Tijdschrift van het NERG

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DE VERENIGING NERG

Het NERG is een wetenschappelijke vereniging die zich ten doel stelt de kennis en het wetenschappelijk onderzoek op het gebied van de elektronica, signaalbewerking, communicatie- en informatietechnologie te bevorderen en de verbreiding en toepassing van die kennis te stimuleren.

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De jaarlijkse contributie bedraagt voor gewone leden € 43,- en voor studentleden € 21,50. Bij automatische incasso wordt € 2,- korting verleend. Gevorderde studenten aan een universiteit of hogeschool komen in aanmerking voor het studentlidmaatschap. In bepaalde gevallen kunnen ook andere leden, na overleg met de penningmeester voor een gereduceerde contributie in aanmerking komen.

HET TIJDSCHRIFT

Het tijdschrift verschijnt vijf maal per jaar. Opgenomen worden artikelen op het gebied van de elektronica, signaalbewerking, communicatie- en informatietechnologie. Auteurs, die publicatie van hun onderzoek in het tijdschrift overwegen, wordt verzocht vroegtijdig contact op te nemen met de hoofdredacteur of een lid van de Tijdschriftcommissie.

Voor toestemming tot overnemen van (delen van) artikelen dient men zich te wenden tot de tijdschriftcommissie. Alle rechten berusten bij de auteur tenzij anders vermeld.

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Voor u ligt het eerste nummer van het Tijdschrift van 2006. Onze oproep voor kopij heeft twee artikelen opgeleverd.

De studierichting elektrotechniek aan de technische universiteit Delft bestaat dit jaar 100 jaar. Naar aanleiding hiervan was er op donderdag 19 januari 2006 een symposium. De rede die emeritus hoogleraar Jan Davidse daar hield is in dit nummer opgenomen.

Rond de tijd dat in Delft de studierichting elektrotechniek van start ging, kreeg Fleming zijn patent op de vacuümdiode. Dit wordt in het algemeen gezien als het ontstaan van het vakgebied elektronica. Emeritus hoogleraar Hans Wallinga van de universiteit Twenthe geeft in dit nummer een overzicht van de ontwikkeling van de diode (zowel de vacuüm- als de halfgeleiderdiode) in de afgelopen 100 jaar. Dit artikel is geschreven naar aanleiding van de themabijeenkomst "100 jaar diode" die op 10 maart 2005 gehouden werd.

Jasper Goedbloed heeft een artikel geschreven dat gaat over reciprociteit en EMC-metingen.

Op woensdag 25 mei 2005 was er een themabijeenkomst over de berging van de Koersk. De voorzitter van de tijdschriftcommissie, Huib Visser, was bereid om een bestaande publicatie (met toestemming van de rechthebbenden) te bewerken tot een artikel voor het tijdschrift.

Ten slotte bevat dit nummer een oproep voor donaties en sponsors van de stichting PHOHI monument. Deze stichting wil op een rotonde in Huizen een monument realiseren. Dit monument is een (verkleinde) replica van de twee masten die deel uitmaakten van het zendstation van de PHilips-Omroep-Holland-Indië (PHOHI) dat zich in Huizen bevond.

Honderd jaar elektrotechniek

J. Davidse

Honderd jaar elektrotechniek. Dat is een aanzienlijk deel van de totale leeftijd van deze technische kunde. Daarmee ontmoeten we al meteen één van haar vele fascinerende aspecten. Bijna alle technische verworvenheden kunnen bogen op een eeuwenlange geschiedenis. Zij vonden hun wortels in het diepe verleden, steunend alleen op intuïtieve kennis van de natuurverschijnselen die eraan ten grondslag lagen. Lang voordat de wetten van de mechanica en de hydrodynamica op formule waren gebracht, slaagden de mensen erin gebouwen en bruggen neer te zetten die niet instortten, en schepen die in de vaart bleven.

Elektrotechniek kent niet zo'n ambachtelijke aanloop. Hoe dat komt is duidelijk: elektrische verschijnselen zijn niet direct zintuiglijk waarneembaar. Technische toepassingen ervan waren pas mogelijk na hun wetenschappelijke exploratie.

