Eskom Power Plant Engineering Institute

EPPEI

Eighth Student Workshop

A Virtual Event
11 & 12 November 2021

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Preface

Welcome to the eighth EPPEI student workshop, which is our second virtually driven event. The EPPEI student workshop is one of the most important events on the EPPEI calendar and remains a highlight every year. The workshop provides an opportunity for students to share their research with Eskom staff, EPPEI academics and fellow students, while Eskom colleagues get the opportunity to provide feedback and guidance to the EPPEI research activities. Even though a little more difficult over the internet, it also provides an opportunity for research academics and Eskom technical personnel to interact and strengthen the networks that have been established over the past ten years.

Attached to the workshop is our traditional panel sessions, one per day of the workshop. Our hope is that you will participate and enjoy these sessions and that they will become a forum for informative discussion and further engagement between the EPPEI students, academics and Eskom subject matter experts. This year our panel sessions are titled 'Smart Power' and 'Digital Twins'. Both sessions comprise a healthy mix of national and international experts and are guaranteed to inspire discussions on these important matters which are of significant relevance to Eskom in this time of change.

It is always a pleasure to see how our EPPEI students have progressed with their studies, gained technical knowledge and increased the confidence to present their results to their peers and other technical experts. We trust that you will find this EPPEI Student Workshop interesting and informative and we look forward to the discussions and ongoing interactions.

Yours in continuous learning,
Dr Titus Mathe & Professor Wikus van Niekerk

Dr Titus Mathe
EPPEI Programme Director

Professor Wikus van Niekerk
EPPEI Consortium Director

Programme

Day 1 – Thursday, 11 November 2021

08h30 - 09h00	**Opening session** – ***Chair: Dr Leigh Jarvis***
08h30 - 08h40	Welcome address & safety briefing – *Dr Leigh Jarvis (UKZN)*
08h40 - 09h00	Words of encouragement – *Dr Titus Mathe (GM of RT&D / EPPEI Programme Director)*
09h00 - 10h30	**Panel session 1: Smart Power** – ***Chair: Dr Rob Stephen*** ***Panel: John Mc Donald, Malcolm van Harte & Simon Higgins***
10h30 - 11h00	**Tea break**
11h00 - 12h30	**Panel session 2: Smart Grids** – ***Chair: Dr Andrew Swanson***
11h00 - 11h15	The value of smart inverter control in distribution energy management systems and virtual power plants, and opportunities for South Africa – *Ria Xavier (Renewable Energy)*
11h15 - 11h30	Coordinated control of conventional power sources and plug-in hybrid electric vehicles for a renewable power system – *Mohammed Kader (High Voltage DC)*
11h30 - 11h45	Modelling and simulation of a digital area radio channel serving multiple DNP3 telecontrol remote terminal units – *Kenneth Brown (High Voltage DC)*
11h45 - 12h00	Study the topology effect on a G3-PLC based AMINetwork – *Thobekile Ngcobo (High Voltage DC)*
12h00 - 12h15	Technological interventions to maximise benefits in electrification programme – *Mashangu Xivambu (High Voltage DC)*
12h15 - 12h30	A study of semi-dry flue gas desulphurization in a spray dry scrubber; Experimentation and CFD modelling – *L Koech (Emission Control)*
12h15 - 13h15	**Lunch**

13h15 - 14h45 Session 3: Renewable Energy, HV & MV – *Chair: Prof Chandima Gomes*

13h15 - 13h30 Critical evaluation of large-scale gravity energy storage using linear Vernier hybrid machine technology – *CD Botha (Renewable Energy)*

13h30 - 13h45 Wind-Turbine controlled demagnetization for overvoltage in Multi-Terminal Direct Current System (MTDC) with Modular Multilevel Voltage Source Converter (VSC/MMC) under AC faults – *David L Mulashe (High Voltage DC)*

13h45 - 14h00 Voltage stability challenges on a highly compensated utility-scale system: A case study – *Aroon Sukhnandan (High Voltage DC)*

14h00 - 14h15 Influence of pre-existing space charge on HVDC transmission line lightning attachment – *Gavin Strelec (High Voltage AC)*

14h15 - 14h30 A stochastic analytic-probabilistic approach to distributed generation hosting capacity evaluation of active feeders – *M Chihota (Renewable Energy)*

14h30 - 14h45 Supraharmonics in power networks – *Johannes Lambrechts (Renewable Energy)*

14h45 - 15h15 Tea break

15h15 - 16h45 Session 4: Materials – *Chair: Dr Bernard Bekker*

15h15 - 15h30 The effect of graphene as a hydrophobic additive on the pollution performance, tracking and erosion of coatings when applied to AC and DC high voltage ceramic insulators – *Barend du Plessis (High Voltage DC)*

15h30 - 15h45 Formation of modified Z-phase in a 12Cr1MoV (X20) steel during long-term creep – *William Goosen (Materials and Mechanics)*

15h45 - 16h00 Validation and application of small sample punch test for toughness measurement of steels – *Andrew Hlupo (Materials and Mechanics)*

16h00 - 16h15 Microstructural evaluation of ex-service 1CrMoV turbine rotor steels – *Hlanganani Nyembe (Materials and Mechanics)*

16h15 - 16h30 Dislocation density measurement in fatigue tested AISI316 using x-ray diffraction – *Duduzile Ramasimong (Materials and Mechanics)*

16h30 - 16h45 Influence of post weld heat treatments on P91 weldments – *Tinashe Jambo (Materials and Mechanics)*

Day 2 – Friday, 12 November 2021

08h00 - 09h00 Session 5: Asset Management & Performance Testing – *Chair: Prof Innocent Musonda*

08h00 - 08h15 Investigation of the uncertainty of wall thickness testing of boiler tubes with fly ash erosion degradation – *A Ulassi (Asset Management)*

08h15 - 08h30 Assessing the effect of toe drainage systems on seepage volumes and stability of an ash dam with permeable foundation – *Jacob Sibanda (Project Management)*

08h30 - 08h45 Optimization of project controls towards construction projects within the energy utility – *Lufuno Ratsiku (Project Management)*

08h45 - 09h00 Investigating coal fired thermal power plant performance testing – *Comfort Molemi (Project Management)*

09h00 - 10h30 Session 6: Digital Twins – *Chair: Prof Volker Bertram*
Panel: Annie Bekker, Thomas Hildebrandt & Peter Palensky

10h30 - 11h00 Tea break

11h00 - 12h30 Session 7: Digital Twins & Emission Control – *Chair: Prof Stephan Heyns*

11h00 - 11h15 Leveraging digital twins of existing assets to support predictive maintenance – *Ambrose Chikukwa (Project Management)*

11h15 - 11h30 The influence of coal pellet properties on its emissions and thermal performance in a semi-continuous coal stove – *Winroe Meyer (Emission Control)*

11h30 - 11h45 An empirical analysis of residential fuelwood consumptions rate and its pattern from villages in Thulamela municipality, South Africa – *Ibironke Enitan (Emission Control)*

11h45 - 12h00 Spatiotemporal variation of PM2.5 and the potential health risk: A case study of Thulamela municipality in Limpopo province – *Tolulope Aniyikaiye (Emission Control)*

12h00 - 12h15 Discrimination between nearby and direct lightning strikes to a long operational medium voltage line to assist in the determination of the Basic Insulation Level (BIL) – *Willem van Schalkwyk (High Voltage AC)*

12h15 - 12h30 Development of a test section for the evaluation of dilute gas-particle flow measurement devices – *MJ Roberts (Emission Control)*

12h30 - 13h15 Lunch

13h15 - 14h45 Session 8: Energy Efficiency, Materials & Combustion – *Chair: Dr Reshendren Naidoo*

13h15 - 13h30 Power station thermal efficiency performance (STEP) method evaluation – *Heeran Heelall (Energy Efficiency)*

13h30 - 13h45 Dynamic turbine expansion modelling using a paired thermofluid and FEA method – *Michael Ross (Energy Efficiency)*

13h45 - 14h00 Effect of prior austenitisation temperature on creep rupture in grade 22 steel – *Soraya Von Willingh (Materials and Mechanics)*

14h00 - 14h15 Machine learning structure-property models for low carbon steels – *Lindsay Westraadt (Materials and Mechanics)*

14h15 - 14h30 Measurement of combustion airflow into burners in coal fired plants – *Sizwe Manqele (Combustion Engineering)*

14h30 - 14h45 Separation and combustion characteristics of coal microlithotype particle types – *Lesigen Moodley (Combustion Engineering)*

14h45 - 15h00 Tea break

15h00 - 15h30 Concluding remarks and prize giving – *Chair: Prof Wikus van Niekerk*

Topics to be covered include the following:

- Digitization before digitalization
- The need for a strong grid before smart grid
- Utilising communications as the enabling technology that allows automation
- Convergence of operations and information technology groups within the utility to support enterprise data management
- Journey to digital transformation (reactive to predictive to autonomous)
- Smart power and future grid innovations with regard to improving grid performance and resilience
- Use of smart technology to enhance Generation performance

The panel will be chaired by Rob Stephen (immediate past president of CIGRE). Panellists are:

- **John Mc Donald** (USA) – Smart Grid Business Development Leader, Senior Fellow Grid Solutions, GE Renewable Energy
- **Malcolm van Harte** (Eskom) – Strategic Support Manager, Snr Manager – Dx Smart Grid (Acting) Centre of Excellence – Network Operations
- **Simon Higgins** (Eskom) – Asset Condition Monitoring Corporate Specialist

The panel is of interest to engineers from utilities, academia, consultants and manufacturers.

The value of smart inverter control in distribution energy management systems and virtual power plants, and opportunities for South Africa

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Justification of the project

The increasing proliferation of DER systems in the distribution network leads to technical problems that compromise the stability, reliability and quality of the electric grid. Smart inverters have various advanced features that allow for more efficient application and integration of DERs such as voltage/frequency regulation, ride-through, ramping and more. Although there are many benefits to smart inverters, they provide limited and localized benefits when working autonomously. For maximum benefits, these smart inverters, need coordinated control, for instance using distributed energy resource management systems (DERMS) and virtual power plants (VPPs).

Purpose

The objective of this paper is to review the benefits and operational requirements of DERMS and VPPs through a literature review and to comment on whether DERMS or VPPS are feasible in South Africa.

Theoretical framework

This paper investigates the characteristics and benefits of the existing coordinated control techniques of smart inverters as applied in contexts of high DER penetration internationally. The value of smart inverter coordinated control is presented through a literature review and international examples. Based on the review of international practice, recommendations for South Africa are made considering the local context regarding existing infrastructure and grid regulation restrictions, which affect the necessary communications protocol for coordinated control through a DERMS or VPP.

Results and conclusions

It is recommended that a VPP be rolled out first in South Africa to aggregate DERs into virtual generating units, with the goal being to provide the utility with grid stability, advanced control and the potential for energy trading. A gradual transition towards DERMS can be implemented after the utility gains familiarity with real time control and optimization of DERs.

Implications for Eskom and the power industry in Southern Africa

The current South African grid-interconnection requirements limit many aspects, the technical advanced functionality of inverters and the communication capability of inverters in small scale generation. These regulations reflect the conventional and centralized power plant model of last century's power grid and of technologies that are not aligned with modern and advanced capabilities – such as smart inverters. The regulations will have to be upgraded for the country to implement VPPs or DERMS. Revision to the standards should include standardized smart inverter functions and requirements, methods of compensation for reactive power control, bidirectional communication protocols, cybersecurity measures and a regulatory framework for energy trading and aggregation specific.

Key words: smart inverter, low-voltage distribution networks, centralized control, DERMS, VPPs

Coordinated control of conventional power sources and plug-in hybrid electric vehicles for a renewable power system

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Justification of the project

The purpose of this research is to provide a solution to reduce the system frequency/ voltage fluctuations caused by Renewable Power Systems (RPS) and Plug-in Hybrid Electric Vehicles (PHEV). Renewable energy sources (RES) and Electrical Vehicles are increasing in popularity due to clean energy and reduced impact on the environment. PHEV can help mitigate the strain from the grid by extracting the surplus power which in turn helps distribution transformers from sustaining overload damage. The penetration of RES and PHEV in the power systems has frequently caused disturbances in terms of frequency instability and PHEVs with the irregular charging patterns of PHEV result in the overload of the microgrid. Load frequency control (LFC) methods using Fuzzy Logic Type 2 Fractional Order PID controllers (FLT2-FOPID) can help the interconnected system to achieve steady state at a faster rate with optimization techniques such as Artificial Bee Colony (ABC). The stability of the grid is of outmost importance to manage the loss of load experienced on Eskom's networks.

Purpose

The need for the electrical power industry to be compliant to the 4th Industrial Revolution (4IR) cannot be overemphasised with the rapid integration of RES, Electrical Vehicles, smart grid and green technologies in order to have clean and affordable energy. The continuous depletion of coal, aging of generating units and other network facilities have led to incessant load shedding in South Africa. However, the introduction of RES into the grid might be a solution to the load shedding problem but might as well introduce instability into the network, hence, the purpose of this project is to investigate different frequency control methods using a two area interconnected power system as a case study. Electric vehicles owners can also assist the country at rare moments to reduce the brink of a blackout [1].

Theoretical framework

Renewable Energy Systems is clean energy mainly used in the modern world. The issue with this system is the reduction of system inertia caused by the RES [2]. The mismatching between power generation and the load demand due to the high penetration of RES, frequency becomes difficult to control [3]. Therefore, LFC methods such as FLT2-FOPID is used to reduce the overshoot, improve system response and accelerate system stability time [4]. Further optimization by using ABC optimization techniques will improve the results [5]. With the addition of PHEVs in the system, electric vehicles can act as power storage units or a dump load as an application of smart grid technology. This can be managed through an aggregator using centralized control.

Results and conclusions

The research is currently under way with the modelling of the system being undertaken. From the results shown on the simulations done on MATLAB/Simulink so far, a two-area interconnected power system displays positive results with the inclusion of PHEVs and PID controllers. The PID control shows positive results of overshoot, fast rise time and steady-state error but can be improved with further iteration of manual tuning parameters. The penetration of the RES has shown to negatively affect the frequency of the system as shown on trial simulations. The modelling is still ongoing which will provide better insight of the research.

Implications for Eskom and the power industry in Southern Africa

This research will provide stability to the grid when South Africa increases the usage of clean energy systems. Also, with new innovation of motor vehicles mainly incorporating electric motors, the increase in demand for charging facilities will be required. Therefore, coordination will be required for the massive variable loading patterns which can assist with lack or surplus of power. This can also attract individuals by mitigating displeasing load shedding/reduction, be compensated for Vehicle-2-Grid (V2G) connection and recover some of the costs in electricity while charging the vehicle by aiding the country when required.

References:

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Key words: Renewable Energy System (RES), Load Frequency Control (LFC), Fuzzy Logic Type 2 Fractional Order PID (FLT2-FOPID), Plug-in Hybrid Electric Vehicles (PHEV), Artificial Bee Colony (ABC), Vehicle-2-Grid (V2G), Two Area Network

Modelling and simulation of a Digital Area Radio channel serving multiple DNP3 Telecontrol Remote Terminal Units

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Justification of the project

Eskom Distribution makes extensive use of its UHF Area Radio networks to facilitate the Telecontrol (SCADA) of most of its medium-sized and small substations (both HV and MV) and line-mounted reclosers. The limited bandwidth and shared nature of this telecommunications medium leads to throughput challenges especially during high traffic demand situations such as occur during power system disturbances e.g. during storms. There are many parameters available that influence the throughput performance of these systems during periods of heavy contention. An accurate model of this system would make it possible to optimize these settings and determine the maximum number/size of devices that can share a UHF repeater and still provide the required worst-case message throughput performance.

