Institution: Cardiff University

Unit of Assessment: Engineering (12)

Title of case study: Enhanced overvoltage protection of electrical systems through improved practices, standards and infrastructure

Period when the underpinning research was undertaken: 2000 - 2020

Details of staff conducting the underpinning research from the submitting unit:

Name(s):	Role(s) (e.g. job title):	Period(s) employed by submitting HEI:
Abderrahmane Haddad	Professor	01/08/1992 – present
Maurizio Albano	Lecturer	23/10/2006 – present
Stephen Robson	Lecturer	08/01/2013 – present

Period when the claimed impact occurred: 01/08/2013 – 31/12/2020

Is this case study continued from a case study submitted in 2014? No

1. Summary of the impact (indicative maximum 100 words)

Overvoltage of electrical systems can cause hazardous working environments, significant damage to infrastructure, and blackouts. Cardiff's research into overvoltage protection has enabled greater reliability and safer working practices in electrical networks through changes to international standards, national policies, and industrial infrastructure. These include:

- defining best practice in International Electrotechnical Commission (IEC) standards for overvoltage protection;
- establishing safer working policies and more effective protection of critical infrastructure through a longstanding collaboration with National Grid, resulting in annual savings of £220,000 and improved performance;
- saving £9.6M for Tata Steel by eliminating flashover events at the UK's largest steelworks plant through application of a Cardiff-designed mitigation solution.

2. Underpinning research (indicative maximum 500 words)

Electrical networks are subject to internal and external voltage and current surges, mainly generated by switching operations, system faults, and lightning strikes. Overvoltage incidents can lead to safety risks on the system and degradation of equipment, which can cause catastrophic failure if not mitigated.

The Cardiff University Advanced High Voltage Engineering (AHIVE) research centre, led by Haddad, has been central to developing expertise and understanding of electrical networks under transient and fault scenarios, addressing insulation reliability, and optimising overvoltage protection. AHIVE's research outputs include:

- optimising network reliability and surge overvoltage protection **[3.1, 3.2]**;
- enhancing earthing systems **[3.3]**;
- designing National Grid insulation systems **[3.4, 3.5]**;
- exploring the replacement of harmful insulation gases **[3.6]**.

In recognition of the research, in 2005, the National Grid Electricity Transmission company selected AHIVE as one of their three company-funded Centres of Excellence for High Voltage Research, renewing this award every five years since.

2.1 Optimised network reliability and surge overvoltage protection

Research on condition monitoring of surge arresters, exploiting the superior qualities of zinc oxide over traditional silicon carbide, led to the development of new methods for monitoring and better assessment of power consumption and losses **[3.1]**. These methods were incorporated in the 2013 revision of International Electrotechnical Commission (IEC) Standard 60099:5 as recommended techniques for monitoring of surge arresters for protection of high-voltage substation equipment. Building on this work, further research on transient network

modelling led to the development of criteria to optimise surge arrester location and insulation co-ordination of transmission systems **[3.1]**.

Furthermore, through new measurement techniques at a live 400kV substation and transient modelling of the network, work on switching overvoltages on cable circuits proved beyond doubt that, if underground transmission cable lines are not directly earthed after de-energisation, high levels of trapped charge voltage remain on the cable circuit over much longer time periods (up to 12 hours) than originally believed **[3.2]**.

2.2 Enhancing earthing systems and safety

AHIVE's characterisation and modelling of earthing systems included the creation of a new Impedance Measurement System (IMS) able to overcome the effects of system noise **[3.3]**. Staged-fault testing – in which a fault is deliberately induced into a system – is rarely conducted in the UK, instead relying on fall-of-potential tests that use low voltage energisation and test currents of low amperes, although results can be difficult to ascertain due to standing voltages in the earthing system.

The AHIVE IMS, based on variable frequency injections using lock-in amplifiers, is able to provide accurate measurements and quantify safety voltages under AC conditions. This was successfully tested at large electrical installations including a generating station and railway supply substation **[3.3]**.

2.3 National Grid-approved insulation systems

Through EPSRC funding **[G3.1]**, AHIVE investigations on textured insulation surfaces **[3.4]** led to optimised patented texture geometries and materials **[3.5]** that are now being exploited (with National Grid funding, £800,000) to develop and trial full insulators up to 400kV, with support from UK manufacturer Allied Insulators. The developed design for textured insulator surfaces improves performance of overhead lines and substations under harsh environmental and pollution conditions **[3.5]**. The project won the 2019 National Grid Chairman's Award for Innovation, competing with 240 entries across UK and US National Grid businesses.