Tot het einde van de negentiende eeuw werden de elektrische verschijnselen begrepen in termen van velden en stromen. Deze beschrijvingswijze bood reeds ruime mogelijkheden tot technische applicaties, zowel in de energietechniek als in de communicatietechniek. De elektrische telegraaf werd ervaren als een hoogtepunt van technisch kunnen en de maatschappelijke invloed daarvan was groot: het startpunt van wat we nu noemen het 'global village'. De krachtwerking van de elektrische stroom vormde al spoedig een bedreiging voor de alomtegenwoordige stoomtechniek. Eén van de toepassingen, waarvan nu nauwelijks meer beseft wordt hoezeer zij de architectuur van het stedelijk landschap veranderde, is de elektrische lift, die hoogbouw praktisch mogelijk maakte. De thermische werking van de elektrische stroom legde de basis voor een revolutie in de lichttechniek. Geloofde men halverwege de negentiende eeuw dat de toen tot bloei komende gasverlichting een nauwelijks meer te overtreffen mirakel was, het zou alras blijken dat dit mirakel slechts korte tijd repertoire zou houden. Het elektrische licht verkreeg ook al snel de status van een mirakel, met misschien wel mysterieuze gevaren, getuige de bijgaande gebruikersinformatie in een Amerikaans hotel. Onze huidige zorg over gezondheidsrisico's van elektrotechnische producten is niet uniek.

Aan het einde van de negentiende eeuw kwam een inzicht tot rijping dat opnieuw een grote invloed zou hebben op de samenleving. Bepaalde natuurkundige experimenten lieten zich alleen verklaren op basis van een geheel nieuwe zienswijze, die zich baseerde op de opvatting dat elektrische lading een corpusculair karakter bezit. Dit concept opende de weg tot geheel nieuwe domeinen van technisch kunnen. Het elektron deed zijn intrede in het denken. De kunst van het dresseren van elektronen kreeg pas later een naam: elektronica. Al kwam de naam later, als geboortejaar van deze wereldveroveraar wordt algemeen het jaar 1906 gekozen, het jaar waarin Lee de Forest de vacuümtriode uitvond: de eerste elektronische versterker.

Dat de elektronica zich zo explosief kon ontplooien is te danken aan een unieke eigenschap van het elektron, te weten de extreem hoge waarde van zijn specifieke lading: $1{,}76 \cdot 10^{11}$ C/kg. Deze unieke fundamentele eigenschap maakt het mogelijk elektronische structuren te vervaardigen die

- zeer snel zijn; elektronici praten ongegeneerd over nanoseconden en picoseconden;
- met zeer weinig vermogen toekomen; opnieuw weer nano en pico;
- zeer weinig materiaal vragen; chips bevatten miljoenen tot miljarden elementaire structuren in een volume in de orde van mm^3.

Daar komt nog bij dat het verreweg belangrijkste werkmateriaal het onuitputtelijk beschikbare silicium is, het op één na meest voorkomende element op aarde.

De technologische expansie mag daarmee verklaard zijn, maar vanwaar de enorme verscheidenheid van toepassingen en de onvoorstelbare invloed daarvan op de samenleving? Elektronische structuren bieden de mogelijkheid tot het manipuleren van elektrische stromen en spanningen. Omdat die altijd een bepaalde betekenis hebben, spreken we van 'signalen' (Lat. signum = teken). Signalen dragen informatie en zijn vermogen tot omgaan met informatie is één van de pijlers van het succes van de menselijke soort in de evolutie. Een tweede pijler is zijn vermogen tot het naar zijn hand zetten van energetische hulpbronnen. En dat zijn nu juist de speerpunten van de elektrotechniek!