Purpose

Overloaded repeaters cause significant delays in the transmission of critical information for the safe and efficient operation of the power system. Poorly optimized system parameters reduce the "carrying capacity" of a repeater that can require the addition of more repeaters or the provision of alternative telecommunications channels such as satellite or fibre etc. These options are expensive and take time to establish, if available.

Theoretical framework

Much work has been done to model the traffic throughput characteristics of p-persistent carrier sense multiple access (CSMA) systems as used on the Area Radio system. Queue theory techniques and tools will also be studied to produce a reasonably accurate model that can be used to characterize the UHF Area Radio system throughput. This model will then be used to test various settings and produce optimized settings that will allow Eskom to maximize message throughput and thereby improve repeater carrying capacity and protect the performance of the Telecontrol (SCADA) system when it is needed most.

Results and conclusions

This work is still in the literature study phase so results and conclusions are not yet available.

Implications for Eskom and the power industry in Southern Africa

Having accurate models will allow Eskom (a) to optimally utilise the existing UHF Area Radio resource thus avoiding unnecessary expenditure and (b) to have the tools to ensure that repeaters are not overloaded thus ensuring that the Distribution Telecontrol system performs adequately during power system disturbances. Other distributers utilising similar Area Radio technology will also benefit from this work.

References

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Key words: Carrier Sense Multiple Access (CSMA), persistent CSMA, throughput-delay characteristic.

Study the Topology Effect on a G3-PLC based AMI Network

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Justification of the project

Smart grid operates based on the integration of various renewable energy sources, distributed generators and storage units in order to deliver an uninterrupted energy supply to consumers. Such a complex grid requires a network of intelligent sensors and an effective communication infrastructure to provide bi-directional flows of information between different grid entities for monitoring and control purposes. The advanced metering infrastructure is a part of a smart grid communication network, which connects a utility company to its customers in order to support telemetry and remote-control applications. Although different technologies and standards for smart metering systems exist, the G3-PLC, which is based on the power-line communication (PLC) technology, is the accepted standard in South Africa for connecting smart meters to data concentrators. Studying the topology of an AMI network can help to improve the Quality-of-Service of the network and to enable the network for supporting more advanced applications.

Purpose

Physically altering a PLC-based AMI network topology to study its effects can become very costly. Employing network simulators are considered as an alternative method for studying complex network topologies. Therefore, in this research analytical method and simulation tools are used to study the effect of topology on the performance of the G3-PLC AMI network.

Theoretical framework

The thorough investigation of the PLC-based AMI system requires access to power grid infrastructure. However, studying the effect of network parameters and topologies can become very expensive. Simulation framework are considered as an alternative method for studying such parameters [1-2]. In this project, the effect of network topology on the system performance of a PLC-based AMI system is investigated.

Theoretical framework continued

For this purpose, a narrow-band PLC (NBPLC) simulator in accordance with the G3-PLC standard is proposed that employed the OMNeT++ network simulator. This simulator is then used to investigate the effect of network topology on the statistics of the data concentrator's channel and its switch.

Results and conclusions

In this project, we have studied the effect of network topology on the system performance of a PLC-based AMI system. For this purpose, a narrow-band PLC simulator in accordance with the G3-PLC standard is proposed that employed the OMNeT++ network simulator. Different layers of G3-PLC standard and the procedure for modelling this standard using OMNeT++ basic modules have been described. Moreover, two different topologies for an AMI network were considered and it was shown that the topology of the AMI network has an impact on the performance of the system in the sense of decreasing the collision percentage on the DC switch.

Implications for Eskom and the power industry in Southern Africa

The G3-PLC has been widely used by Eskom to connect SMs to DCs, and it can be considered as the de facto standard for the AMI's neighborhood-area network (NAN) in South Africa. In this study, we investigate the effect of topology on the QoS of an AMI NAN based on the relative location of a DC to the installed SMs.

References:

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Key words: Smart grid communication; Smart meter communication standards; Advanced metering infrastructure (AMI); G3-PLC

Technological Interventions to maximise benefits in electrification programme

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Justification of the project

Expansion of economic infrastructure such as electrification and telecommunication were identified as foundation for social and economic development in the United Nations development goals 2030 [1] [2].The programmes are currently implemented independently and the success of both programmes are dependent on customers paying for the services they receive.The culture of non-payment of electricity is growing very fast and if not addressed, it has a potential to collapse the economy of the country. In Soweto, non-technical are currently at 70% costing Eskom about R 270 000 on monthly basis and over R3 billion annually [3] [4].The total loss of revenue due to the current strategy employed to manage the losses is disconnecting non-paying consumers which is often met with resistance resulting in damage to important infrastructure and threat to the lives of technicians working in the areas. Some of the technical solutions like installation of smart meters for tamper detection did not work since customers bypass the meters completely [5] [6].The project is looking at the solution that will entice the customer to keep the energy meter running in order to have internet connectivity.

Purpose

The purpose of the project is to leverage on affordable internet access offered by fibre networks to coerce customers to buy legal electricity through integration of an energy meter with internet router in a single unit. Customers will have a benefit of affordable internet access and electricity that will improves quality of education and knowledge dissemination as well as other socio economic benefits [2].

Theoretical framework

Fibre network telecommunication is an integral part of the electricity generation, transmission and distribution. It is currently used for tele control and protection of the equipment [7] [8]. The installed infrastructure is underutilised and services can be extended to the medium voltage network to increase benefit for customer experience while increasing opportunities for revenue collection [7]. The proposed solution will integrate the electricity prepaid meter and Wi-Fi modem into a single unit. The internet access will be disconnected when the electricity meter is bypassed and customers will enjoy affordable internet access when the meter is on.

Results and conclusions

The study is still in progress but the current information gathered and literature review conducted envisage that the customers will benefit reliable electricity supply and affordable internet access if the project can be successfully implemented [2] [1]. The affordable internet access will encourage customers not to tamper with the energy meters and power interruptions due to equipment damage will reduce and the quality of life for the customers will improve.

Implications for Eskom and the power industry in Southern Africa

The network performance will improve, safety incidents will drop and revenue collection will increase resulting in profitability and sustainability of Eskom.

References:

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A study of semi-dry flue gas desulphurization in a spray dry scrubber; Experimentation and CFD modelling

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Justification of the project

Post combustion sulphur dioxide (SO_2) emission is a major problem for coal-based power plant production. There is increased awareness of the potential detrimental effects of SO_2 on human health and the environment, and consequently increased pressure to build power plants with flue gas desulphurization (FGD) systems. FGD is a commercially proven technology for removal of SO_2 from flue gas which is considered as a significant pollutant to the environment. Spray dry scrubbing (SDS) process represents a type of semi-dry FGD which is a low-cost retrofit SO_2 control technology that could be used in already existing coal-fired power plants. This study explores the experimentation and computational fluid dynamics (CFD) simulation of the SDS process with an aim of contributing towards the understanding, modelling and design of an industrial SDS process.

Purpose

The purpose of this project is to model and optimize the performance of a laboratory scale spray dryer for flue gas desulphurization. This involved performing experiments using the spray dryer to obtain performance data for CFD modelling and validation and for response surface methodology (RSM).

Theoretical framework

The intricate relation of the drying rate and the absorption rate is a key phenomenon in the removal of SO2 from flue gas in spray dry scrubber. This further depends on the flow behaviour which determines the heat, mass and momentum transfer within the system. The multiscale, multiphysics and multiphase nature of this process has to be accurately captured, making CFD modelling appropriate for the analysis [1]. The particle-source-in-cell technique (PSICT) first proposed by Crowe [2] is used to model the continuous and discrete phase. SO2 from flue gas is absorbed at the droplet surface, reacts to form sulphurous acid, ionizes and migrates to reaction front, where it is neutralised by the dissociated sorbent species [3]. In this work Starccm+ is used the CFD modelling platform.

Results and conclusions

A systematic experimentation program (RSM) was used to assess the influence of spray characteristics on SO_2 absorption in the spray dryer. The axial profiles of SO_2 concentration along the spray chamber indicated two regimes of drying i.e., the constant drying phase which accounts for high SO_2 absorption and the falling rate period where dry porous particles are formed. The analysis of the spray parameters show that Ca:S ratio, slurry solid concentration and slurry pH impacted positively on SO_2 absorption. High inlet gas phase temperatures were found to accelerate evaporation which limits SO_2 absorption. CFD modelling revealed 3D asymmetric flow patterns within the dryer. Single phase heat flux modelling of the SDS was in agreement with reported data [4] and showed good agreement with measured temperature variables. Implementation of the dispersed phase into the model and subsequent evaporation together with SO_2 absorption modelling was validated with experimental data proving the reliability of the developed model.

Implications for Eskom and the power industry in Southern Africa

This study shall play a significant role in contributing towards knowledge generation regarding post-combustion desulphurisation in coal-fired power plants through the development of expertise in semi-dry SO2 absorption processes.

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Key words: Semi-dry FGD, spray dry scrubbing, Response surface methodology, CFD modelling, optimization

Critical evaluation of large-scale gravity energy storage using linear Vernier hybrid machine technology

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Justification of the project

Energy storage technologies are viewed as a promising solution to some of the challenges associated with integrating large amounts of renewable energy sources into the grid. Given the wide range of energy storage technologies, it becomes difficult to determine the best storage technology for a given application. It is thus important to develop and analyse the technical and economic feasibility of energy storage systems, as well as other attributes.

Due to some of the disadvantages of existing storage technologies, for example the location restrictions and water usage of pumped hydroelectricity energy storage, this project proposes and investigates a novel gravity energy storage method, the linear electric machine-based gravity energy storage (LEM-GES) system.

Purpose

The main objective of this project is to investigate a novel linear electric machine-based gravity energy storage system to determine its techno-economic feasibility. A techno-economic model can be used to determine the optimum use for any given energy storage technology, while also allowing accurate comparisons to be made between different energy storage technologies.

Theoretical framework

The technical analysis of the system is done using equations for the energy storage capacity, energy and power density, while the sizing of the masses (called pistons) is done using the air gap shear force of the electrical machine [1]. The economic feasibility is analysed using a levelized cost of energy storage (LCOS) calculation [2]. The linear electrical machine is investigated using an analytical model of the air gap flux density, the Taguchi-method for the force ripple and cogging force as well as finite element for the optimisation process [3,4].

Results and conclusions

The LEM-GES system has the potential to be a cost-competitive energy storage solution. It offers many strong advantages, such as nearly limitless cycling ability, the possibility for high roundtrip efficiencies, no self-discharge or degradation, and fast response times. The biggest disadvantage of the system is the very large initial investment costs. The LCOS study and system optimisation done shows that the LEM-GES system is very cost competitive when used for applications like primary response, and when a large height difference is available. The 1 000 m primary response application appears to be the most economically promising application.

Implications for Eskom and the power industry in Southern Africa

The LEM-GES system offers a cost-competitive alternative to other energy storage systems for short discharge duration applications like primary response, while also offering a long lifetime, no self-discharge or degradation through use. If investigated further, the system could offer an effective solution to short term fluctuations caused by variable renewable energy sources.

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Key words: renewable energy, gravity energy storage, levelized cost of storage, electromechanical energy storage

Wind-turbine controlled demagnetization for overvoltage in Multi-Terminal Direct Current System (MTDC) with Modular Multilevel Voltage Source Converter (VSC/MMC) under AC faults

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Justification of the project

South Africa energy demand need seek and exploit potential wind energy, including offshore wind power generation, given the coastal geographic position. This requires development of technology that will enable integration and distribution of large wind power so that Eskom can meet the growing energy demand. MTDC is best suitable for integration and distribution of wind farm larger power. For the growing energy demand, MTDC technology has the benefit to allow large scale integration of renewable sources and connection of remote AC systems. Developing MDTC reliable system will require proper integration with existing AC grid. Therefore, effects of known AC faults need to be taken into account when planning for their development.

Purpose

MTDC systems require reliable Fault Ride Through (FRT) capability to clear AC faults. This project aims develop a FRT control that relies entirely on controls and software without communication and external devices. Through simulation with PSCAD, Wind turbine controlled demagnetization is approved as suitable to improve and increase FRT capability. This method will improve the future MTDC reliability.

Theoretical framework

Fault Ride Through is crucial to MTDC systems to clear AC faults that result DC overvoltage. Increasing FRT capability relies on improved and enhanced controls of converters. The need for multidirectional power flow and enhanced control make Voltage Source Converters (VSC) suitable for this application over Line Commutated Converter (LCC), although a mature technology. Modular Multilevel Converter (MMC) is a type of voltage source converter, considered for this project, which has proven suitable for fault behaviour. To avoid overvoltage the amount of power supplied to the DC grid has to be reduced by means of enhanced controls.

Results and conclusions

In order to clear DC overvoltage from onshore AC faults, the severity of the fault is measured through direct measurement of the DC voltage. Minor faults can be cleared through power redistribution using voltage droop control without affection the wind turbine generator. A severe fault will require reduction of wind power supplied to the DC grid. Power reduction is achieved by control of the wind turbine terminal converter. Given the limit to amount of power reduction, controlled demagnetization is used to increase the power reduction limit and eliminates the need for external devices. In this project power reduction is done using wind turbine AC voltage reduction for the fast response.

Implications for Eskom and the power industry in Southern Africa

Stepping into wind power generation will allow Eskom effectively benefit South Africa from its offshore wind power potential to meet its energy demand. But also meets its goal to shift from coal power generation. MTDC development will enable South Africa to strengthen the Southern African HVDC point to point network already existent.

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Key words: Fault Ride Through, Overvoltage, Voltage Source Converter, Modular Multilevel Converter, Controlled Demagnetization

Voltage stability challenges on a highly compensated utility-scale system: A case study

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Justification of the project

Power systems having unusually high levels of capacitive compensation are not only rare but are suspected to yield dissimilar results for industry standard strengthening solutions aimed at improving transfer capacity and voltage stability. This case study is an applicative research undertaking that increases the body of knowledge in the voltage instability mitigation sphere as this research is performed on a utility-scale, real-life network, having unusually high capacitive compensation. System stability has become an increasingly important topic requiring specialist skills within Eskom, in the medium term as Eskom's network remains heavily stressed, and in the long term as its complexity increases as a result of new transmission and interconnected generation coming on stream as a result of IPP build programmes and penetration of renewables. This thesis, with the accompanying increase in skills transfer, will enable an enhanced understanding and deal with future challenges of highly compensated networks, like the KZN system.

Purpose

The overall objective is to compare the impact and efficacy on voltage stability of a few generally-used options such as EHVAC circuits (SuperGrid), a traditional line-commutated converter (LCC) type HVDC bi-pole (such as the existing line between Cahora Bassa and Apollo), and a new voltage source converter (VSC) type HVDC line.

Theoretical framework

Both static and dynamic analysis was used to perform tests on a base case network model that was created using a bespoke methodology for network reduction and rationalisation. An onerous challenge was endured between the conflicting objectives of computing burden and detailed models to establish a simulative study with a suitable degree of detail that was vitally important to achieve meaningful results.

PowerFactoryTM which is an industry appropriate software for static and dynamic power system modelling was used for this investigation. Other equipment that have a significant impact on voltage control and stability were modelled with an appropriate level of detail.