2.4 Mitigating the harm of SF_6 insultation gases

Sulphur hexafluoride (SF_6) is used extensively within electrical insulation of subsystems. It is, however, extremely harmful to the environment, and is a Kyoto-designated harmful SF_6 gas with a Global Warming Potential 23,500 times that of CO_2. Supported by over £3M in funding from National Grid, EPSRC, WEFO and Brush Ltd, Cardiff's collaboration with National Grid led to the identification and characterisation of practical SF_6 replacements including trifluoromethyl iodide (CF_3I) and Novec family gases (Fluoronitriles:$(CF_3)_2CFCN$ and fluorketones:$C5F_{10}0$) **[3.6]**.

3. References to the research (indicative maximum of six references)

[3.1] A Haddad and D Warne (Eds.), 'ZnO Surge Arresters' in: *Advances in High Voltage Engineering,* IET Power and Energy Series, vol. 40, 2004, pp.191-255. PDF.

[3.2] F Ghassemi, S Dennis, A Ainsley, **A Haddad**, **S Robson**, '275 kV cable discharge field measurement and analysis of SVLs chain failure using ATP', *Electric Power Systems Research*, vol.161, 2018, pp.95–102. doi: 10.1016/j.epsr.2018.04.009

[3.3] H Griffiths, P Jones, N Harid and **A Haddad**, 'Proposal for measurement of earth impedance using variable frequency injection', *IOP Measurement Science and Technology*, vol. 21 (8), 2020. doi: 10.1088/0957-0233/21/8/085102

[3.4] A Haddad and RT Waters, 'Insulating Structures', GB Patent 2406225, September 18, 2003.

[3.5] M Albano, P Charalampidis, RT Waters, H Griffiths and **A Haddad**, 'Silicone rubber insulators for polluted environments part 2: Textured insulators', *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 21(2), 2014, pp.749-757. doi: 10.1109/TDEI.2013.004016

[3.6] A Beroual and **A Haddad**, 'Recent Advances in the Quest for a New Insulation Gas with a Low Impact on the Environment to Replace Sulfur Hexafluoride (SF6) Gas in High-Voltage Power Network Applications', *Energies*, 10 (8), 2017. doi: 10.3390/en10081216

Selected grant:

[G3.1] PI: **A Haddad**, 'Textured Insulators for Overhead Lines and Substations', EPSRC EP/F02844X/1. Nov 2008 to April 2012, total value £462,878.

4. Details of the impact (indicative maximum 750 words)

Cardiff's Advanced High Voltage Engineering (AHIVE) research centre applied their research to improve the safe and efficient working of electrical systems. This included:

1. guiding international standards for surge arrester systems;
2. informing extensive changes to National Grid policy, guidance, and strategy;
3. eliminating flashover events in the UK's largest steelworks substation, saving Tata Steel £9.6M.

4.1 Developing International Standards for overvoltage protection

Haddad is the UK's technical expert on International Electrotechnical Commission (IEC) Technical Committee 37 (TC37), responsible for developing and maintaining international standards on surge arresters and surge protection devices. Haddad has twice (2015 and 2018) been nominated and elected by representatives of the group's 44 countries to represent TC37 on the IEC Advisory Committee on Electricity Transmission and Distribution (ACTAD).

In May 2013, the IEC published a major update on the 1998 standard IEC 60099-5 *Surge Arresters Part 5: Selection and application recommendations* **[5.1]** and included Haddad's methods to monitor surge arresters when protecting high-voltage substation equipment, citing five of his publications **[3.1]**. Alongside the published global best practice, CENELEC (European Committee for Electrotechnical Standardization) approved the revised 60099-5 as the European standard, and since September 2013 all 34 members of CENLEC have adopted the IEC text into their own national standard.

The IEC 60099-5 standard was further updated and republished in January 2018 **[5.2]**, with Haddad's methods continuing to be cited, and was adopted into national standards by IEC member states in March 2018. Cardiff research techniques are, therefore, part of the standard procedures used throughout the world to protect high-voltage substation equipment, with the exception of North America which has its own standards.

