, errors even though minor, which can be considered/treated as plant uncertainty [12].
3. Linear LCC HVDC plant transfer functions were derived from nonlinear HVDC dynamics thus introducing errors even though minor, which can be considered/treated as plant uncertainty [12].

The designed controller should meet the performance specifications in spite of the variations of the parameters of the LCC HVDC plant models. QFT works directly with such uncertainties and does not require any particular representation. A key element of QFT is embedding the performance specifications at the onset of the design process. These specifications establish design goals that enhance and expedite the achievement of a successful design. The performance specifications includes percentage overshoot and settling time (t_s) which is defined as the time required by the step response to settle within ±δ% of the final value, where δ is defined.

One of the fundamental aspects in control design is the use of an accurate description of the plant dynamics. QFT involves frequency-domain arithmetic, therefore, the plant dynamics must be defined in terms of its frequency response. The term "template" is used to denote the collection of an uncertain plant's frequency responses at given frequencies. Samples of plant templates at different frequencies are illustrated in Figure 1. The use of templates alleviates the need to develop any particular plant model representation. Once the plant templates are developed, QFT converts closed-loop magnitude specifications into magnitude and phase constraints on a nominal open-loop function.

These constraints are called *QFT bounds* (illustrated in Figure 2). A detailed discussion on the method used to plot templates on the stability margin based on plant parameter uncertainty can be found in [11]. The size of the templates indicates whether or not a robust design is achievable. If a robust design is not possible, then the templates can be used as a metric in the reformation of the control design problem. Another aspect of the QFT design process is the ability to concurrently analyze frequency responses of the plant transfer functions that represent the non-linear dynamical system through its operating environment. This gives the designer insight into the behaviour of the system. The designer can use this insight for such things as picking out the key frequencies to use during the design process, as an indicator of potential problems such as non-minimum phase behaviour, and as a tool to compare the nonlinear system with the desired performance boundaries. Non-minimum phase behaviour occurs when the loop transfer function has real poles and zeros in the right half plane or even consists of dead-time.

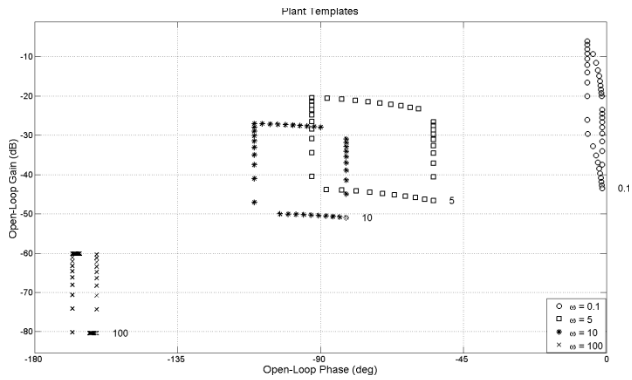

Figure 1: Plant Templates for various frequencies

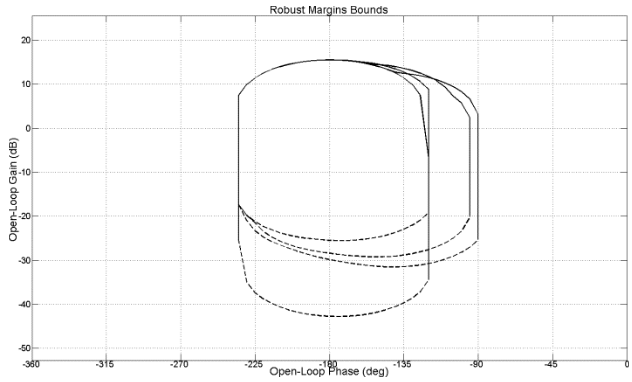

Figure 2: QFT Bounds at various frequencies

The non-minimum phase behaviour will restrict the maximum gain cross-over frequency and will therefore affect the achievement of the specifications. The plotting of the loop transfer functions on Nichols Chart gives the designer a first look at any areas of the design that may present problems during simulation and implementation. To obtain a successful control design, the controlled system must meet all of the specifications during simulation. If the controlled system fails any of the simulation tests, using the design elements of QFT, the designer can trace that failure back through the design process and make necessary adjustments to the design.

3. LCC HVDC CONTROL SYSTEM

The LCC HVDC scheme shown in Figure 3 represents a monopolar link or one pole of a bipolar link. The direct current flowing from the rectifier to the inverter is given by [10]:

$$I_d = \frac{V_{dor}.\cos\alpha_r - V_{doi}.\cos\gamma_i}{R_{cr} + R_L - R_{ci}} \qquad (1)$$

By controlling the internal voltages ($V_{dor}.\cos\alpha_r$) and ($V_{doi}.\cos\gamma_i$), the direct voltage and the current (or power) can be controlled. This is accomplished continuously via the control system and the gate control of the valve firing angle.

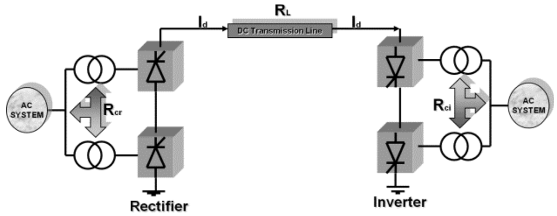

Figure 3: LCC HVDC Scheme

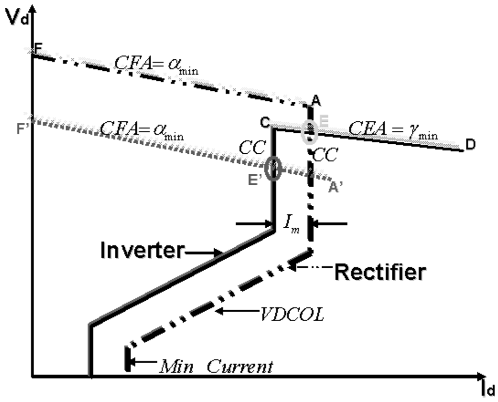

Figure 4: Steady-state V-I Control Characteristics

An important requirement for the satisfactory operation of the LCC HVDC link is the prevention of large direct current fluctuations by rapidly controlling the converters' internal voltages by manipulating the rectifier and inverter firing angles. In effect, the adjustment of the rectifier and inverter firing angles are utilized to improve the small signal stability of the HVDC control system.

To satisfy the fundamental requirements, the responsibilities for dc voltage control and dc current control are kept distinct and are assigned to separate converter stations. Under normal operation, the rectifier maintains constant dc current control (CC), and the inverter maintains constant direct voltage control (VC) by operating with constant extinction angle (CEA) [10]. The basis for the control philosophy is illustrated in Figure 4. Under normal operating conditions (represented by the intersection point E) the rectifier controls the direct current and the inverter controls the direct voltage. With a reduced rectifier voltage, the operating condition is represented by the intersection point E'. The inverter takes over the direct current control and the rectifier establishes the direct voltage. Under low voltage conditions, it is not be desirable or possible to maintain rated direct current or power [10]. The problems associated with operation under low voltage conditions may be prevented by using a "voltage dependent current order limit" (VDCOL) [10]. This limit reduces the maximum allowable direct current when the voltage drops below a predetermined value [10]. The VDCOL characteristic is a function of the dc voltage.

Figure 5 illustrates the scheme for practically implementing the LCC HVDC control system. It should be noted that the rectifier and inverter have the same control system structure. The VDCOL function strives to reduce the dc current order for reduced measured dc voltage. The static characteristics of the VDCOL function are displayed in Figure 6. The phase locked oscillator (PLO) is based on the Phase Vector technique [9]. This technique exploits trigonometric multiplication identities to form an error signal, which speeds up or slow down the PLO in order to match the phase. The output signal θ is a ramp synchronized to the Phase A commutating bus L-G voltage. The block diagram of the PLO is shown in Figure 7. Both the rectifier and the inverter have current control amplifier (CCA) function as illustrated in Figure 5. The main function of the current control amplifier is to improve the dynamic operation of current control loop. The main requirements of the current control loop are:

1. Fast enough step response
2. Insignificant current error at steady-state
3. Stable current control

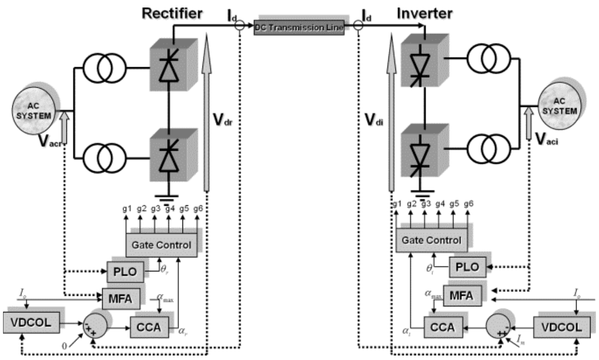

Figure 5: LCC HVDC Control System

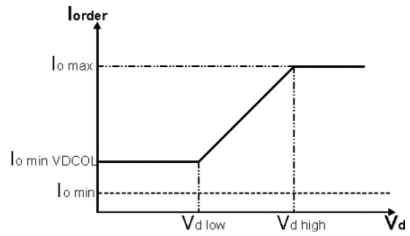

Figure 6: Static characteristics of VDCOL [10]

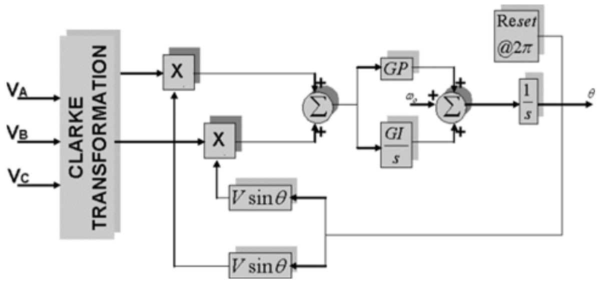

Figure 7: Phase Locked Oscillator (PLO) Implementation

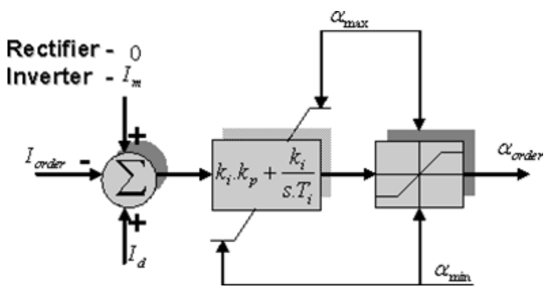

Figure 8: Current Control Amplifier Implementation

The CCA has a proportional part ($k_i.k_p$) and an integrating part ($\frac{k_i}{s.T_i}$), as illustrated in Figure 8. The CCA also has a summing junction, in which the difference between the current order, the current response and current margin is formed. The subsequent firing angle order is determined by the following equation:

$$\alpha_{order} = -\left[k_i.k_p + \frac{k_i}{s.T_i}\right](I_{order} - I_m - I_d) \qquad (2)$$

The current controller's proportional gain and integral time constant parameters should be designed to achieve the best stability performance.

The gate control compares the firing order α_{order} to the phase locked ramp signal θ and produces the gate firing pulses.

4. PERFORMANCE SPECIFICATIONS AND CONTROL PROBLEM DEFINITION

Erikson et. al [3] specifies that a minimum phase margin of 40^o from the Nyquist point should be maintained for all frequencies. On the Nichols chart, the 40^o phase margin specification corresponds to the 6dB M-circle. Therefore the control problem is defined as:
"For LCC HVDC plant transfer functions (P_{cr} and P_{ci}) defined in [12], whose parameters vary according to the Tables defined in [12], design the fastest possible control system. The control system should be designed for the following operating conditions: the rectifier's ESCR varies from 6 to 8 and the inverter's ESCR varies from 6 to 8 with the nominal operating condition being rectifier's ESCR equal to 8 and inverter's ESCR equal to 8. The HVDC control system should be designed so as to maintain the 6dB stability margin for all frequencies."

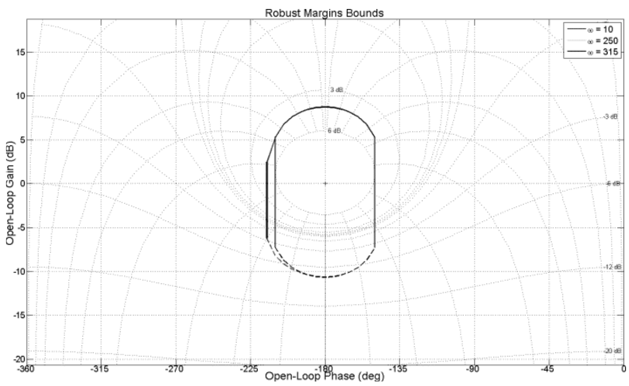

Figure 9: Rectifier Current Control QFT Bounds

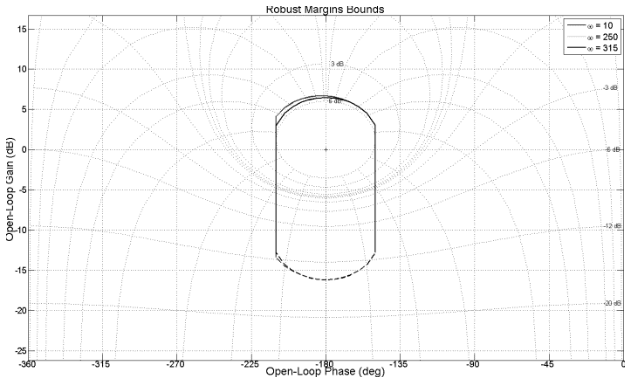

Figure 10: Inverter Current Control QFT Bounds

A fundamental element of the QFT design method is the generation of parametric uncertainty templates and the integration of these templates into the stability margin design bounds. Figure 9 illustrates how the stability margin is modified for nominal rectifier current control plant transfer function, according to parameter variations illustrated in Table 1 of reference [12]. Figure 10 illustrates how the stability margin is modified for nominal inverter current control plant transfer function, according to parameter variations illustrated in Table 2 of reference [12].

5. QFT DESIGN OF LCC HVDC CONTROL PARAMETERS

Since the stability design bounds have been derived, the parameters of the LCC HVDC control system can be designed. The following high-to-low frequency QFT design method was used:

1. The maximum possible gain cross-over frequency ω_{gc} was determined from the non-minimum phase-lag properties of the plant. This gain cross-over frequency will be attempted to be achieved by applying a proportional gain.
2. Then the magnitude of the loop transfer function will be increased, for ω approaching zero, as fast as possible. This will be achieved by applying a first-order integral term.

5.1. Rectifier Current Controller Design

Analysis of Table 1 [12], reveals that the largest time constant is 1.65msec, therefore the performance specifications for the Rectifier Current Controller are defined as:

Overshoot	< 5%
Settling Time (t_s)	< 24.75msec
Steady state error (δ)	< 2%
Gain Margin	< 6dB

The nominal rectifier current control plant is defined as [12]:

$$P_{cr}(s) = e^{-1.65\times10^{-3}s}\left(\frac{-0.026s^3 - 3.424s^2 - 2351s - 9.732\times10^4}{s^3 + 132.7s^2 + 9.049\times10^4 s + 3.829\times10^6}\right)$$

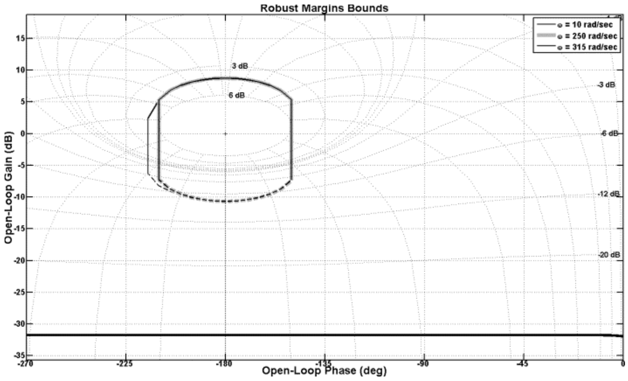

Figure 11: Nichols Plot of $-P_{cr}(s)$

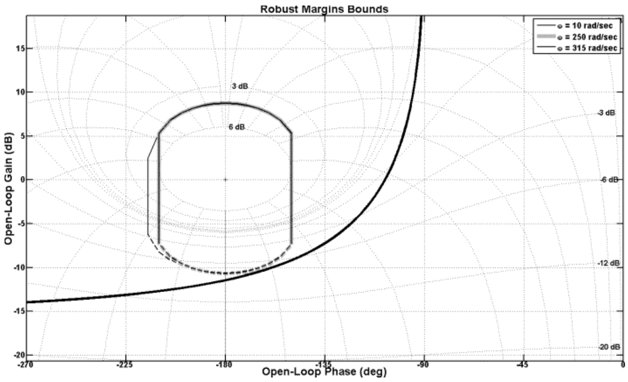

Figure 12: Influence of the designed PI controller on $P_{cr}(s)$

The negative of this plant transfer function is plotted on Nichols Chart with the modified stability margin as shown in Figure 11. To achieve the maximum possible gain cross-over frequency, the gain of the controller was increased, ie k=6.3. To further improve the low frequency performance, a low frequency modifying controller term $(1+\omega_c/s)$ was be used, with ω_c=1750 rad/s. The gain and the low-order controller term define the parameters of the PI controller:

$$G(s) = -6.3\left(1 + 1750 \big/ s\right) \tag{3}$$

Equation (2) describes the actual controller parameters as:

$$G(s) = -\left(k_i.k_p + \frac{k_i}{s.T_i}\right) \tag{4}$$

Equating (3) and (4) and choosing T_i=1msec gives:

$k_i = 11.025$

$k_p = 0.57$

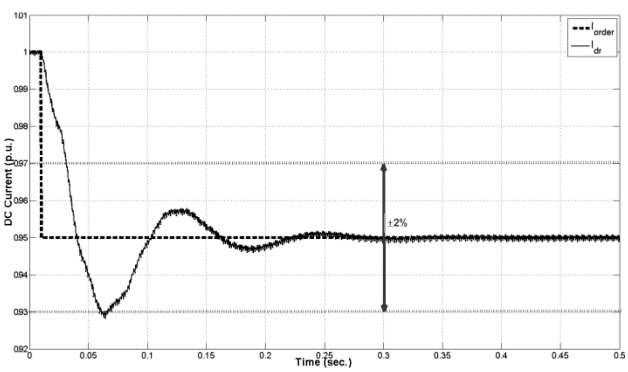

Figure 13: Rectifier DC Current Response

Performance Criterion	Expected	Actual
Overshoot	5%	2.1%
Settling Time (t_s)	24.75msec	23msec
Steady state error (δ)	<2%	<0.1%
Gain Margin	<6dB	<6Db

Table 1: Rectifier Current Controller Performance Assessment

The effect of the controller is displayed in Figure 12. To verify the performance of the control system, the following scenario was simulated in PSCAD/EMTDC:
The rectifier's ESCR was set to 8 and the inverter's ESCR was set to 8. The HVDC system was configured so that the rectifier was in current control mode and the inverter was in voltage control mode. The inverter's firing angle was held constant at 138 degrees and the rectifier's current controller's parameters were set according to equation (3). After the HVDC system is run to steady state, the dc current order was decreased by 5%.The plant output response to the small signal transient is illustrated in Figure 13. The control system performance is evaluated in Table 1, which clearly illustrates that the rectifier controller design did meet the specified performance requirements.