Results and conclusions

Both static and dynamic simulations are able to give an appraisal of this case study network from a transfer capacity and voltage stability point of view. The tests that were chosen were effective in creating ample opportunity for the network to experience voltage stability challenges. Dynamic studies were performed with the use of chosen scenarios containing both static and dynamic contingencies. As part of a larger study, a comparative investigation will aim to investigate the candidate strengthening options in terms of transfer capacity enhancement and robustness towards the selected stability challenging contingencies.

Implications for Eskom and the power industry in Southern Africa

This case study presents the synthesis of models using a bespoke methodology preceding an analysis that evaluates the position of the network from a voltage stability standpoint. It also introduces the various proposed strengthening options that are useful for application in the case study network to improve transfer capacity and voltage stability. The solution options, costing billions of dollars (US) can now be evaluated on a real utility-scale network.

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Key words: Voltage stability, HVDC Transmission, EHVAC Transmission, PV Curves, Stability Analysis

Influence of pre-existing space charge on HVDC transmission line lightning attachment

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Justification of the project

Eskom is planning HVDC lines in the medium term to reinforce the Extra High Voltage (EHV) AC network. Lightning shielding failure to the positive pole conductor is the dominant contributor to lightning-induced faults for HVDC transmission lines. Field data, from Cahora-Bassa [1], as well as extensive experience from China on 500 kV and 800 kV DC lines [2][3][4], indicates the fault rate for the positive pole is about 8 to 10 times higher than for the negative pole. This suggests that the positive pole may require more stringent lightning protection. Quantifying the influence of polarity is critical for determining the implication on the shielding design for transmission lines.

Lightning attachment is highly dependent on the inception of an upward leader from the ground object which results in an advantage due to the effective extension in height in the direction of the approaching downward leader. The polarity has two main effects: Firstly, the DC potential will influence the net potential at the conductor surface and hence electric field that is available for the inception of an upward leader. This potential biases the probability of attachment in relation to the polarity of the approaching downward leader. About 90% of downward leaders globally are of negative polarity [5], therefore the positive conductor more readily reaches the critical field for leader inception and consequently has a higher incidence of attachment [6].

Secondly, the constant DC voltage also results in significant space charges accumulating in the vicinity of the conductor. In still weather this charge sheath around the conductor will grade the electric field and has been shown experimentally to inhibit the leader inception process [7]. Thus the space charge is expected to negate the advantage of the positive potential on the conductor. Whilst there have been several models that include the influence of the DC voltage [8], even recent models neglect the influence of space charge [9][10].

Purpose

Based on clear evidence that the positive pole shielding failure rate is 8 - 10 times higher, it is apparent that upward leader inception is significantly influenced by HVDC polarity. This disparity between the poles is a result of the DC voltage and also the effect of the residual space charges that are developed. Quantifying this influence is critical for determining the implication on the shielding design for HVDC transmission lines.

Theoretical framework

Various models have been proposed for investigating the attachment of lightning to HVDC conductors however the effect of space charge has not been included in past work. This project will model the leader inception and propagation process in order to quantify the effect of the pre-existing space charge in the vicinity of the HVDC conductors on the lightning attachment process to HVDC conductors. COMSOL Multiphysics is a suitable Finite Element Modelling tool for developing this model. The model will be developed in the "Electrostatics module" and will also require the linking of the "plasma module" for the modelling of the space charge generation.

Results and conclusions

The project is still in the design phase and has not yet produced any results. The following is the expected results.

It is expected that the positive operational voltage will increase the likelihood of lightning attachment, under negative downward stepped leader, by increasing the electric field at the conductor surface, thereby potentiating streamer inception and the ultimate transition to a stable upward leader. This leader inception and propagation will be potentiated by the operational positive DC voltage thereby giving the positive conductor an advantage over the negative conductor for the attachment of negative stepped leaders. The negative voltage will have a suppressing influence on leader inception.

These interactions are the primary reason for the marked disparity in the performance of the positive and negative poles. Furthermore, the expected results of this work is that the positive space charge will partially negate the advantage of the positive conductor discussed above. The effect of the pre-existing space has been demonstrated experimentally to delay leader onset and suppress propagation, however has not been included in past work.

Implications for Eskom and the power industry in Southern Africa

The vast majority of transmission lines are designed according to the Electro-Geometric Model (EGM) that proposes a relationship between "striking distance" and peak return stroke current. The EGM is a simple analytical formula and ease of implementation results in wide application. It has been found that the EGM and LPM do not produce good predictions for HVDC lines and hence other computationally tedious methods have been developed for HVDC [8].

By quantifying the direct and indirect (space charge) influence of the HVDC voltage magnitude and polarity on the "striking distance", the subsequent influence on the design can be determined e.g. "shielding angle" etc. for proposed HVDC towers that is relevant for transmission companies.

An analytical formula, ideally in the form of a modified EGM, is required that takes the influence of the HVDC voltage and space charge into account. This formula can be used to design HVDC line shielding geometry for Eskom and other Transmission utilities without the detailed simulations and tedious computation associated with other appropriate models, yet resulting in adequate accuracy.

The formula will also be modified for application EHV AC lines, thereby broadening its value to the industry by facilitating the lightning shielding design of 400 kV and 765 kV AC transmission lines.

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Key words: HVDC, lightning performance, attachment, shielding failure, modelling, electro-geometric

A stochastic analytic-probabilistic approach to distributed generation hosting capacity evaluation of active feeders

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Justification of the project

The installation of renewable energy (RE) generation has increased significantly in recent years. While RE technologies have economic and technical advantages for the power system, the uptake of distributed generation (DG) can result in localized adverse technical performance in existing distribution feeders and can necessitate new planning and evaluation approaches [1]. The occurrence and severity of technical issues depend on a feeder's physical characteristics, the loads, and the location and size of DG units [2]. DG integration studies assess the technical impacts of DG and penetration limits, often termed the hosting capacity (HC) that a network can withstand with or without reinforcement before violating specified operating limits [3]. The selection of the methodology for simulating DG impacts and deriving the HC is critical. The approach must produce realistic results that are not too restrictive (underutilising the RE generation potential) nor too relaxed (increasing the likelihood of technical problems). For accurate assessment of DG impacts, a network integration study must consider the uncertainty related to the loads and DG. This project develops a comprehensive tool for hosting capacity assessment for radial distribution networks with DG. The detailed assessment equips planners for optimal DG regulations to manage impacts and scoping the necessary network upgrades or reinforcement to meet penetration targets in the future.

Purpose

This project provides an uncertainty-based tool for detailed assessment of the hosting capacity of distribution networks to various forms of DG. The tool considers three core sources of uncertainty in the problem: (1) the stochasticity of customer loads, (2) the uncertainty in DG outputs, and (3) unknown DG allocation conditions. The tool has significant implications for the optimal regulation and planning of networks with DG penetration.

Theoretical framework

(1) Statistical load modelling

The input modelling process captures the diversity of customer loads and the uncertainty in DG power outputs, both characterized by beta probability density functions (PDF) in each time interval. The beta PDF is selected for its versatility, suitability to model bounded load data, and established fitness to model the diversity of residential customer loads in South Africa [4], [5]. Its fitness to characterize DG uncertainty for applications such as PV [6] and wind [7] has has also been demonstrated.

(2) Stochastic DG allocation

Stochastic simulation models the uncertainty in the allocation of DG: the placement at a point of connection to node and phase and the installed system's capacity. The Monte-Carlo simulation method is used for the random selection of DG allocation scenarios.

(3) Probabilistic analysis of feeder performance

The HBE transform applies statistical moments to achieve probabilistic load flow (PLF) solutions with a single-pass calculation. It accommodates loads, DG, and shunt-capacitors. The approach is robust and computationally efficient [8], [9]. With repeated PLF calculation corresponding to the conducted MCS DG allocation scenarios, the feeder performance under a wide range of future loading conditions is achieved.

Results and conclusions

Uncertainties complicate feeder performance assessment under DG penetration and challenge conventional deterministic methods for power system analysis. The project has addressed the complexities associated with DG impact assessment for radial feeders. The developed assessment tool boasts comprehensive analysis of a wide spectrum of operating scenarios at high computational efficiency. Comparing the proposed method to other variants of uncertainty characterizing methods shows the importance of explicit uncertainty modelling for PV allocation and load flow analysis, as they significantly impact HC accuracy.

Other sensitivity studies indicate that feeder HC is significantly influenced by simulation assumptions about customer phase assignments and PV yield per kWp installed. Penetration limits per customer need to be carefully selected and regularly revised, considering the expected DG penetration. The developed HC tool allows planners to make well informed and risk reflective decisions regarding DG penetration regulation, as well as the scope of required network upgrades or reinforcement to meet penetration targets in the future.

Implications for Eskom and the power industry in Southern Africa

This project's developed tool and findings equip planners to make well informed decisions on DG regulation, mitigation of impacts, and reinforcement planning. The capacity for detailed analysis allows the formulation of optimal regulation standards for DG penetration on South African networks.

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Key words: probabilistic load flow, Herman-Beta extended, distributed generation, DG penetration, hosting capacity, network integration studies

Supraharmonics in power networks

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Justification of the project

Main contribution towards Eskom project for power quality in the future grid (Distribution). The type of work is fundamental research for Eskom to gain knowledge and experience in the field of high frequency harmonics. Work will contribute research to address following points from Eskom's perspective.

- Impacts of embedded generation on Dx network
- The extent of the risk and impact of harmonic propagation in Dx network
- Harmonic interference with PLC communication equipment
- Eskom and customer equipment failure
- Research to contribute to further develop standards like NRS048

Purpose

The purpose of the work can be summed up in the following points:

- Develop methods and equipment to determine sources/contributions of supraharmonics
- Develop appropriate operational and regulatory framework for the measurement of supraharmonics
- Share knowledge gained to line groups via ongoing workshops and to regulatory boards
- To quantify current supraharmonic levels on the LV network

Theoretical framework

Some of the main technical concepts in the work are:

- High Frequency Measurements
- Filter Design
- Signal Processing
- Power Electronics

The theory is that modern fast switching electronics like EV chargers, VSDs and Inverters are the main contributors to high frequency harmonics or supraharmonics on the power network. The process measuring the high frequency harmonics is non-trivial and this works covers the in-depth theory of signal measurement and signal processing.

Results and conclusions

Main results are the development of an active high pass filter to enable the measurement of supraharmonics, including an in-depth study on the current standards of high frequency measurements. Also, some field measurements were done to show the harmonics spectrum on different inverters in various topologies.

Some preliminary conclusions are that inverter-based technology are the main source of supraharmonics in the power network and that harmonics levels are sometimes high enough to interfere with PLC communication systems, cause equipment malfunctions and exceed regulatory limits.

Implications for Eskom and the power industry in Southern Africa

Eskom gained the knowledge and ability to measure supraharmonics to do further research on the topic. Eskom also gained knowledge and experience in supraharmonic propagation and insight into various inverter topologies for power quality embedded generation in the Dx network.

Key words: Supraharmonics, High Frequency Measurements, Signal Processing, Filter Design, Power Electronics, Harmonic Propagation, Embedded Generation, Power Line Communication Interference, Compatibility Levels, Measurement Standards

The effect of graphene as a hydrophobic additive on the pollution performance, tracking and erosion of coatings when applied to AC and DC high voltage ceramic insulators

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Justification of the project

Superhydrophobic Room Temperature Vulcanised Silicone Rubber (RTV SR) coatings are under development. One of the applications of these coatings under investigation is to improve the performance of glass cap and pin disc insulators under severe environmental polluted conditions. Eskom requires independent research into the pollution performance of these coatings (ex. graphene doped RTV SR) when tested using broadly accepted test methods, e.g. hydrophobicity- and accelerated ageing. The hypothesis is that superhydrophobic coatings may offer the advantage of low wettability, high thermal resistance, self-cleaning, and self-healing effects. These benefits will not only increase the reliability of transmission systems but may also reduce the capital cost of transmission infrastructure [1].

Purpose

Investigate, identify, procure, and prepare experimental equipment for laboratory hydrophobicity-, hydrophobicity transfer- and inclined plane (tracking and erosion) tests according to both IEC and Cigré standards. Thereafter commence and compare/evaluate experimental results of the effect of graphene doped RTV SR coatings when applied to ceramic materials

A sub-part of the research project involves the refurbishment of the old Koeberg Insulator Pollution Test Site (KIPTS) equipment to be used as the power source for the Mobile Test Rig (MTR), which can produce both constant HVAC and HVDC excitations to evaluate power line insulators under severe coastal polluted conditions. The MTR's main design was completed by another Eskom employee and this base design will be used as a guide to construct, install, and commission the MTR at the new KIPTS test facility.

Obtain post-graduate degree, peer-reviewed publications and present results to Eskom.

Theoretical framework

The properties and applications of superhydrophobic coatings in high voltage insulation are reviewed by Arshad et al. [1], who concluded that these coatings have the potential to be used for power network applications.

Dong et al. [2] studied the incorporation of graphene/RTV silicone composites by preparing graphene nanosheets into a Polydimethylsiloxane (PDMS) matrix.

J. Zhang et al. [3] describe possible reasons that account for the enhancement of thermal conductivity after the addition of graphene into an epoxy matrix.

The first series of tests involves an experimental investigation into the hydrophobicity- and hydrophobicity transfer capabilities of candidate porcelain tile coated (graphene doped RTV SR) samples. IEC 62073 [4] and Cigré TB442 [5] standards are to be used, respectively.

The second series of tests is an experimental investigation into the erosion and tracking of successful candidate porcelain tile coated insulator samples subjected to HVAC and HVDC excitation in accordance with the IEC 60587 standard [6] using the existing inclined plane tester at Eskom.

The third series of tests is to compare/evaluate the outdoor pollution performance in accordance with the IEC 60815 standard [7] of the candidate coatings and will commence if the first two tests series produce suitable results.

The general principles regarding the selection and dimensioning of insulators are given in the guides of the Cigré technical committees, TB361 [8] for AC and Cigré TB518 [9] for DC power networks.

Results and conclusions

The project is currently in its test methodology development phase. Resultantly, no laboratory or outdoor results are available at present.

A comprehensive literature survey is finished, and the research methodology is currently being refined.

A local coating manufacturer was approached by the HVDC Specialisation Centre (SC) based at the University of KwaZulu-Natal and Eskom. The manufacturer has agreed to provide base RTV SR coating material to be modified by including graphene. At present, the coatings to be tested are prepared by mixing the graphene and the base coating supplied by the industry at the HVDC SC. The graphene is also produced at the centre using two methods, i.e. a chemical route and a mechanical route.

Laboratory space and testing equipment are identified, which will be prepared for hydrophobicity-, hydrophobicity transfer- and inclined plane testing (tracking and erosion) experiments.

The flexibility of Eskom's insulation performance research and testing is to be improved by the addition of the MTR construction project, which can generate test voltages at various altitudes and in different South African environments.

Research is ongoing to explore solutions aimed at maintaining the advantages of superhydrophobicity for long term applications. Therefore, the partial hydrophobicity transfer characteristics of the RTV SR coated insulator materials will be compared to the full hydrophobicity transfer characteristics enhancement when adding graphene into the provided silicone rubber host.