4.2 Impact on National Grid standards, practices and designs

AHIVE research changed multiple National Grid policies and practices that affect electrical networks across the UK, including the examples detailed below.

a. Best practice when retrofitting transformers with surge arrester

Overvoltage can lead to costs of around £5M to repair or replace each transformer and over £10M to resolve faulty cable systems **[5.3]**. Paul Gallagher, Head of Innovation at National Grid, confirmed that Cardiff research "*was central to National Grid's 2016 revision of the Technical Guidance Note (TGN) 027*" that specifies the safe working proximity when retrofitting surge arresters on transformer replacement schemes **[5.3]**. National Grid implemented TGN 027 in 2020 and noted that this "*has resulted in a reduced risk of failure of plant, and hence improved reliability of the transmission system*" **[5.3]**.

b. Safer working practices near overhead lines

Cardiff's insights also directly affected the safety of overhead lines across the UK, resulting in improved safe working practices: "*Cardiff's research on induced currents and voltages was key input to the recent revision of National Safety Instructions (NSI) 04*" which sets the mandatory rules for any National Grid staff working with, or near, high voltage lines **[5.3]**. The new guidelines affect around 150 overhead line staff, and "*research from Cardiff has helped*

to improve safety precautions while increasing efficiency of work on or near High voltage overhead lines" **[5.3]**.

c. Policies to mitigate trapped cable charges

National Grid switch off cable circuits to control voltage levels during low demand at night, but reactivation can lead to overvoltages from trapped electrical charges on the cable. AHIVE determined that cable circuits may retain significant trapped voltages for more than 12 hours after opening the cable circuit and proposed the solution to completely discharge the cable circuit before re-energisation, effectively removing the threat. This enabled National Grid to "*eliminate the reclosing-type of fault, mitigating the serious impact upon system reliability*" **[5.3]**. This protocol has been implemented across the entire network, and "*directly informed our new design policy for network switching through underground power cables*" **[5.3]**. National Grid confirmed that, as a result of AHIVE's work, "*no failure had occurred on such cable networks since the implementation of this new switching protocol*" **[5.3]** and estimates that improved reliability will save around £220,000 annually.

d. Strategic plans for replacing SF_6 gases

National Grid is exploring alternatives to sulphur hexafluoride SF_6 gases in switchgear, including the use of alternative gases researched at Cardiff. Although SF_6 provides excellent insulation for substations, it has 23,500 times the global warming potential of CO_2. AHIVE's research was adopted by National Grid to inform its strategic investment plan: "*Given Cardiff's expertise, work on alternative gases is informing National Grid on available options for future replacement of SF_6. This further informs policy changes and discussion with Ofgem*" **[5.3]**. Cardiff's research, therefore, set the strategic direction for eliminating these important greenhouse gases.

e. Overvoltage protection of the new T Pylon design

Cardiff research supported National Grid's £840 million project to deliver a new 57km high-voltage electricity transmission line connecting Hinkley Point C Nuclear Power Station. The connection runs through a designated Area of Outstanding Natural Beauty, and National Grid sought to pilot the use of a new T-Pylon design to minimise impact on the local area, replacing the prolific steel tower design. National Grid engaged Cardiff to evaluate the new pylon's overvoltage resilience, noting that the "*insulation coordination work has helped National Grid have confidence in electrical performance of the T-Pylon design*" and how "*Cardiff's research was fundamental to underpinning the insulation coordination and surge overvoltage protection of the new pylons*" **[5.3]**. This work was critical to enabling the use of these new pylons.

4.3 Preventing flashover events in Tata Steel

In 2016, Tata Steel approached Cardiff to investigate the source of substation flashover events at their Port Talbot steelworks. According to Martyn Duggan, the Manufacturing Director at Tata Strip Products UK Hub, flashover events can lead to circuit interruption or "*total black out*", and previously forced an emergency shutdown of the steelworks causing significant disruption to plant production and the wider supply chain **[5.4]**.

Cardiff's investigation indicated that the cause was likely a mix of pollutants on insulator surfaces and early morning condensation. AHIVE proposed a solution to coat all insulators with ambient temperature Vulcanised RTV polymeric coatings, developed with a local business.

Tata Steel confirmed Cardiff's investigation resulted in a complete mitigation of flashover events from the substation: "*Since the implementation of the proposed RTV coating in 2016, no flashover failures have occurred and based on previous experience this would have potentially resulted in two delays, giving rise to an improvement in an economic impact of £6.4M to date and expected to be £9.6m by July 2020, in addition to no process safety incidents*" **[5.4]**.

5. Sources to corroborate the impact (indicative maximum of 10 references)

[5.1] IEC 60099-5: 2013 (BS EN IEC 60099-5:2013). *Surge arresters - Part 5: Selection and application recommendations*

[5.2] IEC 60099-5: 2018 (BS EN IEC 60099-5:2018). *Surge arresters - Part 5: Selection and application recommendations*

[5.3] Testimonial: Paul Gallagher, Head of Innovation, National Grid

[5.4] Testimonial: Martyn Duggan, Manufacturing Director, Tata Steel