5.2. Inverter Current Controller Design

Analysis of Table 2 of reference [12], reveals that the largest time constant is 0.89msec. It should be noted that there exists a 1msec communication time delay with regard to the current order being processed at the rectifier station and then transmitted to the inverter station. Therefore the specifications for the Inverter Current Controller are defined as:

Overshoot	< 5%
Settling Time (t_s)	< 28.35msec
Steady state error (δ)	< 2%
Gain Margin	< 6dB

The nominal rectifier current control plant is defined as [12]:

$$P_{ci}(s) = e^{-0.89\times10^{-3}s}\left(\frac{-0.02s^3 - 2.478s^2 - 1676s - 6.535\times10^4}{s^3 + 124.9s^2 + 8.388\times10^4 s + 3.348\times10^6}\right)$$

The negative of this plant transfer function is plotted on Nichols Chart with the modified stability margin as shown in Figure 14. To achieve the maximum possible gain cross-over frequency, the gain of the controller was increased, ie k=5.62. To further improve the low frequency performance, a low frequency modifying controller term $(1+\omega_c/s)$ was be used, with ω_c=2400 rad/s.

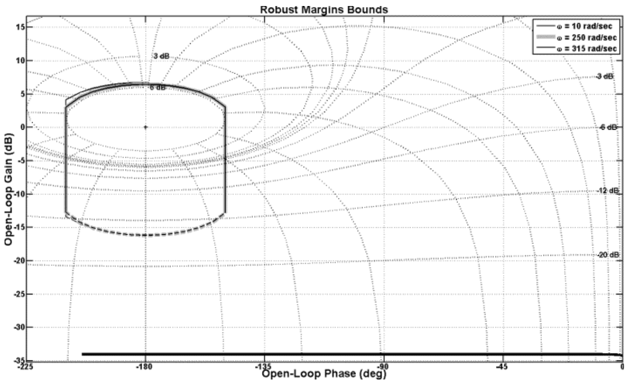

Figure 14: Nichols Plot of $-P_{ci}(s)$

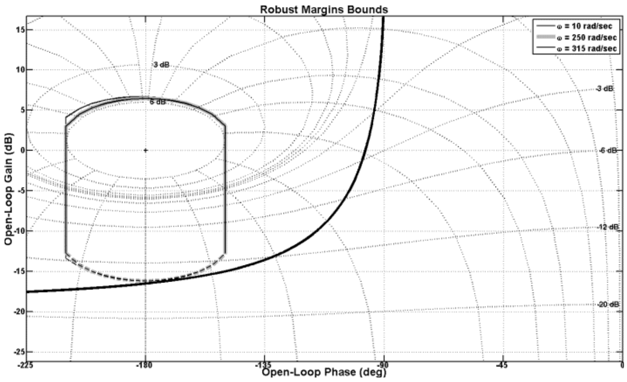

Figure 15: Influence of the designed PI controller on $P_{ci}(s)$

The gain and the low-order controller term define the parameters of the PI controller:

$$G(s) = -5.62\left(1 + \frac{2400}{s}\right) \qquad (5)$$

Equation (2) describes the actual controller parameters as:

$$G(s) = -\left(k_i . k_p + \frac{k_i}{s.T_i}\right) \qquad (6)$$

Equating (5) and (6) and choosing T_i=1msec gives:

$k_i = 13.5$

$k_p = 0.417$

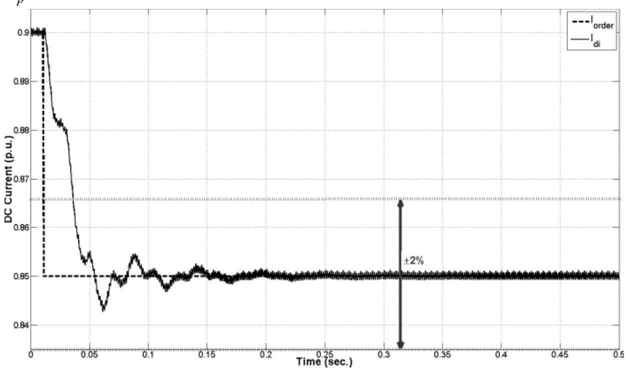

Figure 16: Inverter DC Current Response

Performance Criterion	Expected	Actual
Overshoot	5%	1.3%
Settling Time (t_s)	28.35msec	23msec
Steady state error (δ)	<2%	<0.13%
Gain Margin	<6dB	<6dB

Table 2: Inverter Current Controller Performance Assessment

The effect of the controller is displayed in Figure 15. To verify the performance of the control system, the following scenario was simulated in PSCAD/EMTDC:

The rectifier's ESCR was set to 8 and the inverter's ESCR was equal to 8. The HVDC system was configured so that the inverter was in current control mode and the rectifier was in voltage control mode. The rectifier's firing angle was held constant at 27 degrees and the inverter's current controller's parameters were set according to equation (5). After the HVDC system is run to steady state, the dc current order was decreased by 5%. The plant output response to the small signal transient is illustrated in Figure 16. The control system performance is evaluated in Table 2, which clearly illustrates that the inverter controller design does meet the specified performance requirements.

5.3. *Start-up Performance*

The design of the LCC HVDC control system has been sectionalized into separate design and analysis of THE control systems that constitute the LCC HVDC control system. The design and analysis of the complete LCC HVDC control system was validated by integrating the control systems as illustrated in Figure 5. The stability of the integrated LCC HVDC system was verified by simulating the following scenario in PSCAD/EMTDC:

The rectifier's ESCR was set to 8 and the inverter's ESCR was equal to 8. The firing angle of the inverter station is deblock first at $t_o = 10ms$. The rectifier's firing angle was deblocked at $t_1 = 50ms$ and then ramped up. The rectifier's current controller's parameters were set according to equation (3) and the inverter's current controller's parameters were set according to equation (5). Analysis of start-up response (Figure 17) reveals that the dc current increases after t_1. Between time t_3 and t_2, the dc voltage has not increased above the minimum required dc voltage (0.2 p.u.) as specified by the VDCOL, therefore the current order is constrained to the minimum current order (Rectifier – 0.3 p.u. and Inverter – 0.2 p.u.) as defined by the VDCOL. During this period of time, the designed LCC HVDC control system ensures that LCC HVDC system operates stably and according to the requirements of the VDCOL.

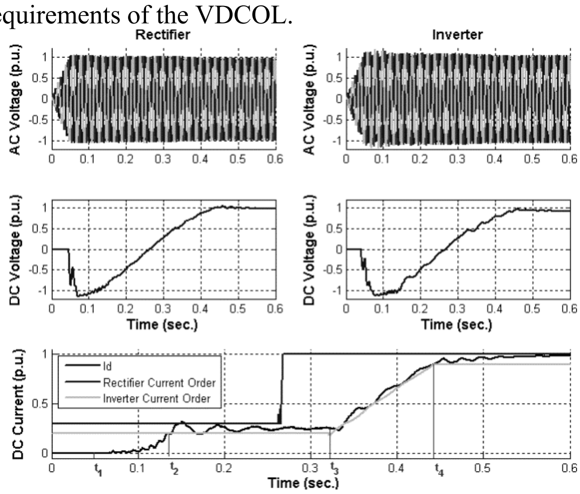

Figure 17: Start-up Response of the LCC HVDC System

Between time t_4 and t_3, the dc voltage increases above the minimum required dc voltage and the current order is determined by the inverter VDCOL. During this period of time, the designed LCC HVDC control system ensures that LCC HVDC system operates stably and according to the requirements of the inverter VDCOL. After time t_4, the inverter receives more current than is ordered therefore the current control moves to the rectifier station. During this current control transitional period, the designed LCC HVDC control system ensures that the LCC HVDC system operates stably and according to the requirements of the rectifier current control amplifier.

6. TRANSIENT ANALYSIS OF LCC HVDC CONTROL SYSTEMS

Transient analysis of an HVDC system provides insight into the interactions between the ac and dc systems. During the transient stability analysis, the rectifier and inverter ac systems' effective short circuit ratios were varied and the LCC HVDC system responses to small disturbances were analysed.

6.1. *Step decrease in rectifier ac system voltage*

The LCC HVDC system responses to a 5% stepped decrease in the rectifier ac system voltage, for varying ac system operating conditions were evaluated. The LCC HVDC system was simulated the following scenarios in PSCAD/EMTDC:

- The rectifier's ESCR was varied from 8 to 6
- The inverter's ESCR was varied from 8 to 6
- The rectifier's current controller's parameters were set according to equation (3)
- The inverter's current controller's parameters were set according to equation (5)
- After the LCC HVDC system is run to steady state, at $t_1 = 10ms$, the rectifier's ac system voltage is decreased by 5%.
- At $t_2 = 0.3\text{sec}$, the current order is decreased by 5%.

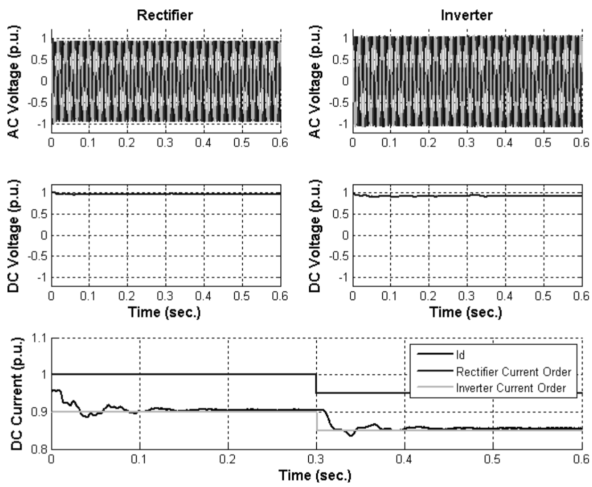

Figure 18: Sample of LCC HVDC System Response to a stepped decrease in the rectifier ac system's voltage

Constant Current Order					
Rectifier ESCR	Inverter ESCR	Characteristics			
		O.S (%)	t_s (msec)	Error (%)	Stable
8	8	1.2	43	0.6	Yes
6	8	1.3	22	0.5	Yes
8	6	2.1	49	0.4	Yes
6	6	2.0	28	0.5	Yes
5% Step Decrease in Current Order					
Rectifier ESCR	Inverter ESCR	Characteristics			
		O.S (%)	t_s (msec)	Error (%)	Stable
8	8	1.6	21	0.5	Yes
6	8	1.6	19	0.6	Yes
8	6	1.9	16	0.6	Yes
6	6	1.9	15	0.6	Yes

Table 3: Analytical Summary of LCC HVDC System Responses to stepped a decrease in the rectifier ac system's voltage

A sample of the LCC HVDC system response to a stepped decrease in the rectifier ac system's voltage is illustrated in Figure 18, for the rectifier ac system ESCR=8 and the inverter ac system ESCR=6. The detailed summary of the LCC HVDC system responses to a stepped decrease in the rectifier ac system's voltage for varying ac system conditions is illustrated in Table 3. Analysis of LCC HVDC system responses reveals that the designed LCC HVDC control system ensures that LCC HVDC system operates stably for varying ac system conditions.

6.2. *Step decrease in inverter ac system voltage*

The LCC HVDC system responses to a 5% stepped decrease in the inverter ac system voltage, for varying ac system operating conditions were evaluated. The LCC HVDC system was simulated the following scenarios in PSCAD/EMTDC:

- The rectifier's ESCR was varied from 8 to 6
- The inverter's ESCR was varied from 8 to 6
- The rectifier's current controller's parameters were set according to equation (3)
- The inverter's current controller's parameters were set according to equation (5)
- After the LCC HVDC system is run to steady state, at $t_1 = 10ms$, the inverter's ac system voltage is decreased by 5%.
- At $t_2 = 0.3\text{sec}$, the current order is decreased by 5%.

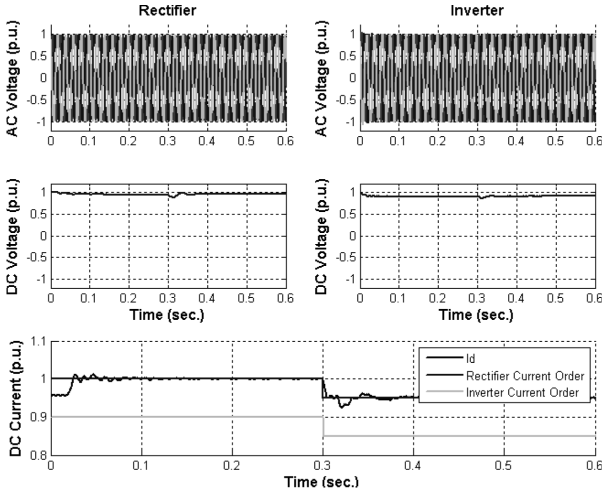

Figure 19: Sample of LCC HVDC System Response to a stepped decrease in the inverter ac system's voltage

Constant Current Order					
Rectifier ESCR	Inverter ESCR	Characteristics			
		O.S (%)	t_s (msec)	Error (%)	Stable
8	8	2.7	27	0.1	Yes
6	8	1.8	26	0.8	Yes
8	6	1.3	37	0.1	Yes
6	6	1.8	38	0.5	Yes
5% Step Decrease in Current Order					
Rectifier ESCR	Inverter ESCR	Characteristics			
		O.S (%)	t_s (msec)	Error (%)	Stable
8	8	2.7	24	0.1	Yes
6	8	3.6	25	1.7	Yes
8	6	2.7	23	0.1	Yes
6	6	4.0	31	1.5	Yes

Table 4: Analytical Summary of LCC HVDC System Responses to stepped a decrease in the inverter ac system's voltage

A sample of the LCC HVDC system response to a stepped decrease in the inverter ac system's voltage is illustrated in Figure 19, for the rectifier ac system ESCR=8 and the inverter ac system ESCR=6. The detailed summary of the LCC HVDC system responses to a stepped decrease in the inverter ac system's voltage for varying ac system conditions is illustrated in Table 4. Analysis of LCC HVDC system responses reveals that the designed LCC HVDC control system ensures that LCC HVDC system operates stably for varying ac system conditions.