Implications for Eskom and the power industry in Southern Africa

If superhydrophobic coatings, when applied to ceramic insulators, are proven to be successful, the impact of its use within Eskom and the Southern African power industry will significantly improve the insulation performance and reliability of the power network. A semi-conductive coating material might also improve the pollution performance of an insulator when wetted completely or partially by fog, mist, light rain, or snow. The reason for this is that a small leakage current could heat up the insulator surface and prevent the previously mentioned conditions from forming on the insulator, therefore preventing flashover.

The MTR will allow Eskom to perform further coating research work, enabling Eskom to regain its position as a leading institute in high voltage insulators research. More insight can then be obtained in the operation of high voltage insulators, leading to improved design and selection of insulators for the distribution and transmission networks. The University of Stellenbosch was also engaged with the possibility to set up a salt fog chamber which could further assist in laboratory testing the modified coatings. Collaboration with this academic institutions is now stronger and more united despite the many challenges currently faced by the COVID-19 pandemic.

Lastly, the reliability and performance of the Eskom network could possibly be improved by reducing System Average Interruption Duration Index (SAIDI), System Average Interruption Frequency Index (SAIFI) figures, as well as transmission system minutes.

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Key words: Graphene, Superhydrophobic Coatings, Hydrophobicity, Erosion and Tracking High Voltage Insulators

Formation of modified Z-phase in a 12Cr1MoV (X20) steel during long-term creep

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Justification of the project

Tempered martensite ferritic (TMF) steels such as 12Cr1MoV (German grade X20) are used extensively for steam pipes, turbines and boilers in several of Eskom's fossil fired steam power plants. It is very important to understand microstructural instabilities that could cause catastrophic failures due to rapid creep-strength degradation for components at an advanced stage of ageing. The formation of the thermodynamically stable modified Z-phase at the expense of MX precipitates in 9-12% Cr TMF steels is an important microstructural instability, responsible for a rapid loss of creep strength during long-term creep [1]. However, the experimental evidence for modified Z-phase in X20 grade steels is limited and has not been subjected to a systematic study.

Purpose

The formation of modified Z-phase in an X20 TMF steel subjected to interrupted long-term creep-testing at near in-service operating temperatures of 550°C and an applied stress of 120 MPa was investigated. Quantitative electron microscopy was used to evaluate the formation of modified Z-phase and its accompanying dissolution of MX precipitates during long-term creep testing.

Theoretical framework

The first systematic studies of modified Z-phase and its effects on creep-strength of power plant steels were conducted by Danielsen and Hald [1] because of a catastrophic failure at a Danish plant. Steels with increased chromium (11-12% Cr) have been shown to be more susceptible to this creep-strength break down. Cipolla [2] found that Nb-rich (Nb,V)X particles more readily converted to the modified Z-phase. Previous analysis performed by Danielsen and Hald [1] on an single ex-service (150 kh at 600°C) X20 grade sample showed relatively low quantities of modified Z-phase. However, the formation of modified Z-phase has been found to be sensitive to small (within specification) deviations in starting chemistry [3] which could be an important consideration when operating plant components from different manufacturers close to their design limits.

Results and conclusions

Modified Z-phase was observed after a test duration of 51 kh in the gauge section of the crept X20 sample. The phase fraction (f_V) and particle size (d_m) of the modified Z-phase precipitates increased with testing time, with an associated decrease in the phase fraction and number density of the MX particles in the gauge sections of the crept samples. This led to an increase in the interparticle distance (λ_{2D} = 1.7 µm) for the MX precipitates as compared to the initial material state (λ_{2D} = 0.8 µm), which will lower the creep-resistance, since the creep-resistance in TMF steels is considered to be inversely proportional to the spacing of the MX precipitates. The grip sections of the crept specimens had a much lower phase fraction of modified Z-phase, implying that the applied stress/creep deformation enhances the formation of modified Z-phase.

Implications for Eskom and the power industry in Southern Africa

The characterisation techniques used in this study have been optimised to reliably quantify the finest of microstructural features (MX) in 9-12% Cr TMF steels. These characterisation techniques can be applied to investigate these microstructural instabilities and provide a more accurate assessment of the material state, which is especially important for plant components in an advanced stage of aging. The quantitative results of this systematic study can also be used to benchmark the microstructural instabilities to the life-consumed fraction in X20 material grade plant components.

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Key words: Tempered martensite ferritic steels, modified Z-phase, long term creep, X20

Validation and application of small sample punch test for toughness measurement of steels

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Justification of the project

Power generation plants and utilities are ideally supposed to last for decades, thus there is need for suitable and innovative analytic methods that enhance the life of these vital components. The integrity, efficiency, and capacity of these components is impaired by damage mechanisms like creep and embrittlement which in turn affect the safety and operation of the power generating plants. The small punch test is a quasi-non-destructive mechanical test that can be applied to determine the mechanical properties of materials from a miniature specimen. Unlike the conventional standard mechanical tests (tensile, fracture toughness, Charpy V-Notch), this test method requires minimal material to be removed from power plant structures for life and integrity analysis, while ensuring continuation of unabated service of the structure under investigation. This will allow power plants to operate at full capacity even during life assessment and mechanical property tests.

Purpose

Numerous attempts have been made to examine the data and information that is obtained from small punch tests, resulting in various approaches adopted. The purpose of this project is to provide a concise and more straight-forward approach in using the small punch test method, in relation to conventional mechanical techniques, to measure mechanical properties and assess materials degradation. In particular, digital image correlation (DIC) is deployed to reliably detect the onset of fracture.

Theoretical framework

According to the CEN Workshop Agreement [1], the small punch test produces results in a load displacement curve (LDC) that can be immediately correlated with the conventional mechanical tests.

The load in the various deformation stages of the LDC can be compared with the tensile test, whereas the deformation energy can be related to the fracture toughness and the Charpy V-Notch impact tests as demonstrated by A. Shekhter et al [2]. The introduction of DIC will enable an improved and reliable method to detect crack initiation and propagation during the small punch tests. Tshamano [3] and Hahner et al [4] used finite element modelling (FEM) with the Abaqus software to simulate the small punch test, a procedure adopted in this project to consolidate the findings.

Results and conclusions

Heat treatment that was carried out on the MACSTEEL VRN 500 steel resulted in three distinct mechanical properties as required to provide a range in ductility and fracture toughness. The tensile tests of the as-received condition resulted in a high yield strength of 1200 MPa, a Young's Modulus of 200 GPa, an ultimate tensile stress of 1658 MPa and a significant plastic deformation region, exhibiting the ductility of the material. This corresponded to the high energy absorbed and high maximum load of the SPT LDC in the same condition, which had a maximum load of 3.1 kN, and a yield load of 0.98 kN. According to method proposed by Hahner et al [4], the yield stress as correlated with the SPT was 1400 MPa, which was an increase of 15% from the tensile test result. The deviation of the tensile property estimations will be improved by carrying out further tests on the other material conditions. There will also be the introduction of DIC for these tests, which will improve the reliability of the SPT, as this will provide better crack initiation and propagation detection.

The results in the as-received material condition show that the data obtained from the tensile test and the SPT can be seen to be able to provide correlations between the two tests. The FEM, Charpy impact tests and the fracture toughness tests are still to be carried out on all three material conditions, creating room for more results and observations before this project is successfully complete.

Implications for Eskom and the power industry in Southern Africa

Having a reliable and repeatable mechanical test that requires minimal material to establish the damage condition of components will enable maintenance and remaining life assessments to be carried out without prolonging downtime. Eskom and the power sector can therefore benefit by being able to consistently supply power to meet demand in a reliable manner, whilst monitoring its plant components without the disruption of operations.

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Key words: SPT, mechanical tests, deformation, fracture, heat treatments, FEM

Microstructural evaluation of ex-service 1CrMoV turbine rotor steels

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Justification of the project

A core sampling and hydro-pillar repair welding (Weldcore™) process was developed at the Nelson Mandela University. This process is able to remove small samples from turbine rotors for non-destructive remnant life assessment (RLA) of in-service components [1]. The original research programme involved the removal of 10 core samples from stage 1 turbine rotors, which were subsequently investigated using optical microscopy and hardness measurements for a RLA. Initial microstructural analysis was conducted by van der Meer [2] using electron microscopy on a selection of the core samples. This project extends this microstructural analysis using a wider range of advanced characterisation techniques that have since been developed in the Centre for HRTEM at the Nelson Mandela University.

Purpose

The purpose of this work is to use analytical electron microscopy to evaluate the effects of service temperature and stress on the microstructural changes that occur in 1CrMoV turbine rotor steels during long-term service. The microstructural features of interest for this material include creep cavities, grain size, dislocation density and precipitate populations. The material states will be compared to existing knowledge of the steel to get an indication of the remaining life of the turbine rotors.

Theoretical framework

The microstructure of 1CrMoV steel is metastable under the high temperature service conditions of temperature and stress. Monitoring these changes offers a potential means for assessing the loss of creep strength due to service exposure and can consequently be used as an indicator of the remaining creep life. The microstructural features considered as an index of creep exposure in 1CrMoV steels are creep cavities, interparticle precipitate distance, carbide phase evolution, composition and proportions; and hardness reduction [3], [4].

Results and conclusions

Three different sampling locations on the turbine rotor were investigated using advanced electron microscopy. The cold section experienced temperatures below 226°C and experienced relatively low stresses, representing the starting state of the steel. The core samples experienced temperatures of ~538°C during service, but the geometry region in the blade attachement area experienced a higher stress (as compared to bulk region) and is considered to be the most susceptible to creep-damage. Localised creep damage was observed in the geometry region of the core sample, with cavity sizes ranging from 0.5 to 2.5 µm, with an area fraction of 0.18%, and a maximum cavity density of 1 568 cavities/ mm^2. It was found that the cold section sample contained coarse M_3C, fine spheroidal MC, and thin platelets of M_2C carbides. The chromium and manganese content in M_3C carbides increased at the expense of iron in the core samples due to the higher temperatures experienced during in service operation. The precipitate phase volume fractions in the cold section were 95% M_3C, 2% MC, 2% M_7C_3, 1% M_2C and <1% $M_{23}C_6$, compared to the core sample with precipitate phase volume fractions of 60% M_3C, 2% MC, 17% M_2C, 13% M_7C_3 and 5% $M_{23}C_6$. The effect of the higher stress in the geometry section of the core sample had a neglible effect on the precipitate composition and phase fractions.

Implications for Eskom and the power industry in Southern Africa

Combining advanced electron microscopy techniques with non-destructive small sampling techniques can be applied as an additional tool to evaluate the remaining life of high value power plant components. This can be done by comparing the microstructural features in the service exposed steel to either existing microstructure-property databases or models to evaluate to life-consumed fraction.

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Key words: RLA, small sample extraction, advanced electron microscopy, 1CrMoV

Dislocation density measurement in fatigue tested AISI316 using X-ray diffraction

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Justification of the project

The evolution of dislocation density in steels is an important aspect of the mechanical response. It could potentially be used as a fingerprint to relate the material state to the life-consumption fraction in materials subject to either creep and/or fatigue conditions. Transmission electron microscopy (TEM) is often performed to determine dislocation density in steels, however, it is quite time consuming and subject to large scatter due to the small areas (25 μm^2) that are typically investigated.

X-ray diffraction (XRD) can characterise the crystallographic structure of materials over larger areas (~ 1 cm^2), requires less data processing and the data acquisition can be automated for a batch of samples. In this study we evaluate XRD as a method to determine the dislocation density in annealed AISI 316 samples subjected to various room-temperature tensile fatigue cycling (annealed, 500k, 1M, 3M and 11M cycles respectively) with a peak stress of 320 MPa. The material states were also characterised using electron backscattered diffraction (EBSD) and TEM for a qualitative comparison to the more representative XRD method.

Purpose

To evaluate a bulk non-destructive examination technique, XRD, by means of performing a quantitative analysis of varying deformation states in a AISI 316 specimen against conventional and known qualitative destructive techniques, i.e. EBSD and TEM. This is undertaken with the aim of developing a capability for early detection of fatigue damage whilst understanding the limitations of the technique.

Theoretical framework

The processes responsible for the broadening of XRD peaks can be grouped into contributions of the a) diffractometer and b) material state of the sample. The contributions of the instrument are typically determined by characterising a standard sample with a known material state. LaB_6 is a NIST standard, with a large crystallite size and zero micro-strain, that is typically used to determine the instrumental peak profile contribution, by scanning the standard on the diffractometer and then performing peak-profile analysis. The samples are then characterised using the same instrumental parameters to collect the experimental XRD patterns. Sample related contributions to the XRD peak broadening consist of mainly a) crystallite size and b) micro-strain (dislocation density), which are convolved with instrumental contributions to produce the experimental pattern.

The various contributions to the XRD peak profile can only be separated by whole pattern analysis (Rietveld refinement) or by analysing several peaks of a pattern using the Williamson-Hall (W-H) method.

Results and conclusions

Laboratory based XRD peak-profile analysis was successfully used to quantify the micro-strain (dislocation density) and the crystallite size for annealed AISI 316 subjected to various levels of room-temperature fatigue. The accuracy and precision of extracted parameters (crystallite size and dislocation density) are sensitive to the data fitting methods, sample surface preparation, and the material state and must thus be interpreted with care. EBSD analysis uses a focussed electron probe that is scanned across the sample surface. This technique is - sensitive to local orientation differences due to deformation in the steel grains that develops during fatigue testing.

The EBSD results mostly show good qualitative agreement with the XRD analysis. TEM analysis was used to qualitatively visualise the individual dislocations but is very time-consuming to perform quantitatively and the results are subject to large scatter.

Implications for Eskom and the power industry in Southern Africa

The study provides a baseline for the development of the XRD inspection technique in evaluating the remaining life of low-pressure steam turbine last stage blades after known cycles of operation. The results indicate that the technique used is viable to determine dislocation density. However, care must be taken to standardise the sample preparation, instrument calibration, and data processing pipeline for reliable measurements.

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Key words: AISI 316, fatigue, X-Ray Diffraction, EBSD, TEM

Influence of Post Weld Heat Treatments on P91 Weldments

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Justification of the project

Since the adoption of Grade 91 steel in power plants, premature failures of weldments have been reported. Grade 91 steel is a 9wt% Chromium (Cr), creep strength enhanced ferritic steel (CSEF) that was developed for improved strength at high operating temperatures. This allows power plants to operate at higher temperatures resulting in improved power plant efficiency. Grade 91 steel is used in the superheater section of the boilers as well as main steam pipe where joining of the pipes is inevitable. In the case of pipe applications, the steel is referred to as P91. A key factor for successful installation of P91 is optimised welding and post weld heat treatment (PWHT), where the latter is deployed to restore the mechanical properties after welding. Although optimum PWHT is prescribed, deviations in the field practices can potentially lead to accelerated component degradation and failure. Consequently, a full understanding of cross-weld behaviour as a function of deviation in PWHT is required.

Purpose

Weldments are generally highly composite in nature (includes base metal or parent metal, heat-affected zone (HAZ) and the weld metal with varying mechanical properties. Macro-tensile properties will not differentiate the behaviour of the different weld zones. This study focuses on the localised strain across a welded tensile test specimen. A localised strain map is obtained during high temperature tensile deformation which assists in understanding the influence of PWHT on the overall performance of the cross-weld, and in particular allows the identification of the most vulnerable microstructure components.

Theoretical framework

Middleton et al [1] assessed the risk of weld-related failures following reports of premature weld-related failures in P91 steel. They created a weld failure location predictor diagram that gives a broad perspective but, it does not accurately identify the region where failure occurs in the different weld zones.

Doubell et al [2] investigated the effects of variations in heat treatment parameters on performance of CSEF welds but the tensile test and cross-weld hardness results were limited to room temperature testing only. Van Rooyen et al [3] used 3D digital image correlation to measure creep deformation of ex-service 12% Cr steel and the Gleeble 3800 thermomechanical simulator for accelerated creep testing. Their work gives insight into the parabolic temperature profile and stress distribution on a tensile test specimen as well as a comparison of thin and thick gauge sections. K Singh et al [4] developed an experimental technique for mapping high temperature strain localisation in steel weldments using 2D digital image correlation and the Gleeble thermomechanical simulator for tensile testing. Their results show a similar parabolic temperature profile to that reported by Van Rooyen et al and tensile tests performed at room temperature, 300°C and 500°C present clear indications of strain localisation at cross-weld positions dependent on test temperature. In this work, 3D DIC is used for non-contact strain measurement and the Gleeble 3800 thermomechanical simulator is used for high temperature tensile tests.

Results and conclusions

Mapping of the localized strain identifies the location of the peak strain during a tensile test. The location of the peak strain coincides with the region most susceptible to failure across the weldment. It was observed that the post weld heat treatment (PWHT) condition is the major factor affecting the location of peak strain. The location of the peak strain is not influenced by the temperature profile across the tensile test specimen as it does not always occur in the region with the highest temperature on the specimen. Location of peak strain can be separated into weld-related failures (WRF) and parent metal failures. The experimental results show 25% weld-related failures with the remaining failures in the parent metal for the different test temperatures and heat treatments. WRFs in the heat affected zone (HAZ) were observed in specimens subjected to PWHT at 760 °C and 800 °C for 2hrs. There is clear indication that the location of damage initiation is influenced by the PWHT parameters, namely, the location of peak strain shifts from the ICHAZ towards the FGHAZ as the PWHT temperature increases.

Implications for Eskom and the power industry in Southern Africa

The results obtained give insight into the implications of deviations in PWHT practice for P91 pipe installations. The identification of changing tensile behaviour across weldments as function of PWHT contributes to understanding the metallurgical risk associated with deviations in PWHT field practices.

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Key words: Post Weld Heat Treatments, Strain Localisation, 3D DIC, P91 Steel, Gleeble

Investigation of the uncertainty of wall thickness testing of boiler tubes with fly ash erosion degradation

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Justification of the project

There has been an increase in the number of failure incidents [1] reported in the Power Generation industry [2] despite the routine performance of non-destructive testing (NDT) to detect and prevent such failures. Situations arise where the components were declared ready to be returned to service but were later found to be defective and not fit for service. The present study is focused on the occurrence of boiler tube failures. In many instances root cause analysis investigations indicate that the ultrasonic wall thickness measurements were incorrect. Boiler tubes were possibly returned to service below the minimum wall thickness, which contributed to the number of unexpected boiler tube failures. The uncertainty in NDT measurement accuracy leads to poor plant reliability and hence increased downtime.

Purpose

To investigate and provide a framework to pro-actively analyse the accuracy of NDT testing and improve the reliability of NDT on boiler tube piping subject to fly ash erosion degradation.

Theoretical framework

- Machine Learning and artificial intelligence have the ability to automatically learn and improve from experience without being explicitly programmed.
- The benefits of an artificial intelligence system such as neural network analysis has been proven in the optimal design of structural systems [3] [4] and adaptive mesh generation [5].

- In this study of applying neural network analysis, the supervised machine learning method will be used whereby clearly labelled inputs and corresponding outputs are used. In the learning phase, it utilises a function that can automatically identify the features of the dataset. It identifies trends or relationships between data, which it learns and thus utilises to predict future data [6].
- The use of the Monte Carlo Simulation will further improve the prediction of the probability of failure with the Neural Network Analysis [7].

The combination of the models utilised in conjunction with qualitative surveys will indicate the influencing factors on the NDT accuracy.

Results and conclusions

- Experimental data and historic plant data have been obtained from outages which served as data inputs to the neural network.
- A preliminary neural network model has been developed, which will be further refined after additional data analysis.
- The subsequent steps will be to conduct qualitative surveys and to develop the Monte Carlo simulation model.

Implications for Eskom and the power industry in Southern Africa

- The models simulated will indicate the influencing factors contributing to the uncertainty of boiler tube wall thickness measurements.
- Guidance on how to improve NDT inspection reliability for the specific method utilised.
- Guidance on how to Improve RBI inspection and testing in Eskom.

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Key words: non-destructive testing; measurement uncertainty; neural network analysis; Monte Carlo analysis

Assessing the effect of toe drainage systems on seepage volumes and stability of an ash dam with permeable foundation

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Justification of the project

Although seepage control and filter design technology is not new, many old embankment dams were not fitted with drainage systems/filters that are meant to prevent internal erosion. Instead of rectifying this by means of remedial works, many of these dam owners chose to rely heavily on surveillance, periodic inspections and monitoring [1]. However, this does not guarantee any protection against failure due to piping (internal erosion) and environmental degradation (contamination of groundwater). Several investigations were carried on the groundwater in the area and the nearby water source (Witbank dam), the findings indicated a possible contamination in both. Due to the suspected seepage, internal erosion can also be expected.

For the dam in this study, sufficient drainage for seepage control was not provided, and a resolution for the apparent seepage (that is the major concern to the environment) is required as per the Water Use License agreement. Furthermore, it is essential to investigate slope stability issues that may be caused by seepage and determine the most effective toe drainage system that is more suitable for the dam.

Purpose

The objectives of this study were to investigate and evaluate a suitable toe drainage system that could possibly assist in controlling seepage in an existing ash dam and preventing further contamination to the groundwater and the nearby water source, also to assess the stability of the dam with the proposed solution.

Theoretical framework

Given the current conditions of the ash dam (weathered rock foundation, underground and toe seepage), challenges that may be introduced by temporal halt of operations and the fact that the dam in this study is an existing structure, three possible solutions were identified based on the practicality of implementation. Nedrigy [2], presented different toe drainage solutions for seepage control and seepage estimation in order to improve embankment monitoring based on the approach proposed by Wang et al. [1]. Aboelela [3] models incorporated the effect of the catch drain location (next to the toe of the embankment), which will be investigated further by means of seepage (FEM) tools in order to effectively catch underground seepage water for the ash dam in this study.

Results and conclusions

Relative seepage discharge and the location of the catch drain showed a clear relationship. Increasing the catch drain location (i.e. away from the toe of the embankment) showed a decrease in relative seepage discharge. However, the locus (Lc value), which is the distance at which the phreatic surface intersects the embankment base/foundation, increased with an increase in the location of the catch drain.

The location of the catch drain governs the effectiveness of the system to catch underground seepage water. In permeable foundation conditions, it would be favourable to increase the Lc value (i.e. by increasing the distance between the toe of the dam and the catch drain) in order to effectively draw the phreatic surface towards the toe of the embankment, which will effectively reduce underground seepage.

Implications for Eskom and the power industry in Southern Africa

The results of this study would ensure environmental protection and long term stability of ash dam facilities, even after the decommissioning of the dam. Moreover, this will provide the prospect of improved tailings (fly ash) management and power generation that will enhance the energy supply with minimal safety risks to the environment and tailings dams.

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Key words: Seepage, Toe Drainage, Internal Erosion, Slope Stability, Monitoring

Optimization of project controls towards construction projects within the energy utility

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Justification of the project

According to Baban, Seneviratne and Nielsen (2020), the studies that are conducted concerning project controls still leave a gap on how the available mechanisms can be optimized to control project performance. In their study, Baban, Seneviratne and Nielsen (2020) emphasized that efforts have been made to control projects in various aspects within the construction projects life cycle, however the available control mechanisms seem to be disconnected, disjointed, and scattered among construction professionals and as such do not address issues that make project to lose control. According to Kgosi, (2018), Eskom requires strict adherence to project controls processes to address the challenges of cost and time overruns for implementation of capital projects. This study will be beneficial to Eskom and will remain in the utility's project management repository's system.

Purpose

According to Mackenzie (2010) and Asiz, Memon, Rahman and Karim (2012), it remains necessary to review the available project control mechanisms and practices to bring effective interventions for improvement of project performance. This study aims to explore, assess the effectiveness of project controls, and investigate project control implementation challenges experienced in South Africa's construction sector with the purpose of establishing a project control framework to improve project controls for successful construction project outcomes.

Theoretical framework

The consolidated views of Baban, Seneviratne, Nielsen (2020); Mackenzie (2010) and Asiz, Memon, Rahman and Karim (2012) strongly suggest that the main reason for continuous poor performance of construction projects lies within the available project controls mechanisms, systems, and processes.

Various project management researchers seem to agree that the components of project controls can be summarized as factors that drive performance on project cost, time, and quality. According to Besteiro, Pinto and Novaski (2015), the success of construction projects is fully dependent on monitoring and control processes which are driven by the functional project controls, and this can be demonstrated in the framework below.

The application of project controls sits within the project life cycle of the project and may vary from project to project depending on the critical areas that have to be controlled (Baban, Seneviratne and Nielsen, 2017). This study will focus on the development of a framework with an intention to optimize the project controls within the energy utility for better delivery of capital projects. Figure 1 below indicates the application of project controls, and this study adopts this approach as a framework.

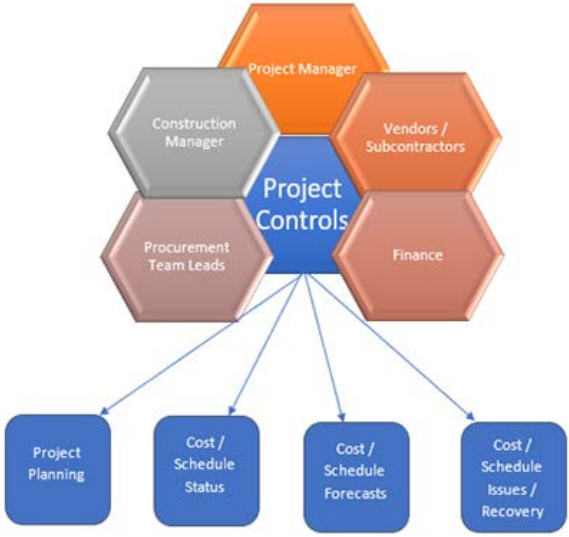

Figure 1: Project Controls among stakeholders. Source: Ghorbani (2017)

Results and conclusions

The reviewed literature indicates that there is an opportunity of looking at optimization of the efficiencies of project controls. This is because most studies have been focusing on the assessing the effectiveness of project controls and it has been widely established that project control are not achieving the envisaged functionality and the results thereof.

There is a gap of studies focusing on the optimization of the effectiveness of project controls. Literature also indicated that to optimize on the efficiency, issues such as skills and the support by management will have to be addressed for better implementation of project controls.

Implications for Eskom and the power industry in Southern Africa

The study will submit recommendations on how to best implement project controls and achieve meaningful results. Several participants who shall have participated on the study will also be prioritized in terms of sending out the results and findings. The lessons learnt that shall have been established from the study will also be shared with various departments together with library of Eskom which is responsible in maintaining the academic repository system.

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Key words: Project controls, Planning and scheduling, Cost estimation, Project management, Cost overruns, Schedule overruns, Construction project management

Investigating Coal Fired Thermal Power Plant Performance Testing

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Justification of the project

This project was undertaken to improve understanding of relationship between factors contributing to uncertainties and boiler efficiencies for STEP measurements. The project also indicates the relationship of uncertainties at different station loads. This benefits the accuracy of reporting before and after outages. All measurements used to determine the plant health would be reported accurately. The accuracy would take into consideration the instruments used to take the measurements. Uncertainties in measurements assist in making accurate decisions in terms of scheduling maintenance on the plant and ensuring that the effectiveness of the maintenance can be accurately determined. Furthermore, this work ensures that the plant behaviour at different loads can be studied and understood in terms of efficiencies and the contribution to uncertainties. The results will ensure that drawing comparison between the baseline and guaranteed parameters can be done accurately, and ensure that contractual requirements are met.

Purpose

This project aims to determine the main contributing factors to relative uncertainties and impact of each on the absolute uncertainty. This will be determined at different loads i.e. 56%, 60%, 80%, 100% and 103%. For each load, the relative uncertainty will be determined and accurately incorporated into the boiler efficiency. Thereafter, the different absolute uncertainties will be compared to determine any relationships and draw conclusions from the results.

Theoretical framework

The main theories employed in this project are the following; indirect method for determining boiler efficiency, and the GUM (Guide to Expression of Uncertainty of Measurement) method for determining uncertainties for random errors. The indirect method determines boiler efficiency by specifying specific losses through Flue gas, sensible heat of Ash & SSC cooling water, unburned organic carbon of ash, Unburned Carbon Monoxide, and Radiation & convection, and the sum of the losses is subtracted from 100% to obtain the boiler efficiency.

The GUM procedure is documented in the BS EN 12952, this method calculates relative uncertainties of the following; relative uncertainty of input / loss calculations, relative uncertainty of oxygen analysing within flue gas, relative uncertainty of flue gas heat capability, relative uncertainty of flue gas temperature, relative uncertainty of net calorific value of coal, uncertainty of radiation and convection loss, uncertainty of unburned carbon monoxide, uncertainty of ash losses by sensible heat & unburned carbon. Furthermore, the boiler efficiency relative uncertainty is calculated from the determined relative uncertainties, lastly the absolute uncertainty of boiler efficiency is determined by multiplying the boiler efficiency by the determined boiler efficiency relative uncertainty. The absolute uncertainty is reported with the boiler efficiency.

Results and conclusions

The STEP was conducted at Medupi power station, on the newly built Unit 3. And the data was used to determine the baseline performance of the unit after commissioning. The efficiencies for the five loads were 92, 90%, 93, 32%, 93, 44%, 93, 70%, and 93, 90%, relative to the loads, with 92, 90% boiler efficiency at the lowest load of 56% TMCR and 93, 90% at 103% TMCR. Furthermore, the largest losses accounted are from specific exhaust gas, which were 6, 36% and 5, 89% for 56% TMCR and 103% TMCR respectively.

Measurement uncertainties were determined according to the BS EN 12952 and it was noted that with lower boiler efficiencies, the absolute uncertainties are higher. This was the case for 56% TMCR with the resulting absolute uncertainty of 0, 31% and 103% TMCR with absolute uncertainty of 0, 29%. The difference is due to the differences in the relative uncertainties of CO, at 56 TMCR the CO value was 1ppm and 54ppm at 103 TMCR. The lower CO content for 56% TMCR produced a higher absolute uncertainty of 0, 31% compared to the 0, 29% in line with the 103% TMCR.

Implications for Eskom and the power industry in Southern Africa

The results are very instrumental when applied to performance and testing of coal powered power plants. Furthermore, these results will assist in increasing the confidence level in the obtained results and setting the baseline performance of the plant, which will be used to schedule maintenance and ensure that the performance is accurately optimized.

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Although a concept developed in 2002, NASA coined the first practical definition of digital twin to improve physical model simulation of spacecraft in 2010.

The digital twin concept consists of three distinct parts: the physical product, the digital/virtual product, and connections between the two products.

It is a real time simulation of the physical device and can be used to analyse, modify and optimise the real product.

Topics to be covered include the following:

- Application of digital twin for the development and life cycle management of turbines, includes flow analysis, performance simulation and application.
- Application of digital twin in a utility grid in Netherlands. Twin, sibling and cousin applications.
- Future simulations using twins.
- Control centre of the future.