7. SMALL SIGNAL STABILITY ANALYSIS OF LCC HVDC CONTROL SYSTEMS

Small signal stability is defined as the ability of the LCC HVDC system to maintain stability following a small disturbance. The small signal stability behaviour of the designed closed loop LCC HVDC control system was obtained by applying a small step output disturbance using MATLAB Control Systems Toolbox. To valid these results, the designed closed loop LCC HVDC system was simulated in PSCAD/EMTDC. The small signal stability behaviour of the designed closed loop LCC HVDC control system was analysed for the Rectifier in Current Control and the Inverter in Voltage Control. The control system illustrated in Figure 20, determines the small signal behaviour of the dc current. The parameters for the rectifier current control plant transfer function were obtained from Table 1 of reference [12]. The solution for the roots of the closed loop system is illustrated in Table 5, which indicates that all the closed loop poles reside in the left hand s-plane, thereby illustrating the unconditional stability of the LCC HVDC system. The lightly damped complex conjugate pole pair at -21.4±273i indicates the response will contain approximately a 43Hz oscillation.

The small signal stability behaviour of the designed rectifier current control loop (Figure 20) was obtained by applying a small (1%) step output disturbance at t = 2.0 seconds using MATLAB Control Systems Toolbox. The same scenario was simulated in PSCAD/EMTDC. The small signal stability behaviour results are illustrated in Figure 21. The results clearly that the MATLAB model results and PSCAD/EMTDC simulation results both concur that the LCC HVDC system is stable which is in agreement with the results and analysis of Table 5.

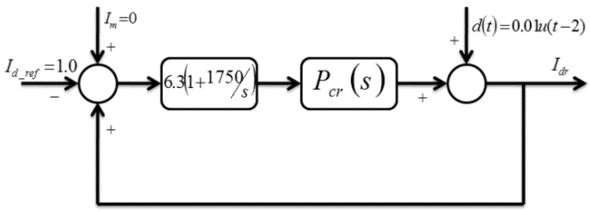

Figure 20: Rectifier Current Control Loop

Eigenvalue	Frequency (Hz)
-20.3	-
-21.40 + 273i	43.45
-21.40 - 273i	43.45
-205	-

Table 5: Eigenvalue Analysis for Rectifier Current Control Closed Loop System

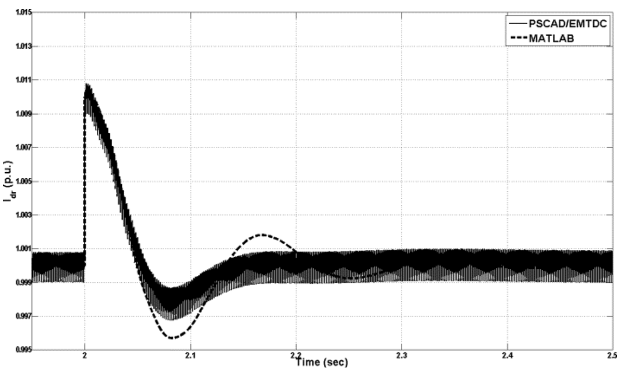

Figure 21: Rectifier DC Current Small Signal Behaviour

The small signal results compare favourably to each other with the approximate 43Hz frequency effect apparent in both the MATLAB model and the PSCAD/EMTDC simulation.

8. CONCLUSION

A LCC HVDC control system design method based on Quantitative Feedback Theory (QFT) was presented. The QFT design method was used to design the rectifier and inverter current controllers for the LCC HVDC system whose parameters are defined by Table 1 and Table 2 of reference [12]. The designed current controllers individually achieved the specified performance specifications. The stability of the integrated LCC HVDC control system was verified by simulating the start-up of a LCC HVDC system with the rectifier ac system's ESCR=8 and the inverter ac system's ESCR=8. The results revealed that the designed LCC HVDC control system does ensure a stable start-up process, thus preliminarily validating the design method. Due to the uncertain nature of the state of power systems, the conditions defining the operating point of the LCC HVDC system vary. The ability of the designed LCC HVDC control system to remain stable during these operating condition variations is categorized as the "Transient Stability of the LCC HVDC System". The stability of the integrated LCC HVDC control system was verified by simulating the start-up and step responses of the LCC HVDC system with the rectifier ac system's ESCR varying from 8 to 6 and the inverter ac system's ESCR varying from 8 to 6. The stable start-up and step responses of the LCC HVDC system, for varying ac system conditions, conclusively validate the QFT design method of the LCC HVDC control system parameters.

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AN EXPLORATORY CASE STUDY ON THE REQUIREMENTS BUSINESS PROCESSES OF A TYPICAL SOUTH AFRICAN HIGH TECHNOLOGY SYSTEMS ENGINEERING COMPANY

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Abstract: This article describes the findings of an exploratory case study into the requirements management and engineering processes of a South African Systems Engineering Company and how these processes affect the business of the company. For the purpose of this article the name of the company is kept confidential. This case study identifies processes that resulted in both successful and unsuccessful project performance, reasons for the problems, successful processes and ideas for practice improvement. The findings illustrate which processes are used, why requirement processes are important, and provide useful insights on causes of project failure and situations to be avoided. The findings also show where the main focus for company improvement should lie. This case study culminates in recommendations on ways to improve the current requirements processes of the company and proposes a theory on the use of requirements management and requirements engineering processes in the company.

Keywords: Requirements Management; Requirements; Systems Engineering; Business Process Improvement.

Abbreviations:
CMM – Capability Maturity Model
INCOSE – International Council of Systems Engineering
SEI – Software Engineering Institute

1. INTRODUCTION

Numerous actions exist on operational and strategic level which South African Systems Engineering and Defence Companies can use to improve their competitiveness. One of these actions is the effective use of requirements management and requirements engineering processes (also referred to as ‘requirements development’ by the Software Engineering Institute [SEI] [1]. There are various definitions for ‘requirements management’ and ‘requirements engineering’, some of which can be found in published literature as illustrated in Table 1.

The primary research objective of this paper is to determine the use of requirements management and requirements engineering processes in the company, and to determine what effect these processes have on project performance. The secondary research objectives are to identify actions and procedures that can be implemented to improve requirements management and engineering efficiency in project execution; identify requirements causes for unsuccessful project performance; and identify areas for improvement in current requirements management and requirements engineering processes. All these processes are critical to the success of the company’s primary business, which is the execution of projects that involve creating complex systems for clients.

The importance of requirements management and requirements engineering is illustrated a number of published sources. On the Software Engineering Institute website, as well as in [2], it is stated that the single biggest problem of building software is to determine what to build, or in other words to define the software requirements. Sommerville [3] also notes this problem and describes requirements engineering as focusing in particular on describing the solution. According to Hood *et al* [4] requirements engineering is accomplished by the requirements definition process. Requirements management and requirements engineering is therefore identified in literature as major areas for process improvement [3]. Brooks [2], Damian, Chisan, Vaidyanathasamy and Pal [5], however, report that there is a need to measure the effect of requirements engineering processes to determine its effectiveness. The Standish Report details that the average number of projects completed on time and within budget improved from 16.2% in 1995 (only 9% for large organisations) [6] to 34% in 2003 [7]. One of the main causes of unsuccessful projects highlighted in both studies is unstable requirements. The 2009 chaos report shows a slight decrease in the percentage of successful projects from 34% to 32% [8]. A study by Hall, Beecham and Rainer [9] indicates that 48% of development problems were caused by requirements problems. Jones [10] identifies project management problems related to requirements. These are the rejection of accurate cost, schedule and technical estimates (*relates to effective* *requirements engineering*), the failure to use automated estimation and planning tools, an excessive irrational schedule definition (*relates to effective requirements engineering*), and the user requirements scope creep (*relates to effective requirements management*). To further illustrate the importance of accurate requirement, the International Council of Systems Engineering (INCOSE) handbook indicates that, based on studies done in the United States, during the concept and definition phase where requirements are established, 8% of the project LCC (Life Cycle Cost) is used up, but up to 80% of the system cost is determined by decisions made [11].

Table 1: Definitions of requirements management and requirements engineering

Term	Definition
Requirements management	The interface between requirements development and all other systems engineering disciplines, including configuration management and project management [4].
	Capability Maturity Model (CMM) v1.2: 'requirements management' [1]: "*manage the requirements of the project's products and product components and to identify inconsistencies between those requirements and the project plans and work products*".
Requirements engineering	Consists of requirements definition, from customer requirements to product requirements and product component requirements [4].
	CMM v1.2: 'requirements development' (also known as requirements engineering) [1]: "*the purpose of requirements development is to produce and analyse customer, product and product component requirements*".

The software and defence industry has responded to the abovementioned problems by creating various process models. These models include the Software Engineering Institute [SEI] Capability Maturity Model [1], International Standards Organisation [ISO] 15288 [12], ISO 12207 [13] and many others. INCOSE created a website of requirements engineering best processes that allows anyone to contribute processes [14]. Damian *et al* [5] noted three predominant requirements engineering process improvement frameworks; these are the CMM, the ISO 15504 [15] and the Sommerville and Sawyer [16] model. Paulk, Curtis, Crissis and Weber [17] lists the benefits of the CMM model as productivity related benefits including cost decreases; improved agreement among team members regarding designs and; more accurate project cost and schedule estimates. Unfortunately there is little empirical evidence in published literature that prove the benefits of the requirements engineering and management process frameworks. Even with these models requirements management and requirements engineering comprise a relatively new field which lacks well established measurement metrics and research data. Most of the practical guides to requirements management and engineering such as those presented in Sommerville and Sawyer [16] and Robertson and Robertson [18] offer only generic requirements processes.

2. MATERIALS AND METHODS

2.1 Previous requirements process improvements

Damian *et al* [5] carried out a case study and documented empirical evidence on the project performance of improved requirements processes and the positive effects thereof on downstream software development in the Australian Company of Unisys Systems (ACUS). The results of the case study conducted by Damian *et al* [5] concluded that the process activities which had the most significant effect on project performance were: collaborating cross functional team involvement resulting in better designs; numerous analysis and requirements review sessions that exposed design flaws and; and real-world (scenario based) test descriptions which meant that systems are tested in the same way that they are used. Faily [19] detailed a case study of improving requirements engineering processes within the European Space Agency Flight Dynamics Division.

Zainol and Mansoor [20] conducted a survey of the requirements management processes and implementation of CMM level 2 activities in the Malaysian software industry. Verner and Cerpa [21] reused the same survey questions as Verner and Evanco [22] to investigate the requirements management processes of Australian software companies. In another study by Verner and Evanco [22] the authors detail the results of a survey into requirements engineering processes, where interviews were conducted with 21 software professionals regarding one successful and one unsuccessful project. In a study by Cox, Niazi and Verner [23] the researchers determined the most useful requirements management processes implemented by surveyed Australian software companies. As basis for the identified processes the authors used the 66 requirements processes identified by Sommerville and Sawyer [16]. In their study Lodhi, Tariq, Naveed, Gul and Khalid [24] identified the requirements engineering best processes used in the Pakistan software industry. Yuclacar and Erdogan[25] evaluated the CMMI level 2 maturity of five Turkish software companies. The study used 39 research questions from all the CMMI process areas (requirements management, project planning, project monitoring and control, supplier agreement management, measurement and analysis, project and quality awareness, and configuration management), including three questions from the requirements management process area. Groves, Nickson, Reeve, Reeves and Utting [26] surveyed selected New Zealand software companies using a questionnaire and in-depth interviews focusing on requirements gathering. Cuevas, Serrano Alan and Serrano Ariel [27] developed a method to access the requirements management processes of a company using a two stage questionnaire based upon the CMM [1]. The authors selected among numerous research questionnaires to evaluate the most accurate questionnaire. The options were the *CMM-Based Appraisal for Internal Process Improvement* (*CBA IPI*) V1.1 [28], Northup Grumman Process Improvement Model and the Institute for Software Process Improvement [IISP] [29].

2.2 Research background

The origins of this research lay in the first author's new role of business analyst within the defence industry, a role that had previously been available only within the commercial/banking industry. In order to fulfil this role the author needed to determine the requirements problem areas and the causes for these problems. Moreover, it has been speculated that the use of requirements management and requirements engineering processes by South African Systems Engineering Companies may be poor, if not non-existent, and that requirements management and requirements engineering have a definite effect on project performance.

This research is important for the following reasons: It will indicate the maturity of the requirements management processes within a South African Systems Engineering and Defence company; allow for a comparison with the requirements management and engineering processes used in other companies; identify areas of requirements management and engineering improvement; add to the (currently) scant empirical evidence on the effect of requirements management and engineering in spite of a considerable body of literature emphasising the benefits; and identify process changes that resulted in improved project performance. The conceptual investigation methods are given in Table 2.

Table 2: Conceptual investigation method per research proposition

#	**Research propositions**	**Conceptual investigation methods**
1	There are specific requirements engineering processes that either increase or decrease the likelihood of successful project completion.	Determine which requirements engineering factors most affect successful project outcome and which most significantly affect failed project outcome.
2	The company does not implement requirements management processes.	Determine which requirements management processes are used within the company.
3	The company does not implement requirements engineering best processes.	Determine a list of requirements engineering best processes and detail which of the processes are used within the company.
4	There are major requirements factors affecting project failure.	Identify the major requirements problems experienced on projects and their impact.
5	There are requirements engineering factors that significantly affect project success.	Identify the major requirements successful action that increased project quality and the impact of each.
6	Improvements can be identified.	Identify the major requirements improvement ideas and the importance of each.

2.3 Research methodology

Yin [30] proposes the use of an exploratory case study method when exploring a new field where little is known. Four sources of evidence (listed in Table **3**) are used in order to probe deeply to gain a better understanding of the requirements management and requirements engineering processes used by the company and the effects thereof.

There is a single unit of analysis which is the company. The chosen sample is the system engineers of the company. Sampling used non probability sampling, which, as described by Merriam [31], is appropriate for qualitative research questions similar to those used in this research.

Table 3: Sources of evidence and research method

Source of evidence	**Detail of implementation**
Survey	• A survey was created reusing the yes/no questions of Verner and Cerpa [22], Zainol and Mansoor [20] and best practice descriptions on the REGAL website [14]. • To ensure validity the survey was reviewed by a senior systems engineer (20+ years' experience) • Experienced senior systems engineers were identified and asked to complete a survey over a period of two months from approximately May to July 2010.
Interviews	• An open-ended and semi-structured interview, lasting approximately one hour, was conducted with the identified systems engineers (the same systems engineers who were surveyed). • The interviews were recorded in short hand notes and analysed for patterns in response. • The interviewees were informed that all company, client, person and projects names are kept confidential. • The interviews focused on one successful and one unsuccessful project that the systems engineer

Source of evidence	Detail of implementation
	was involved in as well as on company requirements processes.
Documentation analysis	• Identify and analyse the project documentation for the successful and unsuccessful projects mentioned by the system engineers. • Only the projects that were conducted within the company could be analysed. • Documents are analysed based on evaluation criteria described later in this article.
Personal (direct) observations	• Company structure and overview • Brief project overview

3. RESULTS

The company used for this research develops electronic warfare products which are incorporated into electronic warfare systems for clients. The company has approximately 30 years of experience and employs 250 people with an approximately R 500m yearly turnover. The company follows a formal systems engineering process model in executing projects. Figure 1 shows the company departments and their interaction.

The product development department is responsible for developing new products based on product specifications. These products, sometimes incorporated into systems, are sold by the Marketing department. Once a system is contracted it is the responsibility of the system engineering department to deliver the completed system. The system engineering department is supported by the Production department, which manufactures industrialised products, and the software department which implements the interfaces between products as well as developing the user interfaces. Once systems are completed the delivered systems are supported by the Logistics department during renewable support contracts. For each system delivered within a project the systems engineering department creates a formal system specification and in response, while the software department creates the software specification.

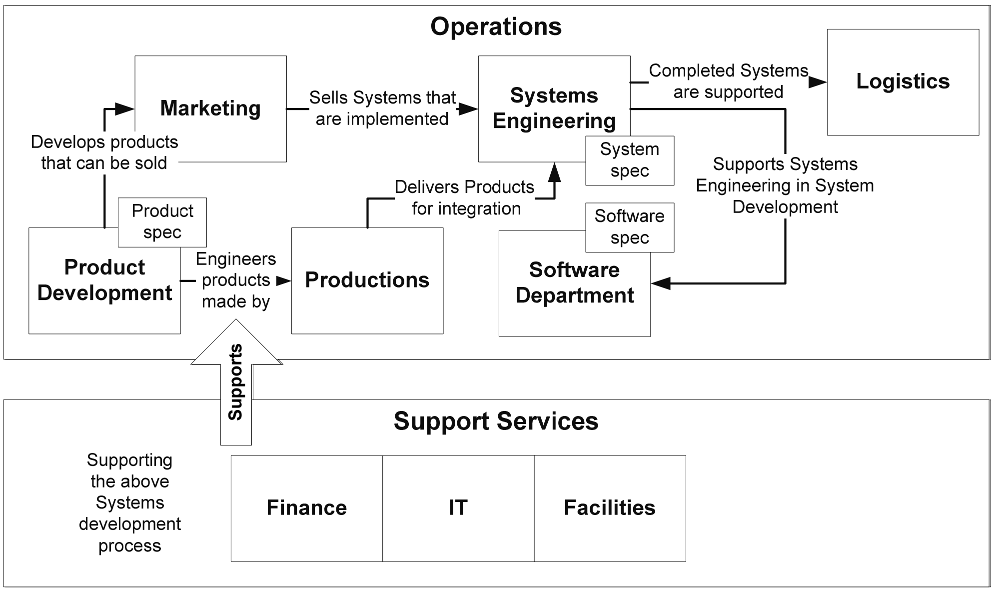

Figure 1: Company business process overview

3.1 Survey results

Figure 2 indicates survey results of which requirements engineering factor most influences project success. The results show that in successful projects, 6) requirements change is very small and that the 3) accurate requirements at the PDR stage, 4) overall clear and accurate requirements and 8) requirements fulfilling client expectations are the factors that most significantly influence project success. Eight survey responses were received (this represents 70% of the systems engineers in the company).

Figure 3 indicates the survey results of which requirements engineering factors most influences project failure. The results indicate that, for failed projects, three factors influence project failure the most. These are 6) Significant project scope change, 3) Accurate and complete requirements at the PDR stage and 4) Overall clear and accurate requirements. Eight survey responses were received (this represents 70% of the systems engineers in the company).

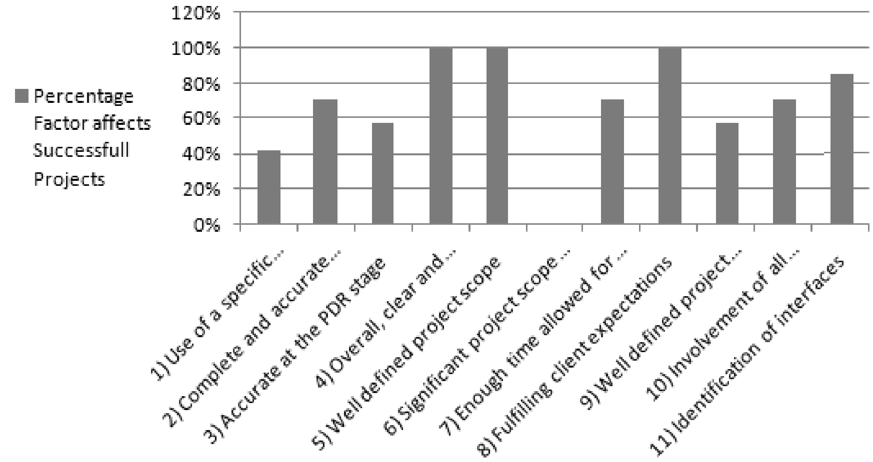

Figure 2: Successful Project Requirements Engineering Factors

Table 4 illustrates the survey results of which requirements management processes are implemented in the company. Eight survey responses were received (this represents 70% of the systems engineers in the company). The results of Table 4 illustrate that of all the requirements management processes 61% are implemented in the company. No modelling, either with UML or SysML, is used to describe requirements and no requirement prototypes are built. Another interesting result is that the company does not have any requirements management guidelines and does not record deleted/rejected requirements.

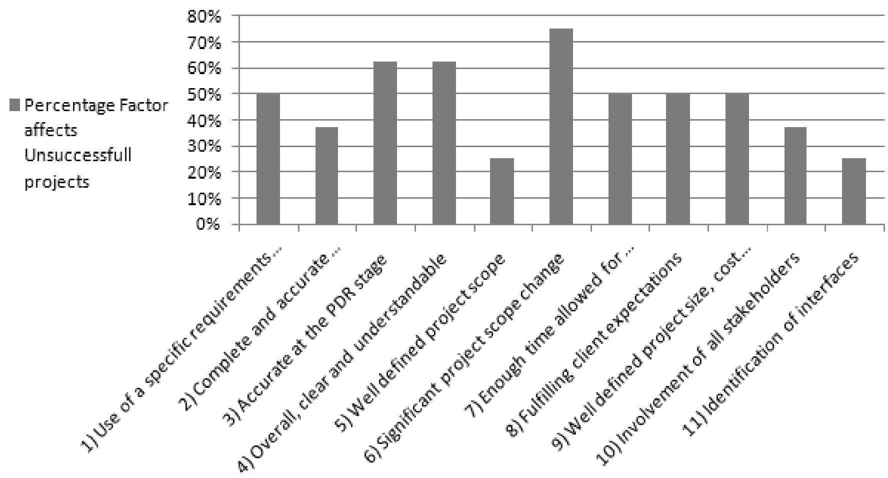

Figure 3: Unsuccessful project requirements engineering factors

Table 4: Usage of requirements management processes

Requirements management practice		**Used**
a.	Do you have standards / templates / documents / tools for describing requirements?	Y
b.	Do you have guidelines on how to write requirements?	Y
c.	Do you use the UML (Unified Modelling Language) to document requirements?	N
d.	Do you use the SysML (Systems Modelling Language) to document requirements?	N
e.	Do you supplement the written requirements with diagram descriptions?	Y
f.	Do you specify requirements with unique identification?	Y
g.	Do you develop a prototype in order to understand poor or complex requirements?	N
h.	Do you re-use requirements from other similar systems?	Y
i.	Do the requirements show the system boundaries?	Y
j.	Do you develop a checklist for requirement analysis?	Y
k.	Do you perform a specific requirements analysis process with a specified output?	N
l.	Do you prioritise requirements?	Y

Requirements management practice		Used
m.	Do you perform any risk analysis on requirements?	Y
n.	Do you use prototyping to demonstrate requirements for validation?	N
o.	Do you have defined policies for requirements management?	N
p.	Do you use a central repository database or requirements management tool?	Y
q.	If you answered yes to the previous question, which one do you use? **No / In-house tool**	
r.	Do you identify risky (cost, schedule or quality - TPM) requirements?	Y
s.	Do you record rejected requirements?	N

The results of Table 5 illustrate the survey results of which requirements engineering best processes are implemented in the Company. Eight survey responses were received (this represents 70% of the systems engineers in the company).

Table 5: Usage of requirements engineering best processes

Best practice		Never	Infrequent	Mostly	Always
3.1	Define a standard document structure for requirements	13%	25%	63%	0%
3.2	Define new products in terms of deltas on existing products	0%	13%	75%	13%
3.3	Ensure that every requirement is quantified	25%	13%	63%	0%
3.4	Establish a verification statement for requirements	25%	25%	50%	0%
3.5	Identify the type of requirements flow-down	13%	50%	38%	0%
3.6	Make use of requirements classification, sorting and filtering	38%	63%	0%	0%
3.7	Propose trade off options against requirements	0%	38%	63%	0%
3.8	Ensure that interface requirements are complete	13%	13%	63%	13%
3.9	Ensure that one and only one requirement in each statement	0%	13%	63%	25%
3.10	Use a simple language to express requirement	0%	13%	75%	13%
3.11	Define Product Scope	0%	13%	88%	0%
3.12	Define the system context	0%	25%	63%	13%
3.13	Document the system goals as part of scope	0%	63%	25%	13%
3.14	Identify relevant stakeholders	0%	50%	38%	13%
3.15	Focus on the problem to be solved	0%	50%	38%	13%
3.16	Identify requirements using scenarios	0%	50%	50%	0%
3.17	Identify the goal of a requirement	0%	0%	100	0%
3.18	Negative scenarios to elaborate non-functional requirements	25%	75%	0%	0%
3.19	Understand the need for the system	0%	0%	75%	25%
3.20	Verify requirements using operational models / scenarios	0%	25%	63%	13%

The results in Table 5 shows that none of the requirements best processes are used on any of the projects, but that 14 of the 20 (70%) best processes are mostly used while six of the 20 (30%) best processes are used infrequently. The survey results from the eight respondents who also indicate that negative scenarios are not used, requirements flow-down traceability is only completed infrequently and system goals are not always defined.

3.2 Interview results

The interview results describing ideas for requirements process improvement are presented in Table 6. The importance value is determined by the number of respondents mentioning the idea and the importance the respondents attached to the idea.

Table 6: Ideas for improvement to company's requirements engineering processes

Improvement idea	Interview feedback	Importance
Conduct BIA on new clients	Three respondents suggested conducting a Business Information Analysis (BIA) on new clients. The purpose is to document the existing client work processes and existing client information definition and data structures.	Low
Multi-disciplined scoping team	Two respondents expressed the idea of using a multi-disciplined team, each with different roles to perform initial project scoping and requirements analysis for complex projects.	Medium
Bid / no-Bid checklist	A suggestion was made by two respondents to use a checklist to ensure that production capacity is taken into account and that Technical risks are identified	Medium

Improvement idea	Interview feedback	Importance
	during the bidding process.	
Product owners input at bid / no-Bid meetings	One respondent highlighted that product owners should be present at bid / no-bid meetings to ensure that technical risk is taken into account.	High
	A need was expressed by all respondents for more accurate technical input into the marketing process to perform requirements analysis.	
	A need was identified by one respondent for the adequate assessment of what is possible with current technologies and future technologies.	
	All respondents highlighted the risk of marketers performing high-level system design without technical inputs.	
Risk budget	Two respondents expressed the need to increase the risk budget allocation on projects.	Medium
	This was also highlighted by a third respondent who stated that the existing budgets on previous systems were inadequate.	
Obsolescence problem	One respondent highlighted that obsolescence of product / product components is not part of the bid process.	Low

The most important new idea highlighted in Table 6 was for the inclusion of technical product owners in the marketing process to perform requirement analysis and system scoping. Table 7 indicates the requirements problems, identified by the respondents, affecting projects. The occurrence value is determined by the number of respondents who mentioned the factor and the impact the respondents thought implementing the factor would have.

Table 7: Most significant requirements problems affecting projects

Factor	Interview feedback	Occurrence
Unrealistic systems sold	All respondents mentioned the problems experienced when marketing sells a system that is not realistic or achievable.	High
New product development during project execution	Three respondents highlighted the risk of having a large component of new development within a project and the use of projects to industrialise products.	Medium
	Two different respondents respectively mentioned projects where significant project development was done during the execution of a project, resulting in one case a seven year (80% new development) and in another case a three year schedule overrun (50% new development and complex product integration).	
Unrealistic requirements	Two respondents highlighted the effect of one unsuccessful project where a proper requirements analysis was only done after four years.	Low
Understand client expectation	Three respondents highlighted that one of the contributing factors to the unsuccessful project was that the requirements were not understood and accurately captured in a specification document.	Low
Negotiation difficulty	Four of the respondents identified negotiation difficulty was making a significant contribution to un-successful projects.	High
	In another instance the relationship with the client was not based upon trust and this meant that accurate requirements analysis could not be performed during project scoping.	
Production capacity	One respondent suggested that production capacity must be taken into consideration during the bidding process	Medium

Table **7** indicates that negotiation difficulty problems and unrealistic systems designed during the marketing process as the main problems that occur most often in projects.

3.3 Document analysis results

In Table 8 it is indicated that the project characteristics and the project document analysis results. For confidentiality purposes the projects are numbered A to N. The documentation of the projects mentioned by respondents was analysed.

Table 8: Project characteristics

#	Project	Complexity	Experience	Negotiation
1.	A	High	High	Difficult
2.	B	Average	H	Difficult
3.	C	Small	Very High	Easy
4.	D	Average	Low	Easy
5.	E	High	High	Not Applicable
6.	F	Small	Low	Easy

#	Project	Complexity	Experience	Negotiation
7.	G	Small	High	Difficult
8.	H	High	High	Difficult
9.	I	High	High	Difficult
10.	J	High	Very High	Easy
11.	K	High	High	Difficult
12.	L	High	High	Difficult
13.	M	High	High	Difficult
14.	N	?	?	?
? – external project about which no information is known				

Table 9: Results of document analysis

Yes (Y) No (N)	Successful projects								Unsuccessful projects					
Document characteristic	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**	**N**
a. Documentation agrees with systems eng. process	Y	Y	Y	Y	Y	Y	N	Y	-	Y	-	N	N	-
b. System engineering tailoring	N	N	N	N	N	N	N	N	-	N	-	N	N	-
c. System specification	Y	Y	Y	Y	Y	Y	Y	Y	-	Y	-	Y	N	-
c. Software specification	Y	Y	Y	Y	Y	Y	N	Y	-	Y	-	N	N	-
e. Traceability system and software requirements	N	N	N	N	N	N	N	N	-	N	-	N	N	-
f. Requirements analysis	Y	Y	Y	Y	Y	Y	N	Y	-	Y	-	N	N	-
g. Unique identified requirements	Y	Y	N	Y	Y	N	N	Y	-	Y	-	Y	Y	-
h. Systems verification criteria	Y	Y	Y	Y	Y	Y	Y	Y	-	Y	-	N	Y	-
i. Software verification criteria	N	Y	N	Y	Y	N	N	N	-	Y	-	N	N	-

Table 9 indicates that tailoring of the systems engineering process was not done and that even through specifications for both software and systems are drawn up, no traceability analysis is completed. Successful projects contrasts to unsuccessful projects by the systems engineering process followed and the definition of software specifications.

An industrialising investigation was completed in 2007 by an external consultant. The contents of the industrialisation investigation report were analysed to determine and identify any correlation with interviews and survey results (see
Table **10**)

Table 10: Feedback from industrialisation report

Department	Description
Marketing	The industrialisation report notes three causes of problems experienced in project execution. These are that the company never says no to a deal; sells un-industrialised products, and that no measure of the production capacity is taken into account when contracting new systems.
Product development	The main problem is that products are not industrialised which, according to the report, is caused by under staffing and technical and administrative short cuts.
Software development	The problems expressed in the industrialisation report is that the software department is overloaded and understaffed and that the department is required to handle a number of parallel projects causing too much rework and quality problems.

3.4 Personal observation results

Table 10 as well as in the problems described during interviews from Table 7 can be understood as follows: due to current processes the marketing department sells un-industrialised products. This increases the workload of the product department to industrialise new products because of rework on old products. The effect of always saying “yes” to projects is to overload the production capacity and the capacity of the software department due to too many parallel projects. The overload of the software and product department reduces the quality and increases the rework required. The negative feedback loop increases the load and reduces output even further resulting in more overruns and schedule delays for subsequent projects unless capacity is increased.

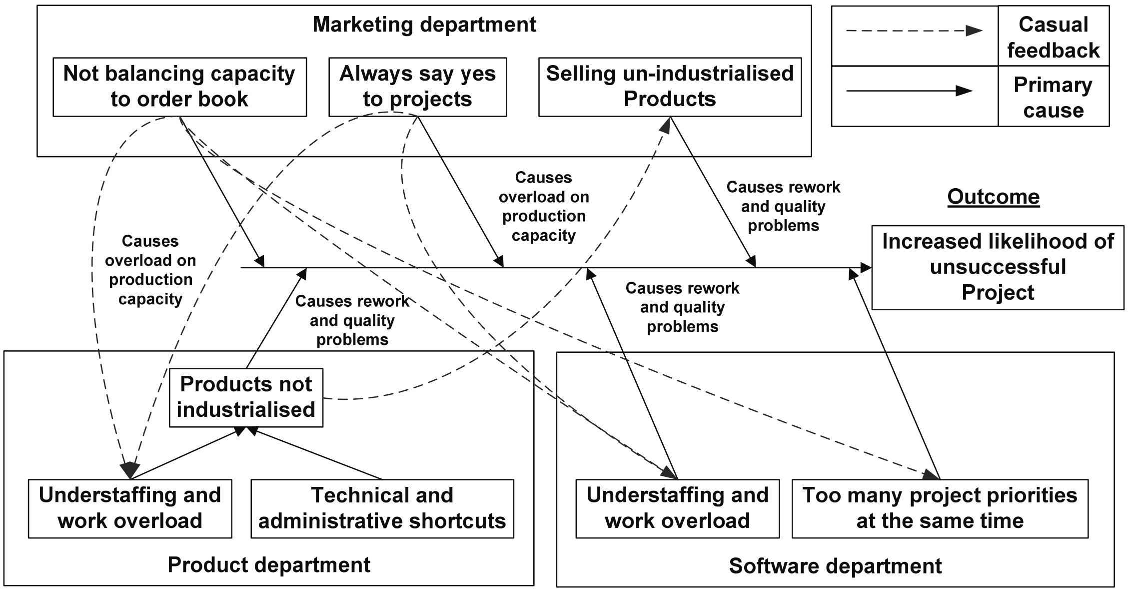

Figure 4: Fishbone diagram showing cause and effect between reported problems

Figure 4 can be understood as follows: due to current processes the marketing department sells un-industrialised products. This increases the workload of the product department to industrialise new products because of rework on old products. The effect of always saying "yes" to projects is to overload the production capacity and the capacity of the software department due to too many parallel projects. The overload of the software and product department reduces the quality and increases the rework required. The negative feedback loop increases the load and reduces output even further resulting in more overruns and schedule delays for subsequent projects unless capacity is increased.