The panel of internationally recognised experts will be chaired by Volker Bertram (Det Norske Veritas)

Panellists are:

- **Annie Bekker** (Stellenbosch University)
- **Thomas Hildebrandt** (Numeca)
- **Peter Palensky** (TU Delft)

The panel is of interest to engineers from utilities, academia, consultants and manufacturers.

Leveraging Digital Twins of Existing Assets to Support Predictive Maintenance

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Justification of the project

As with other developing countries, one of the biggest challenges facing South Africa's electricity supply industry (ESI) is ageing generation, transmission and distribution infrastructure. According to the Development Bank of Southern Africa (DBSA), approximately 75% of transmission lines and transformers are 25 years or older. This is compounded by increased regulation, reduced funding and rising project costs making it even harder to provide power.

One way to address this is to look at brownfield assets and plan for life extension. However, developing an existing site is challenging because access to comprehensive and current information is necessary but, more often than not, records of upgrades and adaptations to the asset may not have been updated accordingly while some may have been completely lost. This makes brownfield less attractive than greenfield projects, given effective and informed decisions need to be data driven in the face of an increasingly strict reporting and compliance regime by regulators.

Purpose

The purpose is the creation of a reliable and accurate as-operated digital twin for a brownfield substation, providing:

- an immersive environment providing access to asset information from combining asset register and other documents within a clickable 3D model and to enable visual operations,
- a basis for development and implementation of a reliability program for asset performance management (APM) aligned to ISO 55 000.

Theoretical framework

The concept of Digital Twins (DT) [1] gaining increasing attention due the potential to drive Industry 4.0. Digital twins make it possible to upgrade to smart grids [2][3] and attain asset information integrity throughout the life cycle of an asset. Digital twins are Internet of Things (IoT) intensive systems thanks to the ability to embed sensor technologies coupled with information and communication technology making it possible to reflect the physical status of systems in a virtual space [4]. However, most of the data collected is referred to as "dark data" because it is underutilised, unstructured, in different formats and scattered across silos across engineering technology (ET), information technology (IT) and operations technology (OT) making accessibility and collaboration a big challenge. DT technology breaks these silos and ease the associated difficulty of access and collaboration.

Through DT predictive analytics, "dark data" can be uncovered and utilized more to optimize the performance of the physical asset through control signals and complete the feedback loop, a hallmark of DT in the literature. Through the concept of a digital thread, which fits in neatly with blockchain, a DT can provide historical snapshots and audit trail of every transaction essential to comply with regulatory requirements [5].

The implementation of a DT for maintenance requires the creation of digital models and several steps need to be followed to achieve a maintenance DT. Communicating information to the right decision maker in an operational support system, (OSS) enhanced by visuals such as a 3D model of the physical object it mirrors is critical. Such a visual operations system brings together information scattered across organisational silos, and displays it to facilitate quick, timely, and accurate decisions. Visual operations can increase productivity, efficiency, and even accuracy since most people tend to learn faster and retain information better when it is presented graphically rather than textually.

Results and conclusions

The expected output is an operational support system, (OSS) for visual operations based on 3D high-fidelity 3D models. This will feed into the next phase towards the development and implementation of a reliability program for asset performance management (APM) aligned to ISO 55 000 based on DT technology.

Implications for Eskom and the power industry in Southern Africa

The contribution of this study is to develop a framework for implementing and measuring the impact of the DT in terms of return on investment (ROI) using established perspectives from the management literature. To bridge the gap between formulation and implementation, the framework will be tested in a case study towards achieving Eskom's stated target of unplanned maintenance levels not exceeding 14% through the ability to calculate Remaining Useful Life (RUL) of an asset.

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Key words: Digital Twins, Visual operations, Predictive Maintenance, Blockchain, Analytics

The influence of coal pellet properties on its emissions and thermal performance in a semi-continuous coal stove

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Justification of the project

More than 4 million South African households rely on coal as a primary fuel source, especially during winter [1]. The household combustion of coal typically produces harmful emissions such as carbon monoxide, sulphur dioxide, nitrogen oxides, fine particulate matter, volatile organic compounds, and polycyclic aromatic hydrocarbons [2].

The total amount of coal fines in the top ten coal-producing countries exceeds 30 billion tons [3]. Since coal is a non-renewable source of energy, it is important to reduce coal fines waste and find cost-effective methods of utilising coal fines that are currently discarded. Several studies suggest that cookstoves that utilise packed bed combustion with homogeneous fuel particles (both in geometry and composition, for example coal pellets) have improved emissions performance compared with ordinary cookstoves [4]. Coal fines are already used to produce low smoke fuels for electricity generation in South Africa, however the literature suggests that these fuels are seldom used in rural and informal settlements.

Purpose

This study aims to determine the thermal and emissions performance of coal pellets with different properties, to identify how these properties influence the combustion thereof in a semi-continuous coal stove. The coal pellets used for this study were not tested in domestic stoves since the cross draft semi-continuous coal stove was already found to produce lower emission levels when compared to domestic combustion appliances.

This research therefore aims to improve on the already "clean burning" semi-continuous coal stove by testing fuel-stove combinations that will further improve the thermal and emissions performance.

Results and conclusions

It was found that the combustion rate of coal pellets was comparable to the combustion rate of lump coal in the semi-continuous coal stove. All the pellet batches produced higher levels of CO compared to lump coal. The emission factors for coal and coal pellets were also compared. It was found that the use of a PVA binder for a domestic fuel application could be advantageous since it does not contribute to the emission levels of coal fines.

It is concluded that the combination of pelletised coal waste and the innovative cross draft semi-continuous stove could provide an affordable and low emission domestic energy technology for the highly air polluted low-income settlements of the South African Highveld. It will however be possible to burn the pellets in a current coal combustion appliance but will likely produce higher emissions levels than when burnt in the semi-continuous coal stove.

Implications for Eskom and the power industry in Southern Africa

It was demonstrated that all the fuel batches coupled with the improved semi-continuous coal stove delivered significantly lower emission levels than when compared to a domestic coal stove.

Households that receive access to electricity rarely move away from coal combustion since electrical appliances are seen as unaffordable and untraditional [5]. Therefore, it is plausible that the large-scale implementation of the semi-continuous coal stove in rural settlements can significantly reduce household pollution and provide an alternative means of domestic energy generation. This study can consequently be used by Eskom as an offset program to aid in the reduction of South African air pollution.

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Key words: Coal; Combustion; Coal pellets; Coal stove, Emissions, Thermal efficiency

An empirical analysis of residential fuelwood consumptions rate and its pattern from villages in Thulamela municipality, South Africa

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Justification of the project

Fuelwoods are used by several households as an alternative source of energy. Burning of solid fuels is the primary source of domestic energy for those living in low- income settlements in developing countries and this is practiced by approximately 3 billion people around the world [1].However, most residential fuelwood burning is an inefficient and incomplete combustion process that takes place in the developing world due to economic reasons where vital energy needs for cooking, heating, and lighting have to be met by fuelwood [2].

Purpose

Using questionnaire survey, this paper investigates factors that determine fuelwood usage, consumption rate and its pattern in Thulamela Municipality to identify fuelwood and factors affecting them.

Theoretical framework

A questionnaire survey was used for data collection [3]. The questionnaires were administered to respondents from two villages namely, Gondeni and Lunungwi villages using purposively and, snowball method [4]. The survey lay emphasis on fuelwood usage of household activities such as cooking and heating.

Results and conclusions

The commonly used fuels for household activities in the two villages were found to be wood and electricity whereas paraffin and candle are not frequently used.

Fuelwood was the main source of energy for cooking for both summer and winter. However, for heating, fuelwood is the primary source of energy during winter while electricity is commonly used during summer. The fuelwood average consumption rates were in the range of 6.3 - 7.9 kg per day in the summer and 7.8 - 9.5 kg per day in the winter with highest usage from Lunungwi village. Results of the empirical analysis [5]. further shows that the consumption rates and patterns for this fuelwood largely depended on factors such as seasonality, the fuelwood availability and price, and socio-economic factors. The relationships amongst the factors influencing the fuelwood usage such as "main reason to use a fuelwood" and "satisfaction with fuel wood burning" were determined using a non-parametric test (Chi-square). Based on the Chi-square test results, there was significant association between respondents of the village and perceptions on firewood usage. In addition, majority of both residents were using fuelwood for either economic purposes only or economic purposes and taste. Implication of high consumption rate of fuelwood for household activities from the study area could be a major contributing factor to air pollution and hence, mitigation strategies need to be put in place.

Implications for Eskom and the power industry in Southern Africa

This study shows that high consumption rate of fuelwood for household activities from the study area could be a major contributing factor to emission and air pollution other than power plant emission. However, if there is reduction in price rate and constant supply of electricity by Eskom, there will be increase in the usage of electricity for household cooking, heating and lighting activities instead of fuelwood which will reduce emission.

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Key words: Fuelwood consumption, Household, Emission, Cooking

Spatiotemporal variation of PM2.5 and the potential health risk: A case study of Thulamela Municipality in Limpopo Province

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Justification of the project

PM2.5 has currently gained the global attention due to its significant potential impacts on human health [1-3]. The absence of consistence and reliable air quality data due to non-affordability of the conventional monitoring equipment in many low-income nations, toughens assessing the gravity of air pollution problem, as there is no evidence to show that air quality is a challenge, thus creating a harmful cycle [4].

Eskom is believed to be the main emitter of air pollutants in South Africa; however, little attention is paid on other sources of atmospheric emissions. Having a background knowledge of the air quality and the corresponding potential health impacts on a rural based environment like Thulamela through the use of a cost-effective device would help in knowing the right remediating or preventive measure to employ.

Purpose

The aim of this study is to determine the spatiotemporal variation in PM2.5 concentrations in Thulamela municipality of the Vhembe District in Limpopo, using Dylos DC1700 from February to July, 2021 and to evaluate the potential health impact.

Theoretical framework

The diurnal, daily, monthly and seasonal variability in PM2.5 concentrations of the ambient environment with changes in meteorological factors were monitored between February and July, 2021.

Results and conclusions

Result showed high concentrations of PM2.5 at night and low particulate concentrations during the day. Also, the number of days with PM2.5 concentrations exceeding the National Ambient Air Quality Standard (NAAQS) daily threshold limit increased as the time extents from summer to autumn and winter. Greater potential health impacts of PM2.5 were also observed in the autumn and winter months.

Implications for Eskom and the power industry in Southern Africa

Eskom is believed to be the main emitter of air pollutants in South Africa, however, little attention is paid on other sources of atmospheric emissions. This study aims at monitoring emissions from rural environment with the aid of a low-cost device, thus providing an air quality data base for Thulamela municipality.

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Key words: Dylos DC1700, spatiotemporal variation, diurnal concentration, potential health risk, metrological conditions

Discrimination between Nearby and Direct Lightning Strikes to a Long Operational Medium Voltage line to Assist in the Determination of the Basic Insulation Level (BIL)

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Justification of the project

Lightning causes between 50% and 80% [1] [2] [3] of faults on MV networks. To prevent line trips due to nearby lightning events, the line Basic Insulation Level (BIL) needs to be as high as possible so that the Lightning Induced Overvoltages (LIOV) do not exceed the line BIL and results in a flashover. On the other hand, in the event of direct lightning strikes to the line, the higher the line BIL, the more energy is stored in the lightning surges progressing along the line to the equipment. This resulted in a high equipment failure rate. It is therefore important to distinguish between nearby and direct lightning strikes to the line to ensure that the BIL is designed optimally and therefore improve the line's lightning performance.

Modelling the electromagnetic coupling between lightning strikes and MV lines are complicated and the input data to the models are not always available. Furthermore, lightning measurements on long lines requires measurement equipment and cameras every few hundred meters. Due to this complexity and logistics, short floating lines were used in previous research. The results were then documented in the IEEE Std 1410-2010 [4] to estimate the lightning performance of long lines in operation. This research used a new method where the estimated lightning performance of MV lines could be measured. It was found that the effect of induced voltages is much less than estimated and resulted in an overdesign of the BIL which in turn resulted in a high equipment failure rate.

Purpose

The purpose of the research was to find an accurate low-cost measurement method that can be used by an ordinary engineer to split the lightning performance of a MV line into faults due to nearby lightning and direct lightning to the line. Lightning performance improvement methods of a MV line requires different opposing designs for nearby lightning and direct lightning to the line. Furthermore, the research also provided information about faults during a storm that were sometimes confused with lightning related faults but is due to other elements in the storm like wind and moisture.

Theoretical framework

As existing electromagnetic coupling models are complex and accuracy / availability of input data is problematic, a new method to distinguish between lightning nearby to the line and direct lightning to the line was developed and verified. The polarity of the Lightning Generated Current (LGC) was measured at the feeder substation and if it is of opposite polarity to the return stroke current polarity as measured by the Lightning Detection Network (LDN), it indicated that it was a nearby lightning strike. Same polarities implied a direct lightning strike to the line. Due to finite soil resistivity the horizontal electric field polarity becomes dominant after about 250 m from the nearby lightning strike termination point that results in a LIOV and LGC polarity change on the line. Should the LIOV exceed the line BIL, a flashover occurred and it was detected using the fault current on the feeder.

Results and conclusions

A two-year data set consisting of 1155 line faults (flashovers) of which 528 were lightning related faults due to a total of 38 675 flashes (126 311 strokes) was created. The faults were categorized into faults due to nearby lightning, direct lightning strikes to the line, weather related faults and other reasons for line faults. This enabled utilities to adjust line designs for optimal MV line performance.

It was found that the IEEE Std 1410-2010 was underestimating the number of faults due to nearby lightning strikes (IEEE Std estimated 219 faults while only five faults were measured) and overestimated the number of line faults due to direct lightning strikes to the line (IEEE Std estimated 97 faults and 262 faults were measured).

Implications for Eskom and the power industry in Southern Africa

The new methodology to measure the MV line lightning performance is a low cost and easy method to exercise. Line designs can then be adjusted to optimize the MV line performance and minimize the equipment failure rate.

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Key words: Lightning induced voltage, Basic insulation level, lightning measurement

Development of a test section for the evaluation of dilute gas-particle flow measurement devices

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Justification of the project

When coal is grinded to a very fine powder and mixed with air it allows for very efficient combustion. The fineness of Pulverized Coal (PC) is described by its Particle Size Distribution (PSD) and is factored into the design of modern coal-fired boilers. Variation in the PSD of PC due to mill wear or change in coal quality will affect the efficiency of the combustion process and it is therefore important to monitor the coal particle PSD on a frequent basis during operation.

On-line measurement of PC PSD has the potential to improve combustion efficiency for real-time feedback allows immediate corrective action and so losses due to poor combustion can be reduced. On-line measurement of PC is not widely employed within Eskom and there is a need to get familiarized with the technology and its practical use. This project aims to grow experience in the implementation and use of an online laser-based measurement device and to contribute to the development of local expertise and knowledgebase.

Purpose

The purpose of this project is to design a gas-particle two-phase flow test section where within online measurement of fine solid particles can be conducted. Once the test section is commissioned a laser-based on-line measurement device is to be installed and measurements on a mixture of fly-ash and air be conducted. Finally the design of the test section is to be evaluated with a comparison of the on-line measurements and CFD predicted particle flow trajectories.