4. DISCUSSION

4.1 Overview of results

The results of the survey into successful and unsuccessful requirements factors show that limited requirements scope change positively influences project success. This is expected due to the nature of the complex projects undertaken by the company. The results show that the respondents perceive significant changes to requirements to have large effect on the project cost and schedule. The results of the survey of requirements management processes indicate that the company performs more requirements management processes than what is usually done in the average Malaysian company [20]. This is expected due to the complex nature of the systems developed and the importance of requirements management for complex projects. The company's requirements engineering processes can be improved by using requirements modelling. The company implements 70% of the requirements best processes. Improvement can however be made by using requirements filtering and sorting, describing requirements using scenarios and implementing traceability (also called requirements flow-down).

Most respondents feel that technical experts should be included in the initial system design and that this design should be performed during the marketing/contracting phase of a system. This is identified as a definite area in which the company can improve. The interviews on factors influencing successful project outcome highlighted the importance of using the systems engineering process and the advantage gained from technical inputs into the marketing process. The two issues that caused the most significant problems on projects were the sale of unrealistic systems to clients and negotiation difficulty experienced with the clients. Investigations should be made on successful negotiation strategies.

The document analysis supports the findings that requirements traceability is not performed adequately in the company. This indicates that the systems engineering process was not followed. An analysis of the industrialisation report shows that the problem of selling systems that contain un-industrialised products with unrealistic requirements has been with the company for at least three years. This causes other problems further along in the project lifecycle as shown in Figure 4.

The company has a limited number of clients; the effect of this is that the company has developed a culture of always accepting client requests and selling systems that do not take current capacity into account. This has resulted in overload on current staff that decreases the quality of delivered systems.

4.2 Theory on the effect of requirements management in the company

The requirements practices and processes used in the company are determined by the requirements defined during the initial project definition and contracting phase.

Usually this is handled by marketing. The absence of business analyst involved during this process produces lower quality requirements. This increases project costs as well as increases the changes of project failure.

4.3 Business improvement recommendations

The recommendations to the company are grouped according to the specific process area.

Table 11: Business improvement recommendations

Process improvement area	**Proposed actions**
System design process	1. It is proposed that systems engineers should investigate the use of System Modelling Language (SysML) and Unified Modelling Language (UML) in systems modelling. 2. The company must standardise and define a standard process for requirements engineering and verification. The guidelines for acquiring and documenting the requirements detailed in [32] can be used as guidance.
System engineering process	3. It is proposed that a policy to encourage strict adherence to implementing requirements traceability should be instilled as a standard work practice with systems and software engineers. 4. It is recommended that all system engineers are educated in this process and that the process is standardised in the company. It is further recommended that the standardisation be coupled with tailoring guidance. 5. It is recommended that the systems engineering process should also be used to perform product development and money should be spent to educate more users on the benefits of using the systems engineering process.
Tender process	6. It is proposed that a tender committee checklist could help with this problem but maybe an even more aggressive approach needs to be taken.
Client communication	7. In the case of negotiation difficulty the following is proposed: investigate the client culture and define specific strategies to enable successful project negotiation. 8. There must be a larger initial focus on gaining client confidence by frequent client visits, joint work sessions, joint training sessions and BIA analysis.
Product industrialisation process	9. Review and improve the product industrialisation process by: a. considering current production capacity in project planning, negotiations and bidding on tenders; b. investigating the increase of production capacity; c. identifying and implementing actions that improve product quality output and; d. improving the use of systems engineering in product industrialisation.

4.4 Conclusion

In conclusion, the survey results indicate that the company does implement requirements management and requirements engineering processes. Therefore this is not the area on which focus should be placed first. The survey results also show that there are requirements factors that significantly contribute to a successful project outcome. These results corroborate what is already documented in published literature on the advantage of using these processes. The interview results highlight the effect that requirements management and requirements engineering processes have on project performance by showing the main problems experienced by system engineers, the successful processes used and ideas for improvement. It is interesting to note that the requirements management and requirements engineering processes, described in the survey, were not mentioned during interviews. The interview results focus mainly on the marketing department and improving requirements analysis during contracting. The document analysis showed the value of the systems engineering process. The advantage of this process was also strongly highlighted during interviews. The most important areas for improvement are:

- Product industrialisation &
- Client communication

4.5 Research limitations

The major limitation of this case study is that it did not include any quantitative project schedule and budget (project cost) information which could have revealed correlation between the monetary and time effect of the specific problems mentioned and requirements management and requirements engineering processes. In future research project cost and schedule data can be analysed to determine the effect of the problems mentioned. The implementation of new requirements processes and procedures could be quantitatively evaluated. Future research can focus on product industrialisation and client communication.

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CROSS LAYER EXTENDED PARAMETER CALL ADMISSION CONTROL FOR FUTURE NETWORKS

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Abstract: The Next Generation Network (NGN) is to deliver anything, anytime anywhere with full quality of service (QoS) guarantees. The network designers need to overcome the NGN's challenges namely; heterogeneous wireless access environments, multiple traffic types, flexible bandwidth allocation and cross layer design issues among others. To guarantee quality of service for these NGN's, a call admission control scheme addressing the main challenges of NGN's is presented. This is a cross layer call admission control (CAC) scheme featuring multiple traffic types. The featured model effectively combines call level and packet level call admission control issues. It is based on Code Division Multiple Access (CDMA) air interface which together with Orthogonal Frequency Division Multiple (OFDM) access are the most popular air interface technologies. Traditionally, signal to interference ratio (SIR) has solely been used as the call admission control parameter for CDMA networks. However, the results indicate that due to the nature of the multimedia traffic more parameters need to be incorporated in the call admission control scheme. The presented CAC scheme uses extended user specified QoS parameters of signal to interference ratio (SIR) and delay to accept or reject a call and guarantee a certain call blocking probability QoS metric. The results from the developed model clearly indicate that a CAC algorithm incorporating more parameters outperforms one with less admission control parameters.

Keywords: Call admission control, CDMA, multimedia

1. INTRODUCTION

Next generation network (NGN) design is a major challenge for current telecommunication designers. They are to deliver any traffic anytime anywhere with full quality of service (QoS) guarantees. To realize this, several challenges need to be overcome. These challenges can be grouped majorly into; network challenges and traffic challenges. The NGN's network challenges include those associated with increasing the network capacity, accommodating diverse heterogeneous networks, mobility management and dealing with diverse network protocols, one of them being CDMA. CDMA, a widely applied multiplexing protocol is interference limited. A CDMA network suffers from graceful degradation as the number of users in the system increases; it has a soft capacity [1]. Therefore to guarantee QoS on a CDMA based network an efficient CAC scheme is required. The NGN traffic is very diverse in QoS requirements and presents a challenge to providing a service that satisfies all the users. Multimedia traffic types can be real time or non-real time with different QoS metrics. Real time traffic has stringent delay requirements and can be less stringent on bit error rate (BER) requirement, whereas non real time traffic might not require stringent delay requirements but stringent BER requirements. Traffic may exhibit other properties such as burstiness, correlation and self-similarity [2]. In [3], several traffic classes are proposed; their main distinguishing characteristics are packet error rate (PER) and the delay requirement. The NGN's must support this heterogeneous mix of services with varying QoS metrics. One of the mechanisms to efficiently provide for QoS for the diverse traffic types of the future networks is CAC. A CAC scheme, must consider the key defining traffics QoS metrics like delay and PER for a particular traffic type and ensure that the QoS is maintained. Therefore a single parameter CAC scheme is not sufficient for such diverse traffic.

The QoS metrics for a network are different at different OSI layers. They could be call blocking probability, signal-to-interference ratio (SIR) or bit error probability (BEP) at the higher and physical layers respectively. The QoS metrics can also be at packet level (i.e., queue throughput, packet dropping probability, delay and jitter) or at call level (call dropping probability). To guarantee QoS at different layer, call or packet level, cross-layer optimization is required. Network designers have bridged the OSI structured design and introduced cross layer design [4][5][6]. Cross layer design improves the performance by optimizing the metrics at different levels. Therefore to maintain QoS in future networks, a cross layer CAC with extended QoS metrics is required.

This paper is organized as follows. In Section 2, closely related work done in literature and its critical review is presented. Section 3 presents the system model; cross layer CAC model, network model and the CAC model. Section 4 presents the analytical evaluation of the following; teletraffic model, SIR capacity and delay capacity. The basis of comparing two different CAC parameters and the performance of the CAC model are discussed in Section 5. Finally the conclusions are presented in Section 6.

2. RELATED WORK

CAC has been an active research area on wireless networks [7]. On a CDMA based wireless network, most CAC algorithms address QoS at one layer and feature only one QoS metric in the admission control algorithm. This tends to be disadvantageous to some traffic types. In [8][9], the physical level QoS metric, SIR, is used as the main parameter for the CAC algorithm. If not directly using SIR, a parameter that translates to SIR is used. In [10], a number based call admission control scheme is developed; however, the equivalent number of users is a function of the SIR. Another parameter used for CAC is power. This is also closely related to the SIR. In [11] only the packet level QoS metric is investigated. Few papers combine both physical level and network level QoS parameters. A CAC scheme which considers both call- and packet-level QoS is required. In [12] packet and call level CAC has been investigated. [13] Extends the call-level and packet-level QoS CAC scheme to adaptive channel allocation. In [6] a cross layer CAC scheme that guarantee both physical layer QoS and network QoS with variable bit rate packet traffic is developed. However, the SIR outage is the major parameter considered even for packet traffic. In the cases reported above, the packet level parameters are not incorporated in the CAC scheme. In [14], a call admission control algorithm for a CDMA system with slotted ALOHA access system is investigated. The CAC algorithm is based on restricting the maximum number of codes allocated to the two traffic types and has a fixed maximum capacity which is not one of the merits of CDMA as it has a soft capacity. The delay is computed in terms of the slots that elapse during the transmission of a packet and is not directly considered in the admission scheme. Delay based call admission control schemes have commonly been used in ATM networks [15]. The admission control is based on the maximum delay bounds. Measurement based call admission control have also been encountered in this networks [16]. These networks are predominantly circuit switched with fixed capacity. CAC algorithms for CDMA networks combining several QoS parameters (delay, SIR) at different levels for future networks have rarely been done in literature. This work develops a CAC scheme to guarantee QoS with the following features:

- Multi criteria CAC scheme with SIR and delay QoS metrics to guarantee a certain call blocking probability. More parameters could further be included in the call admission control scheme albeit for some little complexity.
- A cross layer CAC to maintain both packet level and call level QoS.
- A CAC scheme featuring multiple types of traffic on a variable capacity CDMA link.
- An analytical evaluation of the CAC model capacity featuring CDMA packet scheduling on the wireless link.

3. SYSTEM MODEL

3.1 Cross Layer Model

The CAC model exploits cross layer design to achieve optimal performance. Three different QoS metrics exist at different layers of the protocol stack as follows; call blocking probability at application layer, packet delay at the network layer and SIR at the link layer.

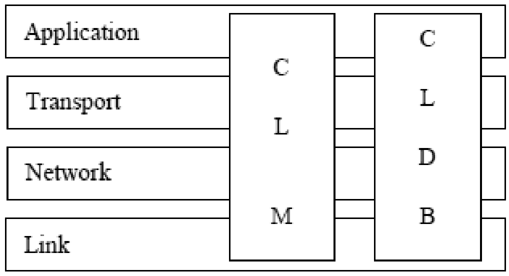

Figure1: The Cross Layer Model

As an adaptation of the models in [4][5], a shared database design is employed. The future CLD design is envisaged to consist of the cross layer manager (CLM) and the cross layer database (CLDB). The CLM is responsible for the interaction between the particular layer and the database. It manages the storage and retrieval of important parameters of a layer and the CLDB. Such a design offers flexibility in terms of expansion and inclusion of other layers and is used in this work. The desired layer QoS metric is stored in the database by the appropriate layer and can be requested by any other layer. The CLD model employs packet delay metric at the network layer, SIR at the link layer to guarantee a particular blocking probability at the application layer.

3.2 Network Model

Consider a wireless mobile network where several mobile stations are being scheduled on the air interface. The multiple access mode used is the CDMA technology. Each mobile station can be of the following traffic types:

- ***Class one***, high priority traffic: Delay and Packet loss sensitive traffic class. This can be the guaranteed service linked to the UMTS conversational traffic type.
- ***Class two***, medium priority traffic: Traffic that can tolerate some delay and packet loss violations. This can be the predictive service linked to UMTS streaming traffic.
- ***Class three***, low priority traffic: The best effort class (BE), the traffic class can be related to the interactive and background traffic classes of the UMTS.

The traffic classes are grouped into the three groups above depending on their desired BER (SNR) and delay. An admitted call generates packets which are policed and then fed in the traffic class's queue. This is shown in Figure 2, where λ_{ik} is the arrival rate of call i of class k and n_k is the number of class k calls. Scheduling on the queues is based on the WFQ for the three traffic classes.

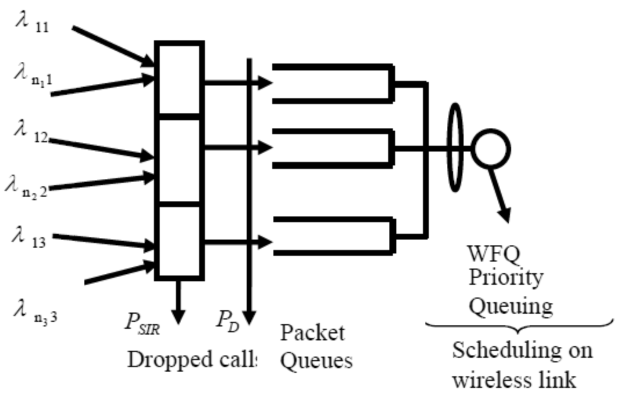

Figure 2: System Model

3.3 Admission Control Algorithm

An arriving call requests admission from the base station. The call admission algorithm is run each time a call arrives and requests capacity and is shown in Figure 3.

```
Call Admission Control Algorithm
An arriving call requests admission from the base station.
  Determine capacity based on SIR ( Eq. 12)
  If there is no capacity
     drop the call
  else
  {
        Determine capacity based on Delay (Eq. 38)
        If there is a violation
           drop the call
        else
          admit the call
  }
```

Figure 3: Call Admission Control Algorithm

The call is either admitted or blocked depending on whether there is capacity based on SIR or delay. The call admission control scheme is based on the two QoS parameters of SIR and delay. To admit a new call i of class k the following conditions must be satisfied. The guaranteed QoS (delay bound $d_{req,ik}$, PEB or $\left(E_b/N_o\right)_{req,ik}$), for the particular call should be provided and the QoS of the existing calls should not be severely affected by admitting the call. The teletraffic model to evaluate the CAC scheme and the analysis of call admission control capacity is done in the next section.

4. MODEL ANALYTICAL EVALUATION

4.1 Teletraffic analytical evaluation

A network with three traffic classes in the system is considered. The system can thus be analysed as markov chain with state $S=\{n_1,n_2,n_3\}$, where n_k is the number of class k calls communicating with the base station. This is a multidimensional markov chain where the effect of the time-varying capacity of the link and the delay bound are incorporated into the arrival process. The different admission priorities are incorporated in the admission control algorithms. The traffic characteristics used in the evaluation of the model are as follows:

- A homogeneous system in statistical equilibrium is assumed and therefore only one cell is analyzed.
- A new call of class k, $\{k=1,...N\}$ arrive at the cell according to a Poisson process with rate λ_k
- The service time of a class k call is exponentially distributed with mean μ_k
- The sources are modelled as ON-OFF with exponentially distributed ON and OFF durations of call i of class k as v_{ik}, w_{ik} respectively.
- The traffic generated by user i of class k when it is ON is characterized by a token bucket filter with parameters (r_{ik}, b_{ik}), class parameter (r_k, b_k).
- The user specifies the QoS parameters as the delay bound $d_{req,ik}$ and the desired BER which can be translated into the desired SIR threshold $\left(E_b/N_o\right)_{req,ik}$

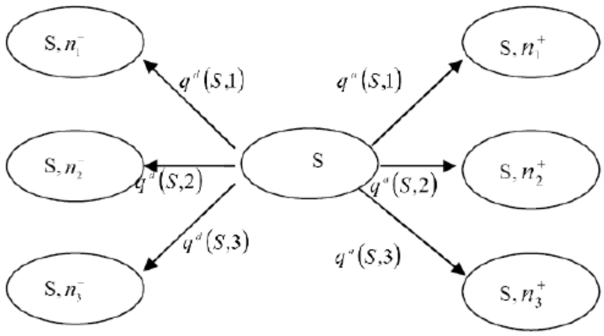

Figure 4: State Transitions diagram

For the system, let $S=\{n_1,n_2,n_3\}$ be the current state of the system, $\left(S,n_k^+\right)$ and $\left(S,n_k^-\right)$ the state after the arrival and departure of a class k call respectively. The state transistions $q^a(S,k)$ and $q^d(S,k)$ represent the arrival and departure of a class k call in state S. The state transition diagram is shown in Figure 4. The transition rates are given by

$$q^a(S,k)=P^a(S,k)\lambda_k \qquad (1)$$

and

$$q^d(S,k) = \mu_k \tag{2}$$

where $P^a(S,k)$ is the probability of admitting a class k call in state S . Let $\pi(s)$ be the stationary probability of state s . The state balance equations must satisy the following equations:

$$\pi(s)\sum_k \sum_i q^a(S,k) + q^d(S,k) = \pi(s^+)\sum_k \sum_i q^d(S^+,k) + \pi(s^-)\sum_k \sum_i q^a(S^-,k) \tag{3}$$

and

$$\sum_{s\in S} \pi(s) = 1 \tag{4}$$

The call blocking probability of a class k call, ψ_k is given by

$$\psi_k = \sum_{s\in S} \{1 - P^a(S,k)\} \pi_s \tag{5}$$

where $P^a(S,k) = p_A^D \cdot p_A^S$ and the values of the SIR and delay capacity, p_A^S and p_A^D are as derived in equations (12) and (38) respectively in the next section.

4.2 CAC capacity based on interference

The received signal to noise ratio $(E_b/N_o)_{ik}$ of user i $\{i = 1,2,..M_k\}$ of class k $\{k = 1,...N\}$ is given by

$$(E_b/N_o)_{ik} = \frac{G_{ik} h_{ik} p_{ik}}{(1+f)\sum_k \sum_{j\neq i} h_{jk}\alpha_{jk} p_{ik} + \eta_o W} , \tag{6}$$

where G_{ik} the processing gain, h_{ik} the path gain, p_{ik} the transmitted power, α_{jk} the source activity factor, η_o the noise factor, W the bandwidth, f the ratio of the external $I_{ext,k}$ to internal $I_{\text{int},k}$ interference. For the users to meet their target SIR, equation (6), under a minimum power, the following equation should be satisfied [17][18]

$$\sum_{k=1}^{M} \sum_{i=1}^{n_k} \alpha_{ik} g_{ik} \leq \frac{1-\Delta_{ik}}{(1+f)}, \tag{7}$$

where g_{ik} the power index and Δ_{ik} the power constraint. They are given as

$$g_{ik} = \frac{(E_b/N_o)_{req,ik}}{((E_b/N_o)_{req,ik} + G_{ik})} , \tag{8}$$

$$\Delta_{ik} = \frac{\eta_o W}{\min_i (p_{ik} h_{ik} / g_{ik})} . \tag{9}$$

From equation (7), introducing a capacity restraining constant φ that can be used to limit capacity for different traffic classes we have

$$Z = (C(t) + \Delta(t) + f(t)C(t)) \leq \varphi , \tag{10}$$

where:

$$C(t) = \sum_k \sum_i \alpha_{ik}(t) g_{ik} . \tag{11}$$

Due to the CDMA soft capacity and wireless nature, Z , is a random variable whose mean and variance can be calculated. The probability of accepting a call based on SIR, p_A^s, is the given by the following equation

$$P_A^S = P(Z \leq \varphi), 0 < \varphi \leq 1 . \tag{12}$$

If equation (12) is satisfied we conclude that there is capacity based on SIR. The mean and variances of Z are calculated next.

Considering that the shadowing and received powers of differently-located mobiles are mutually independent, and $\alpha_{ik}(t)$ is a Bernoulli distributed random variable with parameter α, $f(t), C(t)$ and $\Delta(t)$ are independent [19]. The mean and variance of $C(t)$ are derived as:

$$E[C(t)] = E\left[\sum_k \sum_i \alpha_{ik}(t) g_{ik}\right] = \sum_k \sum_i g_{ik}\alpha , \tag{13}$$

$$Var[C(t)] = \sum_k \sum_i (g_{ik})^2 \alpha(1-\alpha) \tag{14}$$

Assuming that the intracell interference is independent of the intercell interference [20]. The mean and variance of $f(t)$ is derived as:

$$E[f(t)] = E[I_{ext}]E\left[\frac{1}{I_{\text{int}}}\right] \tag{15}$$

$$Var[f(t)] = \left(Var[I_{ext}] + (E[I_{ext}])^2\right)E\left[\frac{1}{(I_{\text{int}})^2}\right] - (E[f(t)])^2 . \tag{16}$$

Following the standard derivations [23], the expectation of intercell interferes for a mobile station l of class k located at a distance r_{lk}^m from its cell site, r_{lk}^o from the cell site of the desired user in the region R_o with received S_k is given by,

$$E[I_{ext}] = \sum_{k=1}^{N} \sum_{l=1}^{M_k} C_{m,other} , \tag{17}$$

where;

$$C_{m,other} = S_k \alpha \iint_{R_o} \left(\frac{r_{lk}^m}{r_{lk}^o}\right)^4 v\left(\frac{r_{lk}^m}{r_{lk}^o}\right) dr_{lk}^o dr_{lk}^m \tag{18}$$

$$v\left(\frac{r_{lk}^m}{r_{lk}^o}\right) = \left(e^{(\sigma \ln 10/10)^2}\right) \bullet \left\{1 - Q\left[\frac{40}{\sqrt{2\sigma^2}} \log\left(\frac{r_{lk}^m}{r_{lk}^o}\right) - \sqrt{2\sigma^2}\frac{\ln 10}{10}\right]\right\} . \tag{19}$$

The variance of the intercell interference is given by,

$$Var[I_{ext}] = \sum_k \sum_l C_{v,\text{inter}} \tag{20}$$

where

$$C_{v,\text{inter}} = \iint_{R_o} (S_k)^2 \left(\frac{r_{lk}^m}{r_{lk}^o}\right)^8 \left[\alpha g\left(\frac{r_{lk}^m}{r_{lk}^o}\right) - \alpha^2 v^2\left(\frac{r_{lk}^m}{r_{lk}^o}\right)\right] dr_{lk}^o dr_{lk}^m \tag{21}$$

$$g\left(\frac{r_m}{r_o}\right)=e^{(\chi \ln 10/5)^2}\left\{1-Q\left[\frac{40}{\sqrt{2\sigma^2}}\log\left(\frac{r_o}{r_m}\right)-\sqrt{2\sigma^2}\left(\frac{\ln 10}{5}\right)\right]\right\} \quad (22)$$

$$Q(x)=\frac{1}{\sqrt{2\pi}}\int_x^{\infty} e^{-\frac{y^2}{2}}dy \quad (23)$$

For intercell interference, the Jensens inequality bound [21] is used to calculate the expectations as follows

$$E\left[\frac{1}{I_{\text{int}}}\right] \geq \frac{1}{\left[\sum_k \sum_{j\neq i} C_{m,\text{int}\,ra}\right]} \quad (24)$$

where $C_{m,\text{int}ra}=S_k \alpha e^{(\beta\sigma)^2/2}e^{\beta m}$ and $\beta=\ln(10)/10$. Similarly

$$E\left[\frac{1}{(I_{\text{int}})^2}\right] \geq \left(E\left[\frac{1}{(I_{\text{int}})}\right]\right)^2 \quad (25)$$

From equation (9), the variance and expectation of Δ_{ik} is given by

$$\text{E}[\Delta]=\eta_0 \text{W}\sum_{j=1}^{N} E[\text{X}_\text{i}]E[\Phi_i], \quad (26)$$

where

$$\Phi_i=\begin{cases}1, & X_I > X_J ....X_K \\ 0 & \text{otherwise}\end{cases}. \quad (27)$$

The expectation $E[X_i]$ can be easily evaluated given that the users are uniformly distributed throughout the cell. From the definition of Φ_i in equation (27), with the help of equation (28) below the expectation $E[\Phi_i]$ is easily derived

$$P(X_i > X_k) == 1-Q\left(\frac{10}{\sqrt{2\sigma^2}}\log\left(\frac{1}{y_{ik}}\left(\frac{r_k}{r_i}\right)^u\right)\right) \quad (28)$$

This is based on the assumption that ζ_i and ζ_k are independent, thus $\zeta_i - \zeta_k$ is a gaussian random variable with zero mean and variance $2\sigma^2$. A similar derivation is obtained for $E[\Delta^2]$ and thus the variance.

4.3 CAC capacity Based on delay

The packet capacity is dependent on the scheduling on the wireless link. Unlike other networks CDMA systems have introduced soft capacity. The scheduling capacity employed in calculating the delay bounds cannot be fixed. The capacity of a CDMA system is power or interference limited. The resources of a CDMA system exhibit the two dimensional nature [22], power and interference. The capacity can be derived in terms of the chip rate R_c and a power element $1-\Delta$ and is given by

$$C=R_c(1-\Delta) \quad (29)$$

For utilizing the capacity weighted fair queuing discipline (WFQ) is used for the different classes. The capacities of the traffic class one C_{μ_1} and traffic class two $C_{\mu 2}$ are

$$C_{\mu_1}=\frac{n_1\phi_1}{n_1\phi_1+\phi_2}\frac{R_c(1-\Delta)}{G_k g_k}=C_1(1-\Delta) \quad (30)$$

$$C_{\mu_2}=\frac{\phi_2}{n_1\phi_1+\phi_2}\frac{R_c(1-\Delta)}{G_P g_P}=C_2(1-\Delta) \quad (31)$$

where ϕ_1 and ϕ_2 are the overall weighting factors of traffic Class 1 and traffic Class 2 respectively, n_1 is the number of Class 1 traffic users and G_k is the class processing gain. Class 3 queue can be treated like a low priority Class 2 queue.

Assuming the term Δ is a log normally distributed random variable with PDF $P_\Delta(x)$ and CDF $F_\Delta(x)$. Its mean and variance have been calculated in the previous section. The pdf's of $P_{\mu_1}(x)$, and $P_{\mu_2}(x)$, are derived from equations (30) and (31) as

$$P_{\mu_1}(x)=\frac{1}{|C_1|}P_\Delta\left(1-\frac{x}{C_1}\right) \quad (32)$$

and

$$P_{\mu_2}(x)=\frac{1}{|C_2|}P_\Delta\left(1-\frac{x}{C_2}\right). \quad (33)$$

The traffic of class k, token limited by (r_k, b_k) is arranged in queues depending on the delay. Consider admitting user i of class k with token parameters r_{ik} and b_{ik}. The delay for the Class 1 traffic queue is given by [16]

$$D_{\max,i1}=\frac{\sum_{s=1}^{n_1} b_s + b_{ik}}{C_{\mu_1}}=\frac{C_3}{C_{\mu_1}}. \quad (34)$$

Utilizing the pdf's of equation (32), the delay probability is evaluated as

$$P_{D_{\max,i1}}(d)=\frac{|C_3|}{d^2}P_{\mu_1}\left(\frac{C_3}{d}\right) \quad (35)$$

Similarly, the delay bound for the predictive class (Class 2) queue is given by

$$D_{\max,j2}=\frac{\sum_{s=1}^{n_2} b_s}{C-C_{\mu_1}-\sum_{s=1}^{n_2-1} r_s}=\frac{\sum_{s=1}^{n_2} b_s}{C_{\mu_2}-\sum_{s=1}^{n_2-1} r_s}=\frac{C_4}{C_{\mu_2}-C_5}, \quad (36)$$

together with equation (33) the delay probability is given as

$$P_{D_{\max,12}}(d)=\frac{|C_4|}{d^2}P_{\mu_2}\left(\frac{C_4}{d}+C_5\right) \quad (37)$$

The specified user delay bound $d_{req,ik}$ translates into a class delay bound d_{bk}. Let the delay in the system for class k be d_{qk} and the delay distribution for class k be $P_{D_{\max,k}}(d)$. A user will be admitted with a probability P_A^D given by

$$P_A^D=\prod_{k=1}^{M} P_{D_{\max,k}}(d_{bk} < d_{qk}) \quad (38)$$

If by admitting the incoming user equation (38) holds then there is capacity based on delay.

Table 1: Simulation parameters

Parameter	Value
Call duration	200 s
Mean on time	0.5s
Mean off time	1s
Packet rate	20pkts/s
Token rate (aggregate)	100tokens/s
Bucket depth	10 tokens
Processing gain	128
Chip rate	1.25MHZ
AWGN	10^{-18}
Max Power	1 W

5. DISCUSSION AND RESULTS

The analytical evaluation is used to determine the performance of the CAC algorithms. The analytical model is validated by a simulation model based on a developed C++ discrete event simulator [24]. The call arrivals were assumed to be Poisson distributed and the service times exponentially distributed. There was traffic shaping and a CDMA link used. The chosen parameters are as indicated in Table 1.

5.1 Call admission schemes comparison

The CAC parameters of SIR and delay have no relationship with each other. The grounds for comparison of the different CAC parameters must be established. In this respect admission control based on the two parameters is independently investigated.

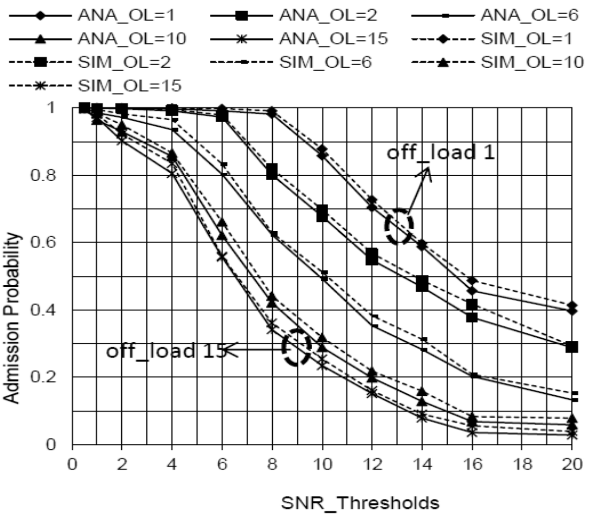

Figure 5: Performance of SIR CAC vs. SIR Threshold

The results of Figure 5 shows the performance of the SIR based call admission control scheme. The results clearly indicate that the admission probability reduces with an increase in the required SIR threshold. This is as expected since the lower the target SNR the higher the probability of admitting the call. This happens for all different offered loads, however, the admission probabilities reduce as the offered load increases. From the results, the analytical results are closely mirrored by the simulation results.

The results of Figure 6 shows the performance of the delay based call admission control model. The results clearly indicate that the admission probability increases with an increase in the required delay threshold. This is as expected since the higher the target delay the higher the probability of admitting the call. This happens for all different offered loads, however, the admission probabilities reduce as the offered load increases. From the results, the analytical results are closely mirrored by the simulation results.

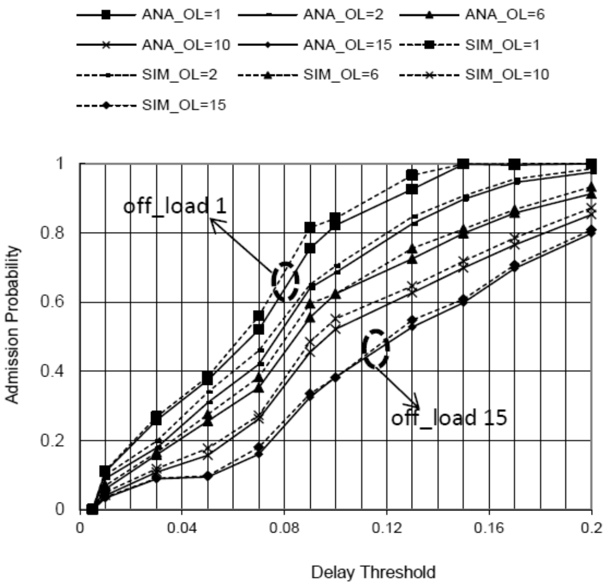

Figure 6: Performance of Delay CAC vs. delay Threshold

Table 2 shows values extrapolated from the SIR based admission control (Figure 5) and Delay based admission control (Figure 6). The table tries to relate the SIR threshold that achieves the same system performance, in terms of admission probability, as the delay threshold. This is done at different offered loads and forms the basis of comparing the call admission control schemes with different performance metrics. For evaluating the performance of the CAC, sets one and two of Table 2 are chosen for comparison purposes.

Table 2: SIR and Delay thresholds comparison

Admission probability	ρ_1		ρ_2		ρ_6		ρ_{10}		ρ_{15}	
	SIR_T	D_T	SIR_T	D_T	SIR_T	D_T	SIR_T	D_T	SIR_T	D_T
1	0.5	0.15	0.5	0.4	0.5	0.5	0.5	0.6	0.5	0.7
0.8 SET1	**11**	**0.09**	**8**	**0.12**	**6**	**0.15**	**4.5**	**0.18**	**4**	**0.2**
0.6	14	0.075	11.5	0.085	8.5	0.095	6.5	0.12	5.7	0.15
0.4 SET2	**20**	**0.054**	**16**	**0.064**	**11.5**	**0.073**	**8.5**	**0.085**	**7.5**	**0.1**
0.2	40	0.02	30	0.03	16	0.04	12.5	0.055	10	0.075

5.2 Performance of Admission Control Algorithms

The results of the system performance in terms of the call admission probability versus the offered load are shown in Figure 7. The results are done for the three call admission control schemes. The parameters are selected as SET 1 and SET 2 of Table 2. The SIR and delay thresholds are selected to achieve a target blocking probability and are applied on the same network. Both the SIR and Delay based CAC schemes achieve the desired admission probabilities as indicated in the table. The Combined CAC algorithm achieves relatively higher admission probabilities for the same parameters. This clearly indicates that using one parameter, underestimates the true network blocking probabilities due to all the network factors. In this case, the delay CAC algorithm is less stringent than both the combined and SIR based CAC algorithm.