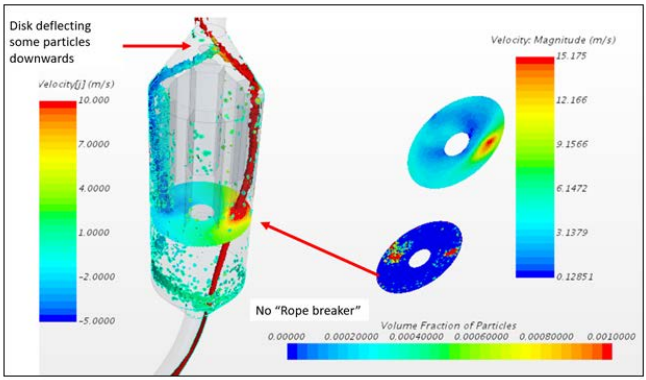
Theoretical framework

The design of the test section needs to meet the practical implementation requirements of an industrial-sized measurement device. The test section is implemented on an off-site gas-particle test loop facility that is of semi-industrial scale. Up-scaling of the test section to physically accommodate the industrial-scale measurement device while at the same time operating on reduced air and particulate flows is an interesting challenge.

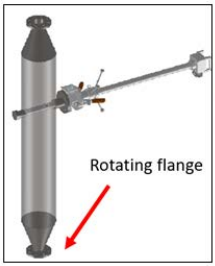
The use of gas-particle two-phase flow theory is used to create conditions where the air-particle mixture flow patterns are both repeatable and quasi-steady. Priori-known conditions allows a training scenario where the purpose of the measuring exercise would be to reproduce the particular known flow conditions.

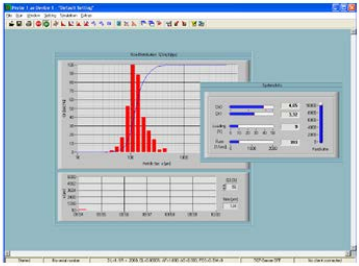
Results and conclusions

CFD was used to predict air and particle flow patterns in various test section design options. The figures below show the test section configuration as well as flow patterns within.



Practical measurements were performed to assess the success of the test section to produce air and particle flow patterns that are conveniently structured to allow demonstration and training in the use of particle measurement devices.





The project allowed an opportunity to investigate gas-particles flows in both a theoretical and practical way. A deeper insight into the dynamics of the flow and particle trajectories within the test section was developed and new and sensible modifications to further improve the test section could be defined. Working physically with fly-ash developed an insight and appreciation for the challenges experienced in handling the material on Eskom plants. Valuable experience and insight in the use of the laser-based on-line measuring device was obtained that can be used to guide further implementation of this technology within Eskom.

Implications for Eskom and the power industry in Southern Africa

The off-site gas-particle loop at North-West University proved to be a convenient facility to test the on-line particle laser-based measuring device due to its round-the-clock accessibility and controlled and safe working conditions. The test section designed during the project allows the industrial-scale laser-based probe to be effectively demonstrated. This opens up opportunity for training in the use of PC measurement techniques as well as to conduct further studies to assess how on-line measurement of PC can be further utilized within Eskom.

Key words: On-line measurement, gas-particle flow, computational fluid dynamics

Power station thermal efficiency performance (STEP) method evaluation

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Justification of the project

The current topic for research and development was initiated from the need for continuous improvement on the thermal efficiency performance/accounting tools. In the current global context, there is a strong focus on cleaner electricity production coupled with affordability. Even though coal-fired power plants are viewed as a "dirty" production process, it is envisaged that coal-fired generation will have a significant contribution to the energy mix in the next fifty years to come. STEP is an instrument that can be used to drive the medium-term objectives of environmental sustainability and cost reduction through energy efficiency maximization. In the current work, the STEP model is extended to evaluate instrument and temporal (random) uncertainties on the model output values. The quantification of these uncertainties, and insights gained from the STEP modelling approach, could lead to an increase in accuracy.

Purpose

The study intends to investigate the accuracy of the STEP model by:

- Reviewing the STEP calculation procedure against industry standards to identify gaps in the modelling approach and develop a verified computer model of the STEP calculation methodology for further expansions to the calculation approach.
- Identifying areas of improvement.
- Conducting an uncertainty analysis to estimate the model confidence and identify key areas where measurement can be improved or investigated further. This area of the study will focus on the input measurement uncertainty impact.
- Establishing ways to minimize input errors.
- Assessing the impact of the input time-series resolution on the accuracy of the model. This area of the study investigates the impact of temporal uncertainty on the model outputs. Establish an ideal input data resolution with cognisance of computational expense.

Theoretical framework

The major standards applied to Eskom's generating fleet thermal performance analysis are the; BS-EN standard [1], BS–EN(IEC), [2], [3]standards and ASME standards [4]–[6]. STEP intends to compare actual performance to an ideal state, where the actual efficiency is expressed as an effectiveness percentage of the ideal efficiency also known as the STEP factor. The ideal efficiency is derived from baseline data acquired from the unit's acceptance tests and is corrected for external factors being different from the original test condition, i.e. coal quality, power factor, load factor, ambient temperature, etc.

There are two main approaches to uncertainty propagation, namely, the derivative approach which is also known as the Law of error propagation [7] and the probabilistic approach. Both these approaches have various numerical methods for their implementation. Typical systematic parameter uncertainties were combined with a case temporal uncertainty. The individual and combined uncertainties were propagated through the STEP model using the Sequential Perturbation technique [8] to evaluate the accuracy of the STEP outputs.

Results and conclusions

The model uncertainty is appreciated by reviewing the efficiency and loss calculations against relevant industry standards (BS 2885, BS EN 12952-15, IEC 60953-0/Ed1, ASME PTC 4, ASME PTC 6). Relatively large deviations were noted for the boiler radiation, turbine deterioration and make-up water losses. Some discrepancies on the heat correction curves were identified using commercial thermodynamic modelling tools. The results from the case study yielded that the thermal efficiency computed by the "direct method", had an instrument uncertainty of 0.756% absolute (abs) versus the indirect method of 0.201% abs when computed at the station level for a 95% confidence interval.

For an individual unit, the indirect efficiency uncertainty was as high as 0.581% abs. The input resolution of the model was studied by discretizing the monthly data into smaller segment sizes and studying the movement of the mean STEP model outputs and the temporal uncertainty. It was found that a 3-hour segment size would be optimal as it gives the maximum movement of the mean of performance metrics without resulting in large temporal uncertainties.

When considering the combined uncertainty (temporal plus instrument uncertainty) at a data resolution of 1 minute and segment sizes of 3 hours, the "direct method", had an instrument uncertainty of 0.768% abs versus the indirect method of 0.218% abs when computed at the station level for a 95% confidence interval. For the case evaluated the mean "indirect method" STEP factor at the station level (the actual efficiency divided by the target efficiency) moved from 86.631% (using monthly process data) to 86.135% (discretized to 3-hour segments) which is roughly 0.188% abs change on the station's thermal efficiency.

This would appear small on the overall efficiency but had a significant impact on the evaluation of the losses and the cost impact by the change in the plant efficiency. E.g. the final feed water loss at a unit level moved from 2.6% abs to 3.5% abs which are significant for diagnostic and business case motivations.

Implications for Eskom and the power industry in Southern Africa

The various recommendations to improve the methodology, will drive lower unaccounted losses calculated by STEP, however, would require the implementation on the software platform used. The study has revealed the need for a review of baseline performance data across the Eskom fleet. The use of the indirect method for thermal accounting is deemed to favourable, however, would require strict controls to ensure measurement integrity. A move towards automated input data processing is envisaged to overcome input errors and temporal uncertainties associated with the resolution of the data analysed.

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Key words: STEP, Thermal performance, Coal-fired, Power Plant, Sequential Perturbation, Uncertainty propagation

Dynamic Turbine Expansion Modelling Using a Paired Thermofluid and FEA Method

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Justification of the project

The contribution of internal clearances in the efficiency and internal damage of steam turbines within Eskom's turbine fleet is significant. With these clearances being impossible to measure in-service, as well as the unavailability of detailed geometric measurements from OEM's, due to intellectual property protection, it is necessary for a numerical modelling solution be formulated to predict these clearances. Given that clearances are often specified by the OEM for steady state conditions, an additional desire to predict the clearance behaviour of turbine components during transient events, such as cold start up and load change, is also necessary.

Purpose

The methodology developed in this study uses a novel, paired simulation approach to model the thermal and structural behaviours of a High Pressure (HP) and Intermediate Pressure (IP) turbine during transient events.

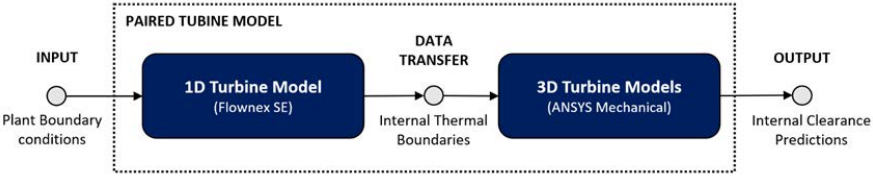

Figure 1: High Level Modelling Methodology

The paired model saw the development of a 1-dimensional, turbine process model, using Flownex SE, in order to derive temperature boundaries of the HP and IP turbines during a full cold start up using reported plant data. These boundaries subsequently were applied to a 3-dimensional FEM turbine model in order to capture the structural behaviour of steam turbine components during the cold start up event.

Theoretical framework

Computational efficiency is central to the comprehensive modelling of steam turbines, particularly during transient events. In the work of Marinescu [1] and Topel [2], both tended towards some form of simplification of either the fluid or solid phenomenon within steam turbines during transient operation. Of interest was the 2-dimensional approach taken by Topel [2], in which a paired modelling approach for solar turbine modelling during start-up was developed. Topel modelled steam expansion within a 1-dimensional MATLAB model, paired with a 2-dimensional COMSOL heat transfer model in order to study off-design start up parameters and the efficiency gains as a result. The findings of this study showed that the paired modelling approach produced results which strongly agreed with measured plant data and reduced computational complexity.

From the work of Fuls [3], an in-house turbine stage component, using the Nozzle Analogy theory, was developed and validated in the work of Clarke [4]. The theory visualises each turbine stage as a series of nozzles (stator and rotor) capturing the temperature gradient of the steam through the main turbine cylinder. This theory was further used in this study.

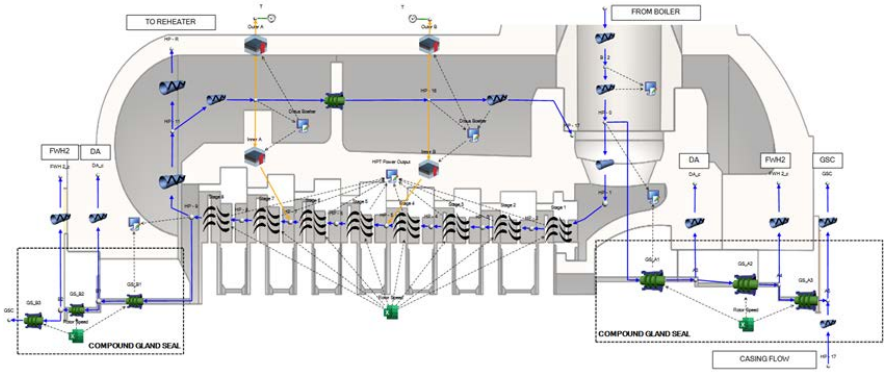

Figure 2: 1-Dimensional High Pressure Turbine Model, generated using Flownex SE

This theory, paired with the capabilities of Flownex SE, allowed for detailed 1-dimensional modelling of peripheral flows within the turbine, as can be seen in Figure 2. In a similar sense to Topel, the results of this model were subsequently applied to a 3-dimensional FEM turbine model, accounting for all of the peripheral flows within the HP and IP turbines.

Results and conclusions

The modelling methodology was tested on a full cold start up procedure on a candidate turbine selected from the Eskom coal-fired power plant fleet. The result of this simulation, using the paired turbine model, achieved accurate results relative to the reported plant data. Figure 3, shows the relative accuracy that the 1-dimensional turbine model had in predicting the exhaust steam from the HP turbine, suggesting a good agreement of the subsequent stage-by-stage temperature gradients predicted by the model.

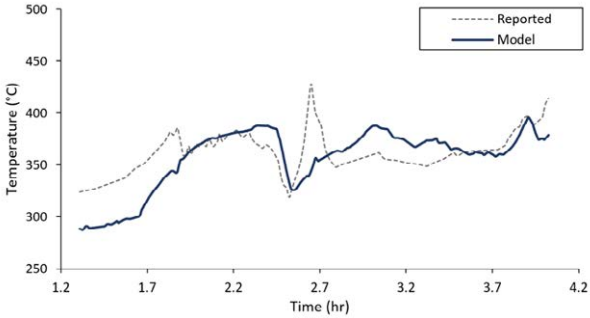

Figure 3: 1-dimensional Model results for HPT Exhaust Steam Temperature

Assessing the results from the FEM models of the HP and IP turbine further allows for one to predict the temperature gradients and the rate of penetration of these gradients through turbine components during start up, as seen in Figure 4.

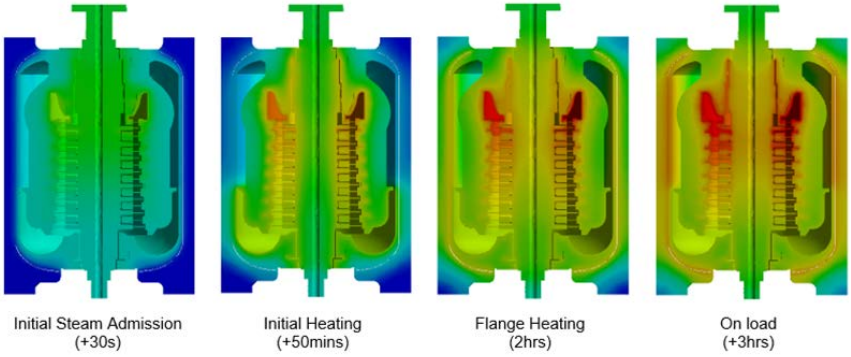

Figure 4: Temperature gradients in HPT during Cold Start Up events

Tracking the temperature at points of interest within the turbine, set to represent thermocouples on the candidate unit, it was confirmed that the paired model had the ability to predict the temperature boundaries and the subsequent heat transfer through turbine components, as shown in Figure 5.

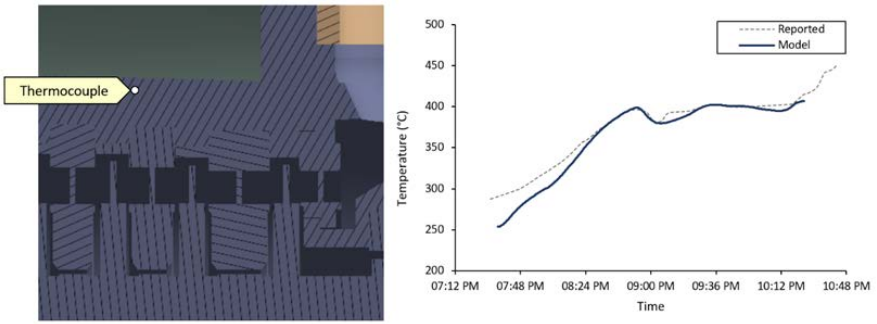

Figure 5: Thermocouple validation of inner casing thermocouple to modelled data

The structural validation of the turbine models was performed against the differential expansion data collected from the candidate unit, which also showed a strong correlation between the modelled and reported data. Figure 6, demonstrates the ability of the model to predict the structural behaviour of the turbine during a cold start within a 5% error, well within the expected accuracy of a numerical model such as this, given the minimal geometric input to the model.