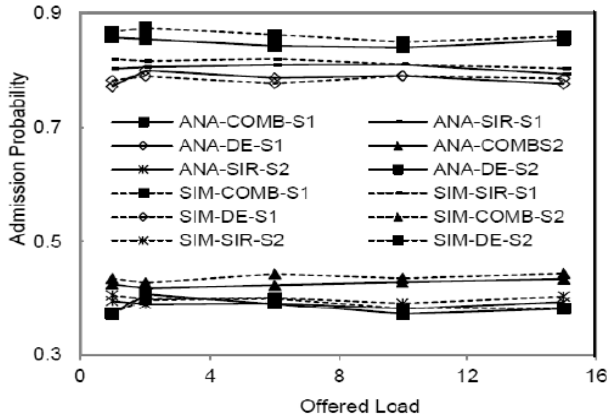

Figure 7 Performances of the CAC Algorithms

Figure 8 shows the same system performance in terms of the outage probability for the call admission control algorithms. Outage is measured as the ratio of calls that do not satisfy QoS parameter. The results indicate that the outage probabilities are slightly lower for all the admission algorithms. However, the combined CAC model achieves the lowest outage probabilities and thus asserting its superiority. The outage also increases as the offered load increases.

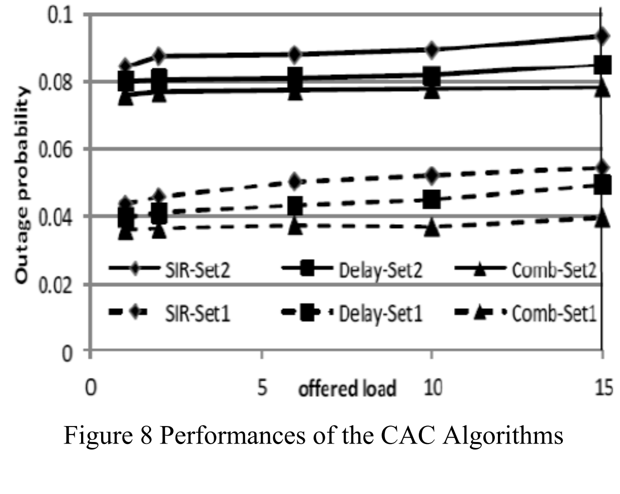

Figure 8 Performances of the CAC Algorithms

6 CONCLUSIONS

This work has developed a model for call admission control on next generation networks with two parameters, delay and signal to interference ratio. Further a test bed for the comparison of two independent CAC parameters is developed. The results from the developed model clearly indicate that a CAC algorithm incorporating more parameters outperforms one with less admission control parameters. The analytical results are validated by simulation results. Generally we can conclude that more parameters need to be incorporated at admission since the traffic types are widespread and have different admission requirements.

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STATE SPACE MODEL EXTRACTION OF A NATURAL CIRCULATION U-TUBE: A NETWORK APPROACH

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Abstract: The Reactor Cavity Cooling System (RCCS) in a High Temperature Gas-cooled Reactor (HTGR) provides protection to the concrete structures surrounding the reactor pressure vessel. The RCCS comprises stand pipes circulating water. These pipes may fundamentally be considered as U-tubes. Since the RCCS is critical in case of a Loss of Flow Accident (LOFA), it is very important to characterise the dynamics of such a system both for systems and control engineering purposes. Detailed Computational Fluid Dynamic (CFD) models do exist, but these models are too complex for the purposes mentioned. The majority of thermohydraulic simulation codes utilise a network approach towards representing thermohydraulic systems. This concept is used to extract state space models from graphic representations of such systems. The purpose of this paper is to illustrate the application of a State Space Model Extraction (SSME) method applied to a fundamental thermohydraulic system, namely a U-tube. The solution of the extracted state space model is compared with a validated systems CFD code called Flownex® and shows good correlation.

Key words: state space model extraction, gas-cooled reactor, U-tube, thermohydraulic systems, linear graph

1. INTRODUCTION

Due to the high temperature operation of HTGRs a challenge related to the characterisation and control of an RCCS is presented. Dynamic models of the RCCS capturing the dominant dynamics play a major role in the temperature control system design of the reactor vessel. Detailed thermohydraulic models for analysing the characteristics of an RCCS do exist [1–4]. However, although these models present valuable answers during the structural design process, they do not present insight regarding the dominant dynamics. Kazeminejad [5] states that over the past 30 years there has been great effort on the part of the power utilities to develop simpler models and modelling tools for the thermohydraulic simulation of reactor dynamics. The use of reduced order models for the study of dynamic behaviour of nuclear reactors is valuable since they allow faster calculation speeds and qualitative understanding of the physical phenomena involved.

A vast number of simulation software on the market use model libraries and graphical interfaces to develop dynamic system models. Only a small number of software packages are able to automatically extract mathematical models in state space format from a graphically designed system [6, 7]. This paper demonstrates a novel method developed by Uren [8] that utilises a linear graph, also called a network, representation of a dynamic system and combines it with a lumped parameter modelling approach to eventually extract a state space model of a thermohydraulic system. This method should not be confused with the standard Finite Element Methods (FEMs). FEMs are normally used in the solution of differential equations representing a thermohydraulic system. The SSME method is focused on extracting reduced order differential equations in state space format, which is ideal for control system design.

Section 2 of this paper will describe the physical system under consideration followed by section 3 explaining the network modelling approach towards thermohydraulic systems. In section 4 a network representation of the U-tube is derived. The state space model extraction of the U-tube is explained in section 5. Finally the state space model validation results are discussed in section 6.

2. PHYSICAL SYSTEM DESCRIPTION

The primary function of the RCCS is maintaining the reactor cavity temperatures within required temperature limits. Fig. 1 shows a section view of the reactor and reactor cavity. The RCCS is a network of pipes surrounding a nuclear Reactor Pressure Vessel (RPV) wall. During normal operation water is circulated through the pipe network by means of forced convection (pumps), but provision is made in case of a LOFA. Such a scenario may be due to a catastrophic mechanical failure of the pumps or due to the loss of power. This scenario is also called the passive operation mode of the RCCS, during which water will still be able to circulate through the pipes due to natural convection [9–11]. Two standpipes of the RCCS are shown in Fig. 2. Cold water enters the standpipe through an inlet manifold. The riser pipe is exposed to the heat radiated from the RPV which causes the water in the riser pipe to be less dense. The cold, more dense water in the downcomer pushes the water in the riser up into the outlet manifold. The water circulates due to natural convection. A standpipe may be viewed as a U-tube where

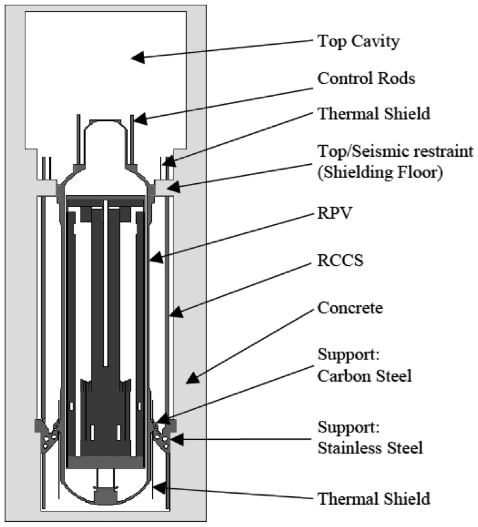

Figure 1: Section view of the reactor unit and reactor cavity [11]

one leg has a fixed temperature and the other leg is exposed to a heat source and both ends of the U-tube have the same pressure reference. It is this part that is of particular interest in terms of state space model extraction and will be the focus of this paper.

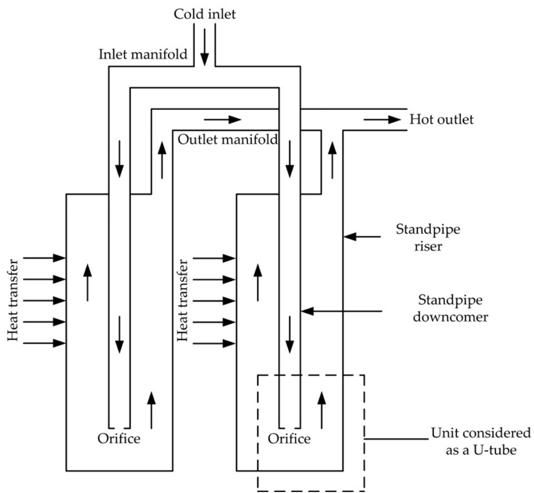

Figure 2: Two standpipes of the RCCS [9]

3. NETWORK MODEL REPRESENTATION OF THERMOHYDRAULIC SYSTEMS

Generalised system elements will be derived that can be used to describe the key system phenomena namely energy generation, storage and dissipation. Following a network approach, a thermohydraulic system can be represented by a network consisting of nodes (squares) connecting components (circles) as shown in Fig. 3. Each component can be broken up into energy networks of generalised

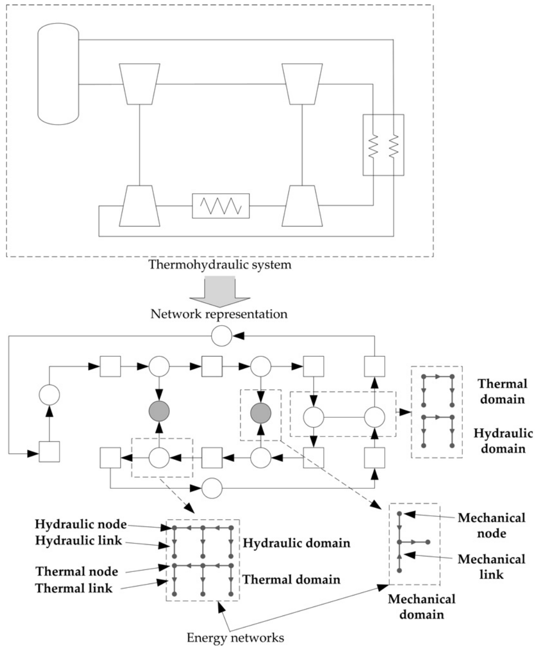

Figure 3: Thermohydraulic system

elements and variables representing the key dynamics of each physical domain present [12]. The unifying link between different physical domains can be regarded as energy transmission. Energy transmission is associated with one through variable (e.g. mass flow) giving the flux of energy flow, and an across-variable (e.g. pressure) giving the pitch of flow. The lines representing each element are oriented to indicate the reference directions of the element effort and flow variables. The convention that is used in this paper is that the line will be oriented in the reference direction of positive flow and decreasing effort. The five generalised elements are summarised in Table 1 and their network representations are shown in Fig. 4.

Table 1: The five generalised system elements [13, 14]

Element category	Elements	Symbol
Energy source	Effort source Flow source	S_e S_f
Energy storage	Effort store (inductive element) Flow store (capacitive element)	L C
Energy dissipation	Energy dissipator (resistive element)	R

The directions of the arrows should not be confused with mass flow direction. The equations that govern fluid flow and heat transfer in networks are the continuity, momentum and energy equations. These equations can be described by first order partial differential equations. However, by using finite volume discretisation these

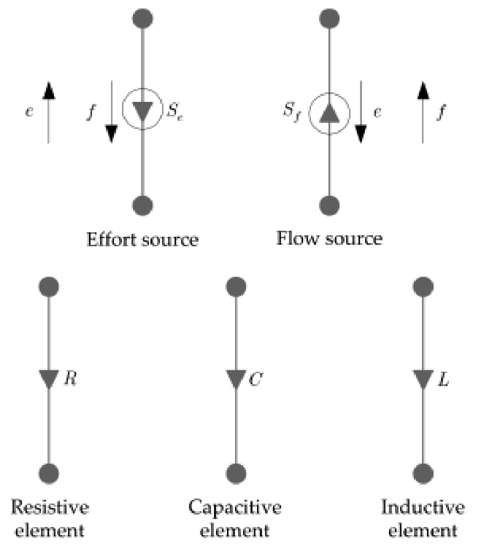

Figure 4: Generalised elements

equations can be transformed into first order ordinary differential equations. The discretisation is used to obtain simpler ordinary differential equations from which the appropriate generalised elements can be derived. The basic building block of a network approach is the control volume (CV), or node, which can represent a certain volume of fluid or solid. Inside this control volume scalar values are assumed to be representative of the average conditions inside the control volume. The fluid and energy flow inside the pipe is assumed to be one-dimensional. This means that only the flow velocity component normal to the cross-sectional area of the pipe is taken into account.

3.1 Hydraulic domain network model

Consider an example of a simple hydraulic network representation of a pipe section shown in Fig. 5. The pressure source elements at the end points represent boundary pressure variables. There are two types of source elements in the hydraulic domain, namely a pressure source S_{eh} and a mass flow source S_{fh}, where the subscripts e and f indicate the generalised variables (effort and flow) and the subscript h indicates the hydraulic domain. k is the source index. Sources may also represent elements such as a pump (flow source) or an elevation head (effort source). The hydraulic capacitance element, C_h, models mass storage. The hydraulic resistance and inductance elements (R_h, L_h) model the friction and momentum phenomena between the control volumes. The conservation of mass equation for a CV is given by

$$\frac{dM_i}{dt} = \sum (Av\rho)_{j-1} - \sum (Av\rho)_j = \dot{m}_{j-1} - \dot{m}_j, \quad (1)$$

where A is the area of the CV, M_i is the mass in the i-th control volume and $\dot{m}_{j-1}$, and $\dot{m}_j$ represent the mass flow entering and leaving the control volume. The variables most often used in the hydraulic domain and which also form the state variables are the pressure, P, and mass flow

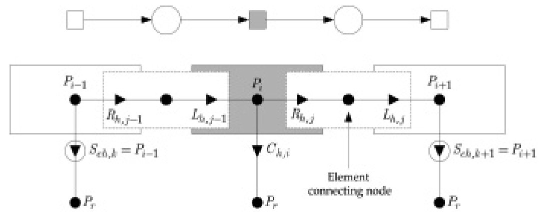

Figure 5: Hydraulic network of a pipe section

rate, $\dot{m}$. It is therefore desirable to introduce the pressure variable into (1) so that

$$\frac{dM_i}{dP_i}\frac{dP_i}{dt} = \dot{m}_{j-1} - \dot{m}_j, \quad (2)$$

and

$$\frac{dP_i}{dt} = \frac{1}{C_h}(\dot{m}_{j-1} - \dot{m}_j), \quad (3)$$

where

$$C_h = dM_i/dP_i = V_i(d\rho_i/dP_i) \quad (4)$$

is called the hydraulic capacitance element. It is an element that describes the compressibility of the fluid.

The momentum equation is given by

$$\ell_j \frac{d\dot{m}_j}{dt} = P_i A_j - P_{i+1} A_j - A_j\, \kappa_j\, |\dot{m}_j| \dot{m}_j + A_j\, \rho_j\, g(z_i - z_{i+1}), \quad (5)$$

where ℓ_j is the length between the nodes i and $i+1$ and κ_j is a friction factor. The gravitational constant is given by g and $(z_i - z_{i+1})$ is the elevation difference between two nodes. Equation (5) may then be written as:

$$\frac{d\dot{m}_j}{dt} = \frac{1}{L_h}(P_i - P_{i+1}) - \frac{R_h}{L_h}\dot{m}_j + \frac{1}{L_h} S_{eh}, \quad (6)$$

where

$$R_h = \kappa_j\, |\dot{m}_j| = \frac{f\,\ell_j/D_j + K}{2\,A_j^2\,\rho_j} |\dot{m}_j|, \quad (7)$$

$$L_h = \frac{\ell_j}{A_j}, \quad (8)$$

and

$$S_{eh} = \rho_j g(z_i - z_{i+1}) = \rho_j g \Delta z_j. \quad (9)$$

R_h is a hydraulic resistance element and L_h is a hydraulic inductance element, where f is the Darcy-Weisbach friction factor, K is the secondary loss factor and D_j is the diameter.

3.2 Thermal domain network model

The energy conservation equation can be written in terms of temperature values and the different heat transfer processes as follows:

$$V_i \rho_i \frac{dh_i}{dt} = \sum(\dot{m}_{j-1} h_{i-1}) - \sum(\dot{m}_j h_i) + \dot{Q}_{\text{cond}} + \dot{Q}_{\text{conv}} + \dot{Q}_{\text{rad}} + \dot{Q}_{\text{gen}}, \quad (10)$$

where $\dot{Q}_{\text{cond}}$, $\dot{Q}_{\text{conv}}$ and $\dot{Q}_{\text{rad}}$ represent heat transfer by means of conduction, convection and radiation. $\dot{Q}_{\text{gen}}$ represents heat generation inside the control volume and $\sum(\dot{m}_{j-1}h_{i-1})$ and $\sum(\dot{m}_j h_i)$ represent the flow streams in and out of the control volume, each representing a loss or gain of enthalpy (h) for the control volume. When an ideal gas is considered, (10) may be written in terms of temperature and a specific heat constant c_p so that

$$V_i \rho_i c_p \frac{dT_i}{dt} = \sum(\dot{m}_{j-1} c_p T_{i-1}) - \sum(\dot{m}_j c_p T_i) + \dot{Q}_{\text{cond}} + \dot{Q}_{\text{conv}} + \dot{Q}_{\text{rad}} + \dot{Q}_{\text{gen}}. \tag{11}$$

The state variable pair for the thermal domain is enthalpy h or temperature T and energy flow, $\dot{w}$. Energy flow can be defined as

$$\dot{w} = \dot{m}h = \dot{m}c_p T. \tag{12}$$

Energy flow is also equivalent to energy heat transfer rate $\dot{Q}$ and therefore $\dot{w} = \dot{Q}$. Equation (11) may be written in terms of temperature and energy flow as follows

$$\frac{dT_i}{dt} = \frac{1}{C_t}\dot{w}_{j-1} - \frac{1}{R_t C_t} T_i + \frac{1}{C_t}(\dot{w}_{\text{cond}} + \dot{w}_{\text{conv}} + \dot{w}_{\text{rad}} + \dot{w}_{\text{gen}}), \tag{13}$$

where

$$C_t = V_i \rho_i c_p \tag{14}$$

and

$$R_t = 1/\dot{m}_j c_p \tag{15}$$

The conduction, convection and radiation terms in (13) can further be expanded in terms of generalised elements [8]. Consider an example of a thermal network of a pipe section in Fig. 6. The resistance elements, R_t, can

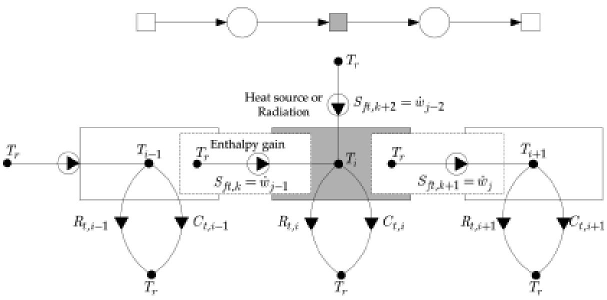

Figure 6: Thermal network of a pipe section

model enthalpy losses, conduction and convection. These elements are connected in parallel with the capacitance elements. Enthalpy gains, energy generation and radiation can be modelled with generalised thermal flow sources, S_{ft}. T_r is a reference temperature.

4. THERMOHYDRAULIC NETWORK MODEL OF THE U-TUBE

Consider a representation of a U-tube in Fig. 7. In the actual system the hot outlet is fed to heat exchangers and storage tanks. Taking this into account it will be assumed that the inlet and outlet of the U-tube are connected to an infinite heat sink. The inlet temperature can therefore be fixed at 15 °C. The RCCS system is open to the atmosphere and therefore the inlet and outlet pressures of the U-tube are fixed at 100 kPa. A constant heat transfer rate of 1 kW will be applied to the riser of the U-tube, simulating the heat radiated from the RPV wall. For illustrative purposes the U-tube will be discretised into four control volumes as shown in Fig. 7. Only a small part of the actual system is considered and hence the length and the diameter of the U-tube are chosen to be 0.6 m and 0.02 m respectively. The hydraulic and thermal behaviours of the U-tube will

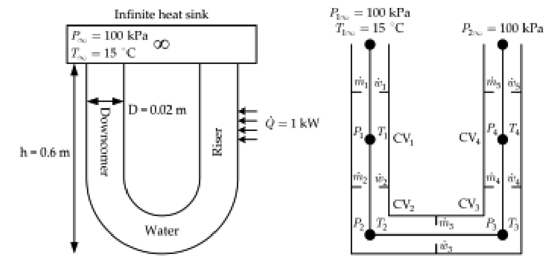

Figure 7: Representation of the U-tube and a conceptual view of the control volumes

be represented by two state space models extracted from hydraulic and thermal networks respectively. These two state space models are coupled by the mass flow rate through the U-tube.

4.1 Hydraulic network model of the U-tube

The hydraulic network of the U-tube is shown in Fig. 8. The atmospheric pressures at the input and output of the U-tube are modelled by hydraulic pressure sources ($S_{eh,1}, S_{eh,2}$). Natural convection is initiated when a body force acts on the fluid in which there are density gradients. This body force is due to gravitation and is modelled as a hydraulic effort source given by

$$S_{eh,k} = \rho_j g \Delta z_j, \tag{16}$$

where

- k is the index of the sources modelling the body forces,
- ρ_j is the mean density between two nodes,
- g is the gravitational constant, and
- Δz_j is the height difference between two nodes.

In Fig. 8 it can be seen that the energy flow direction of the sources are in the opposite direction of the other elements. This indicates that these sources are effort sources.

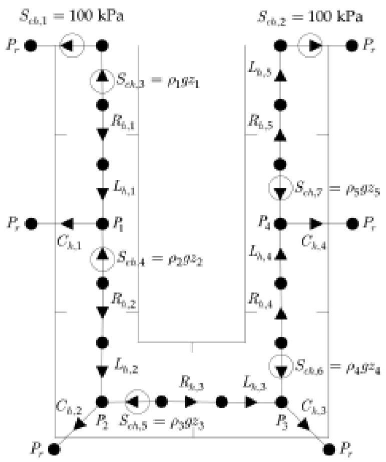

Figure 8: Hydraulic network of the U-tube

4.2 *Thermal network model of the U-tube*

The thermal network of the U-tube is shown in Fig. 9. The energy flows between control volumes are represented by the energy flow sources $S_{ft,1},\ldots,S_{ft,4}$. These energy flow sources as well as the thermal resistances are functions of the mass flow rates that are calculated from the hydraulic model. The energy flow sources $S_{ft,5},\ldots,S_{ft,8}$ represent the external energy transfer.

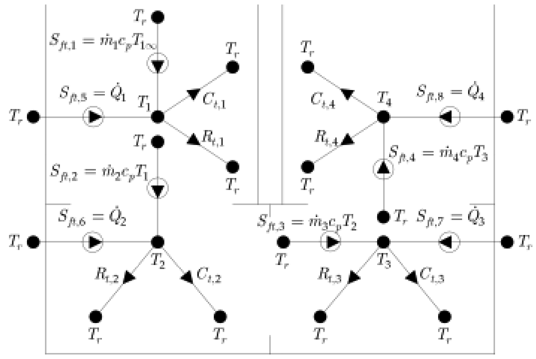

Figure 9: Thermal network of the U-tube

5. STATE SPACE MODEL EXTRACTION

In the previous section a thermohydraulic system, a U-tube, is partitioned into hydraulic and thermal network representations. These networks contain the structural and elemental information about the particular thermohydraulic network. This information can be used to extract a state space model of such a system. A method was developed by Uren [8] based on linear graphs [12] that converts this information algebraically into an incidence and element matrices respectively. These matrices are used along with a graph-theoretic selection of trees, co-trees as well as input and state variables to extract state space representations of the thermohydraulic system [15–17]. The symbolic parameters are then substituted with the relevant numerical values. The state space model can then be solved and validated to make sure it captures the dominant system dynamics. The approach followed from the physical system description up to a final state space model is portrayed in Fig. 10. The hydraulic network

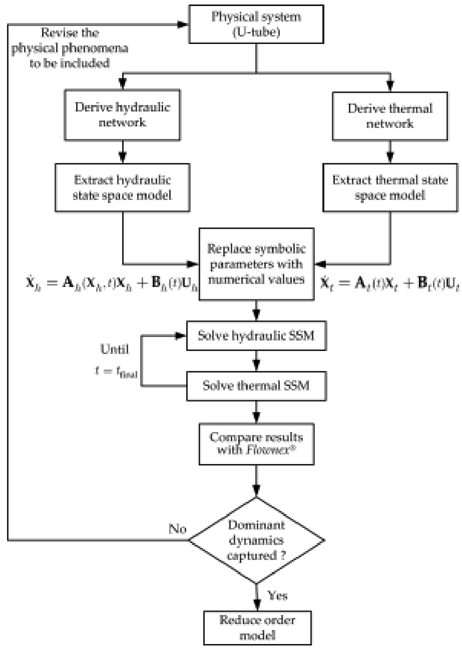

Figure 10: Methodology for reduced order model extraction and validation (U-tube)

is used to construct an incidence matrix representing the structure of the hydraulic domain. Each hydraulic element has a specific elemental equation. All the elemental equations are also represented in matrix form. By applying the state space model extraction algorithm to the incidence and elemental matrices, a symbolic hydraulic state space model is extracted. The hydraulic state space model is given by

$$\dot{\mathbf{X}}_h = \mathbf{A}_h(\mathbf{X}_h,t)\mathbf{X}_h + \mathbf{B}_h(t)\mathbf{U}_h \tag{17}$$

where

$$\mathbf{X}_h = \begin{bmatrix} P_1 & \ldots & P_4 & \dot{m}_1 & \ldots & \dot{m}_5 \end{bmatrix}' \tag{18}$$

$$\mathbf{U}_h = \begin{bmatrix} S_{eh,1} & \ldots & S_{eh,7} \end{bmatrix}' \tag{19}$$

$$\mathbf{A}_h = \begin{bmatrix} 0 & \ldots & 1/C_{h,1} & \ldots \\ 0 & \ldots & 0 & \ldots \\ 0 & \ldots & 0 & \ldots \\ 0 & \ldots & 0 & \ldots \\ -1/L_{h,1} & \ldots & -R_{h,1}/L_{h,1} & \ldots \\ 1/L_{h,2} & \ldots & 0 & \ldots \\ \vdots & \vdots & \vdots & \vdots \end{bmatrix} \tag{20}$$

$$\mathbf{B}_h = \begin{bmatrix} \vdots & \vdots & \vdots & \vdots \\ 1/L_{h,1} & 0 & 1/L_{h,1} & \dots \\ 0 & 0 & 0 & \dots \\ 0 & 0 & 0 & \dots \\ 0 & 0 & 0 & \dots \\ 0 & -1/L_{h,5} & 0 & \dots \end{bmatrix} \quad (21)$$

The state vector, $\mathbf{X}_h \in \Re^{9\times1}$, contains four internal pressures and five mass flow rates. The input vector, $\mathbf{U}_h \in \Re^{7\times1}$, contains the two effort sources representing the boundary pressures and five effort sources representing the body forces due to gravitation. The fragmented representations of $\mathbf{A}_h \in \Re^{9\times9}$ and $\mathbf{B}_h \in \Re^{9\times7}$ given in (20) and (21) contain resistive, capacitive and inductive elements that are time varying (due to densities that vary with time) and nonlinear (the resistive elements are dependent on the mass flow rate as given in (7)).

By applying the state space model extraction algorithm a symbolic thermal state space model is extracted. The thermal state space model is given by

$$\dot{\mathbf{X}}_t = \mathbf{A}_t(t)\mathbf{X}_t + \mathbf{B}_t(t)\mathbf{U}_t \quad (22)$$

where

$$\mathbf{X}_t = \begin{bmatrix} T_1 & T_2 & T_3 & T4 \end{bmatrix}' \quad (23)$$

$$\mathbf{U}_t = \begin{bmatrix} S_{ft,1} & \dots & S_{ft,8} \end{bmatrix}' \quad (24)$$

$$\mathbf{A}_t = \begin{bmatrix} -1/C_{t,1}/R_{t,1} & 0 & \dots \\ 0 & -1/C_{t,2}/R_{t,2} & \dots \\ 0 & 0 & \dots \\ 0 & 0 & \dots \end{bmatrix} \quad (25)$$

$$\mathbf{B}_t = \begin{bmatrix} 1/C_{t,1} & 0 & \dots & 1/C_{t,1} & \dots \\ 0 & 1/C_{t,2} & \dots & 0\dots & \\ 0 & 0 & \dots & 0 & \dots \\ 0 & 0 & \dots & 0 & \dots \end{bmatrix} \quad (26)$$

The state vector, $\mathbf{X}_t \in \Re^{4\times1}$, contains the four internal temperatures. The input vector, $\mathbf{U}_t \in \Re^{8\times1}$, contains four energy flow sources representing the internal heat transfer and another four representing external heat transfer. The matrices $\mathbf{A}_t \in \Re^{4\times4}$ and $\mathbf{B}_t \in \Re^{4\times8}$ are time-varying due to the fact that the thermal resistance, $R_{t,i}$, depends on the mass flow rate and the thermal capacitances, $C_{t,i}$, on the density.

6. RESULTS

Once the state space models for the different domains have been extracted in symbolic form, the symbolic parameters are substituted with numerical values. The state space models are solved in a specific order. The hydraulic state space model is solved first to calculate the mass flow rate used in the thermal state space model to calculate the temperatures. The solution is compared with results obtained from *Flownex*®. *Flownex*® is an advanced and extensively validated commercial thermohydraulic simulation package and is therefore used for validation of the state space models. The accuracy of the state space model is quantified by using the Integral of the Absolute magnitude of the Error (IAE) performance index. This particular index was used since it is widely used in modelling and computer simulation studies [18].

For natural convection to take place, density gradients have to exist. The density profiles of the downcomer and riser pipes are shown in Fig. 11 and were obtained from a *Flownex*® simulation. These density profiles are used when solving the state space model of the U-tube. It can be seen that the density of the water in the downcomer stays constant while the density of the water in the riser decreases as heat transfer takes place. The heat source was activated at time $t = 5$ s. Fig. 12 shows the temperature

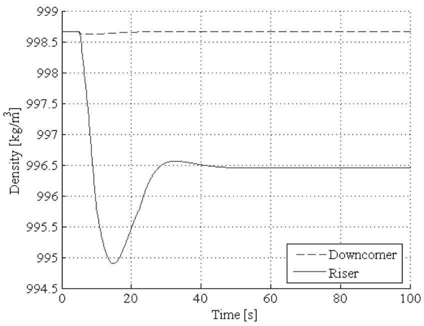

Figure 11: Downcomer and riser densities

of the water in the riser pipe with respect to time. The temperature values calculated by solving the state space model compares well with the temperature values obtained from *Flownex*®. Fig. 13 shows good correlation between

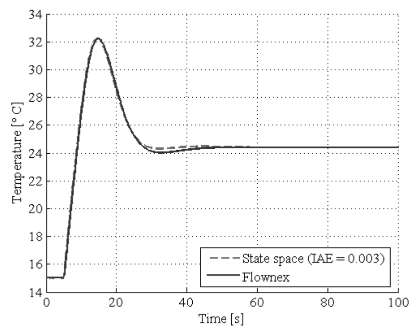

Figure 12: Temperature in the riser pipe

the flow rate values obtained from the state space model and *Flownex*®. The calculated internal pressures are summarised in Table 2 and also show good correlation. The smaller the value of the IAE performance index, the better the correlation between the state space model and *Flownex*®. The performance index also gives an indication whether the state space model does portray the dominant dynamics of the actual system.

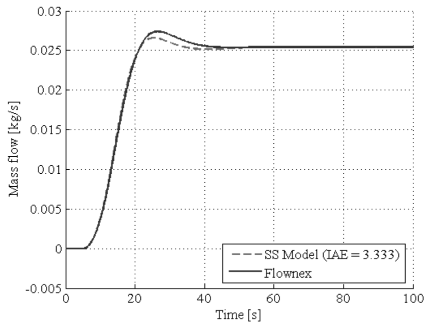

Figure 13: Mass flow rate due to natural convection

Table 2: Calculated internal pressures

Internal pressure	*Flownex*® (kPa)	State space model (kPa)
P_1	102.936	102.937
P_2	105.871	105.874
P_3	105.870	105.873
P_4	102.933	102.934

7. CONCLUSIONS

In this paper generalised thermohydraulic elements were derived from governing equations. These elements model the key dynamics in a thermohydraulic system namely energy storage, dissipation and generation. These elements were used to develop multi-domain network representations of a U-tube. These network representations describe the key dynamics of the system represented. The state space model extraction method converts these networks to symbolic state space models in symbolic form. The symbolic values are then substituted with numeric values and the state equations can be solved using standard differential equation solvers. The solution results showed remarkable correlation with Flownex® simulations. Future work will focus on integrating the state space extraction method with system CFD codes to automatically extract reduced order state space models useful for control systems design.

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