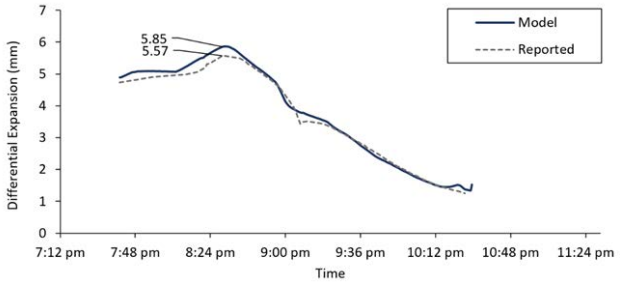

Figure 6: Differential Expansion of HPT against modelled data

From these validations it can be concluded that the paired methodology approach is successful in allowing one to predict the clearance behaviour within an operational turbine.

Implications for Eskom and the power industry in Southern Africa

The implications of such a turbine modelling methodology are the ability for Eskom to perform further investigation into the thermal and structural behaviour of their steam turbine fleet under current and future operating parameters. The ability to model these units within a high degree of accuracy, as presented in this research, allows for these investigations to be performed without the need for large scale OEM input and legislative limitations normally pertaining to after-sale investigations. In a future electrical grid, where turbines will be expected to perform a flexible function the learnings possible through such a methodology would go a long way in managing existing Eskom turbine assets in the future.

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Key words: Turbine modelling, Clearances, Transient modelling, Cold Start Up

Effect of prior austenitisation temperature on creep rupture in Grade 22 steel

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Justification of the project

Prior heat treatment during component manufacture as well as welding procedures in situ will influence the conditioning of austenite during the thermal cycles. Not only will precipitates dissolve and form, but the austenite grain size will grow in proportion to the thermal exposure. Consequently, the microstructure that evolves during cooling, and correspondingly the mechanical properties, will be determined by the combination of phase transformations and diffusion events that occur during the total thermal cycle. The uniaxial tensile creep resistance at 600°C for Grade 22 bainitic steel was measured as function of prior normalisation heat treatment which was carried out in the range 900-1200°C. A decrease in creep rate is favoured by larger prior austenite grain size, but creep ductility is substantially reduced. Of particular interest is the significant difference in creep performance for the 900°C and 1000°C heat treatment conditions. Although the prior austenite grain size is only marginally different for the two conditions, the creep rupture time is substantially longer for the 1000°C condition. Dilatometry tests, which simulate the normalisation thermal cycles, indicate differences in phase dissolution during normalisation and hence it is proposed that variations in solute distribution account for the differences in creep behaviour.

Purpose

The purpose of this study is to explain the relationships developed between normalisation temperature, prior austenite grain (PAG) size, and creep ductility in Grade 22 steel.

Theoretical framework

Grade 22, which is a 2¼Cr-1Mo low alloy ferritic steel, has found application in high temperature-high stress environments, particularly power plant, over many decades stretching back to the mid-1900s. Substitutional elements have a profound influence on the properties of the alloy, although Mo more significantly influences strength and Cr improves oxidation resistance.

However, of no less importance is the role of carbon and the formation of carbides, which stabilise the grain structure during tempering and service ageing. Consequently, the distribution of elements and phases in the steel matrix prior to service will determine the further microstructure evolution and creep behaviour during service. In presenting an historical review of 2¼Cr-1Mo steel, Lundin et al [1] indicate that Mo is by far the most effective element in providing substitutional strengthening of the matrix. At the same time, Mo is a strong carbide forming element and hence, together with Cr and other minor residual elements, complex carbides evolve over time [2,3] that reduce substitutional strengthening but increase grain boundary pinning and hinder motion of dislocations. The net effect is increase in intragranular (matrix) strength, but extended ageing conditions will coarsen the precipitate phases and gradually weaken the microstructure.

Results and conclusions

- Evolution of the intragranular strength during creep testing at 600°C is substantially affected by the normalisation (austenitisation) temperature.
- The normalisation at 900°C results in extensive plastic deformation and in-situ recrystallisation of the bainitic microstructure leading to eventual failure by void coalescence and plastic exhaustion.
- Monitoring of the transformation behaviour during the heat treatment cycles using dilatometry demonstrates the slower than expected dissolution of phases above 900°C. The greater dissolution above 900°C, even up to 1100°C, results in higher solid solution and strengthening of the bainitic microstructure during creep ageing.

Implications for Eskom and the power industry in Southern Africa

Some power plant in South Africa have been operating for over 200 000 hours utilising Grade 22 steel in the form of tubes or pipes within boilers, steam pipes, etc. Repairs to existing installations will result in complex microstructure development in heat-affected zones. Understanding the potential metallurgical risk associated with the creep exposure of the weldments is important in implementing risk-based inspection procedures.

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Key words: prior austenite grain (PAG) size, normalisation heat treatment, Grade 22, bainite, creep ductility, dilatometry

Machine learning structure-property models for low carbon steels

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Justification of the project

Small-punch creep (SPC) testing is used to rank the creep rupture properties of steels used in the petrochemical and power generating industries. This technique, when combined with non-destructive small sampling technologies (Weldcore™), can help to evaluate the remaining life of in-service plant components [1]. In parallel with these efforts, is the development of physical models, aimed at linking the steel microstructures with their mechanical performance, but they are limited by the intrinsic complexity of structure-property relationships. Machine learning (ML) can be used to overcome some of these limitations. Several studies focussing on simulated datasets have shown that this approach works well, but studies on physical data sets are lacking, due to the scarcity of microstructural data linked to the physical testing data [2]. The aim of this project is to apply machine learning techniques to an available small punch creep rupture data set, to train a model that could predict the test result based on an input microstructure alone.

Purpose

A data set consisting of 120 small punch creep rupture tests on low carbon steels was characterised using optical and scanning electron microscopy. The microstructural images were converted into an input feature vector for training against the creep rupture time using various image processing and machine learning regression techniques in order to develop the prediction model.

Theoretical framework

Most applications of machine learning in material sciences to date aim to identify microstructural features using classification. Structure-property predictions require *regression*, where the structural data is converted into a set of input values and then trained to predict target property.

In an earlier study by Westraadt [3] a dataset consisting of 120 low carbon steel microstructures and their associated SPC rupture times was collected from service exposed steels used in the petrochemical industry. Optical micrographs of steel samples were used to train a regression model with the creep rupture time as the target property. While the feature scale considered (largely representing microstructure texture and pearlite volume fraction) had a significant influence on mechanical properties, several samples showed large prediction errors. It is hypothesised that this discrepancy could be due to the multi-scale nature of the microstructure. In the present paper, a selection of samples with the largest testing errors were further investigated using secondary electron imaging to incorporate the finer scaled pearlite sub-structure into the models.

Results and conclusions

This was achieved by classifying the pearlite images taken from the samples according to dominate pearlite type (spheroidised vs lamellar) and adding this additional information to the input feature vector for training the model. The inclusion of the pearlite type significantly reduced the training error for the outlier samples. This result supports the conclusion that creep rupture strength also depends on the finer-scale pearlite type, in addition to the larger-scale microstructure texture and pearlite volume fraction. While the inclusion of multiscale features shows promise, there are practical limitations to their inclusion in standard computer vision techniques. In the current study, the classification of SEM images was a time-consuming manual process. Future work will focus on developing a semantic segmentation processing pipeline to automate the model training into an end-to-end process.

Implications for Eskom and the power industry in Southern Africa

The structure-property ML models can be used as screening tools, identifying microstructures of concern; and can be used to prioritize and/or reduce SPC testing requirements. While the studied microstructure-property dataset was sourced from a petrochemical plant, this statistical approach can easily be modified and applied to other power plant steel families when more data (microstructural and physical property) become available.

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Key words: Structure-property predictions, machine learning, small punch creep-rupture

Measurement of combustion airflow into burners in coal fired plants

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Justification of the project

Combustion optimisation is critical for the purpose of improving the efficiency of coal-fired plants and it also has an influence on the reduction of greenhouse gas emissions. To ensure complete combustion of combustible elements in coal, air is supplied to the furnace in slight excess of the stoichiometric requirements. If combustion air supply into the furnace is less than the required theoretical air, incomplete combustion occurs which results in the emission of carbon monoxide with a possibility of re-ignition which may have disastrous effects on property and personnel [2].

An oversupply of air to the boiler results in a decrease in thermal efficiency due to the loss of otherwise useable heat which is absorbed by the oversupplied oxygen and released through the stack with the other combustion products. To maintain control of secondary air into the burners, the Fossil Fuel Firring Regulations (FFFR) requires the measurement of total combustion air to be maintained to an accuracy of 3% [1]. This is difficult to achieve due to complex duct configuration that results in complex flow patterns.

Purpose

This project analyses the combustion airflow patterns in large ducts at Arnot Power Station which has limited straight runs and changes in cross sectional areas with the aim of identifying the best position for the measurement of secondary air into the furnace. This project also investigates a suitable calibration technique of online airflow measurement devices as required by FFFR.

Theoretical framework

In this project, ANSYS Fluent is used to model the ducts from the air-heater to the inlet into burners. The airflow is then analysed using ANSYS Fluent and the velocity profiles investigated at various positions along the duct run in order to identify a suitable plane where the velocity profile is evenly distributed enough for accurate measurement of the secondary airflow rate. Aerofoils and porous jumps are introduced into the model to modify and evenly distribute the velocity profiles to allow for a more reliable measurement. A 14-hole pitot tube will be employed to measure circulation flow components in the cross-section since this cannot be achieved with conventional pitot tube.

Results and conclusions

From the flow analysis, the velocity profiles variance due to turbulence is high in the duct runs leading into the burners. The high variance indicates that the measurement in a cross-sectional plane in the ducts would yield unreliable measurements. The introduction of an aerofoil to attempt to reduce the cross-section of the ducts where the measurements are taken also yielded a reduced but not satisfactory variance in velocity profiles at the measurement plane which is in the throat of the aerofoil. The introduction of a porous jump media in the ducts yielded satisfactory results in reducing the variance in the velocity components perpendicular to the plane. The investigation concluded that the installation of porous jump is required for a reliable measurement in the ducts. This will be confirmed with measurement campaigns in the actual duct using L-type, S-type and 14-hole pitot traverse measurements.

Implications for Eskom and the power industry in Southern Africa

The results indicate that to have an evenly distributed flow profile for reliable airflow measurement in the large ducts leading into the burners, the installation of a porous jump is required. With a porous jump installed, the 3% accuracy as required by the FFFR can be achieved with confidence.

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Key words: Secondary air, Measurement, ANSYS Fluent, Porous Jump, Ducts, Velocity profile, 14-hole pitot tube, traverse

Separation and combustion characteristics of coal microlithotype particle types

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Justification of the project

Coal is projected to play a significant role in South Africa's power generating capacity for the foreseeable future [2]. However, environmental concerns have been increasing over the associated emissions released during coal combustion [3]. In addition, coal qualities supplied to some South African power stations have declined in recent years and this has resulted in combustion related problems. In order to continue using coal for power generation, it is essential to minimise its impact on the environment and to reduce boiler related combustion problems. This can be achieved by obtaining a better understanding of the combustion characteristics of a new coal source prior to firing. Computational Fluid Dynamics (CFD) models have shown to be accurate in predicting the flow field and gas temperature during coal combustion, however other predicted quantities such as gaseous emissions and burnout have shown to be less accurate in some studies [4]. Burnout predictions are important for estimating the boiler furnace height for new designs and for evaluating potential new coal sources for existing boilers. Due to coal being heterogeneous in nature, pulverising coal for use in power stations produces inter-particle maceral and mineral composition differences which greatly influences the particle characteristics (char combustion, reactivity and unburnt carbon losses). Although these coal particle differences are important, their combustion characteristics are not fully understood, and their individual char combustion effects have not been included in CFD modelling. Eskom R,T&D has automated mineralogical analysis using QEMSCAN or TESCAN and has developed a novel technique to characterise inter-particle maceral and mineral heterogeneity in entire coal particles and classifies each coal particle according to a microlithotype particle type system [5]. The mass distribution of microlithotype particle types have shown to greatly differ for local coals. A better understanding of the char combustion characteristics of microlithotype particle types is expected to lead to the development of better combustion models.

Purpose

The overall aims of this project are to investigate the combustion characteristics and interactions of chars derived from different microlithotype particles types and to derive a method to include these effects into a CFD model to enhance its burnout predictions.

The purpose of this study was to concentrate coal microlithotype particle types and to understand their char combustion characteristics. The CFD model development will be covered in a separate article.

Theoretical framework

Five coals from South Africa and one coal from Poland were sourced for this investigation. Reflux Classifier, Float-sink, De Beers Rhovol and combinations of these processing techniques were evaluated to determine which method could effectively separate and produce sufficient concentrates of microlithotype particles types. The raw and processed samples were submitted for proximate, total sulphur, gross calorific value, true density, particle size distribution and microlithotype defined particle type analyses at R,T&D's Laboratories. In addition, some samples were submitted for petrographic analysis at the University of Johannesburg and the results were compared to R,T&D's QEMSCAN/TESCAN measurements using Bland-Altman plots. The raw (whole) coal and the derived coal/char microlithotype particle concentrates underwent Thermogravimetric Analysis (TGA) at R,T&D to determine their combustion characteristics and the results were post processed to determine peak temperature, maximum reactivity, ignition temperature and burnout temperature using developed Excel algorithms to automate the calculation process. These combustion results were plotted against the sample's microlithotype particle type concentration to determine the relationships.

Results and conclusions

A good agreement was obtained between the TESCAN and petrographic analyses vitrinite measurements. The float-sink method has shown to be better for concentrating coal microlithotype particle types for South African coals. Reflux Classifier processing of the Polish coal produced a high concentration of vitrite80 microlithotype particle type. However, using this technique a much lower enrichment level was achieved with the South African coals. Similarly, a high concentration level (>80%) was not obtained when a South African coal was processed with the De Beers Rhovol machine.

The TGA tests results have indicated that an increase in the proportion of vitrite80 and vitrite60 coal microlithotype particle types have resulted in a decrease in the ignition, peak and burnout temperatures for both the coal and the derived char samples. The opposite trend was noted for the fusinite60 and fusinite coal microlithotype defined particle type tests.

The following are concluded:

- Float-sink processing has shown to be a suitable technique for concentrating coal microlithotype particle types from South African coals. The Reflux Classifier method is suitable for separating out coal microlithotype particle types from Polish coal.
- Ignition, peak and burnout temperatures have shown to be influenced by the mass proportion of certain microlithotype particle types (vitrite80, vitrite60, fusinite60 and fusinite).

Implications for Eskom and the power industry in Southern Africa

In this study, relationships have been determined between coal microlithotype particle type distribution and combustion characteristics (ignition, peak and burnout temperatures). These relationships could be used to predict the combustion characteristics of a new coal source where its microlithotype particle type distribution is known. In addition, the study has highlighted the level of microlithotype particle type enrichment that could be achieved with the Reflux Classifier and Float-sink techniques. Commercial units are available and could potentially be used to improve the coal quality supply to some power stations.

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Key words: coal processing, microlithotype particle types

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