De mogelijkheden van de elektronica tot transport en manipulatie van informatie brachten een nooit eerder vertoonde expansie van systemen voor communicatie en voor informatiebewerking op gang, die een totale reorganisatie van maatschappelijke infrastructurele systemen tot stand brachten. In een tijdsbestek van amper een halve eeuw heeft de samenleving zich totaal afhankelijk gemaakt van de voortbrengselen van deze techniek. Als morgen alle transistorstructuren hun dienst zouden weigeren, zou de dynamiek van de samenleving nagenoeg tot stilstand komen. Auto's zouden niet meer rijden, treinen evenmin. Vliegtuigen zouden aan de grond blijven staan. Geen telefoon, geen TV, geen internet, geen geldverkeer. Liften zouden stilstaan, een groot deel van de gezondheidszorg zou plat gaan. Pikant detail: alle moderne wapensystemen zouden op slag de status van schroot verwerven.

Om misverstanden te vermijden zij terzijde opgemerkt dat deze geweldig expansie niet alleen te danken is aan de inspanningen van pure elektrotechnici. In heel veel moderne technische systemen is de bijdrage van de informatici volstrekt onmisbaar. Elektrotechniek en informatica zijn twee handen op één buik. Terecht zijn beide disciplines thans ondergebracht in één faculteit. Maar vandaag richt het focus zich op de elektrotechniek en het kan trouwens niet ontkend worden dat deze het voor alle systemen onmisbare materiële substraat heeft voortgebracht. Dat is trouwens evenzeer van toepassing op de scheppingen van de elektrische energietechniek, die onder meer de gehele infrastructuur van de elektriciteitsvoorziening omvatten.

De implicatie van deze status quo is dat een hypothetisch verlies van de beheersing van deze kunde niet minder dan een ramp zou betekenen. Hier komt de opleiding van elektrotechnici in beeld en daarmee het jubileum dat ons vandaag bijeenbrengt. Alvorens de aandacht te richten op de honderdjarige geschiedenis van de Delftse opleiding, wil ik u graag eerst bepalen bij een tweetal conclusies die uit het voorgaande getrokken kunnen worden.

Ten eerste: op elektrotechnici rust een grote verantwoordelijkheid. Hun kunde is onmisbaar voor de betrouwbare werking van een alomvattende maatschappelijke infrastructuur. Zij komt op vele wijzen de samenleving zeer ten goede, maar zij kan ook gebruikt worden voor de totstandkoming van de meest perverse en misdadige vernietigings- en machtsmiddelen. De opleiders mogen zich daarom niet onttrekken aan de plicht om de ogen van hun studenten hiervoor te openen. Technici willen nog wel eens de verantwoordelijkheid voor wat er met hun scheppingen wordt gedaan volledig afschuiven op de exploitanten. Natuurlijk rust eveneens op hen een grote verantwoordelijkheid en het is ook waar dat de leverancier van de technische middelen meestal weinig ruimte heeft om misbruik te voorkomen. Als de één niet wil meewerken, dan wel de ander. Maar de technicus kan tenminste bijdragen aan de discussie over het gebruik van zijn inventiviteit en door zijn deskundigheid kan hij consequenties doorzien die een technische leek ontgaan.

Ik heb in deze faculteit jarenlang een eerstejaars college elektronica verzorgd. Ik had de gewoonte het eerste college te beginnen met een beschouwing over de aard van het vakgebied, zijn maatschappelijke implicaties en de daaruit volgende verantwoordelijkheid van zijn beoefenaren. Van zo'n bijdrage moet je niet teveel verwachten, maar hoe dan ook, behoort ingenieursethiek aandacht te hebben in de opleiding.

Het tweede punt: omdat de samenleving zich totaal afhankelijk heeft gemaakt van systemen die afhankelijk zijn van een elektrotechnisch substraat, zal zij ervoor moeten zorgen dat er steeds in voldoende mate mensen zijn die daarmee kunnen omgaan en deze verder uitbouwen. Dat wordt enerzijds beseft, gezien de vele klaagzangen op het tekort aan bèta-interesse, anderzijds niet serieus genomen. Iedere potentiële student weet dat de studie als zwaar geldt. Ook dat je bij behaald succes weliswaar mag rekenen op een behoorlijk gehonoreerde baan, maar niet zo goed als die van functies die bekleed worden door abituriënten van als minder zwaar bekend staande opleidingen. Waarom een ingenieur worden als je met minder inspanning zijn chef kunt zijn?

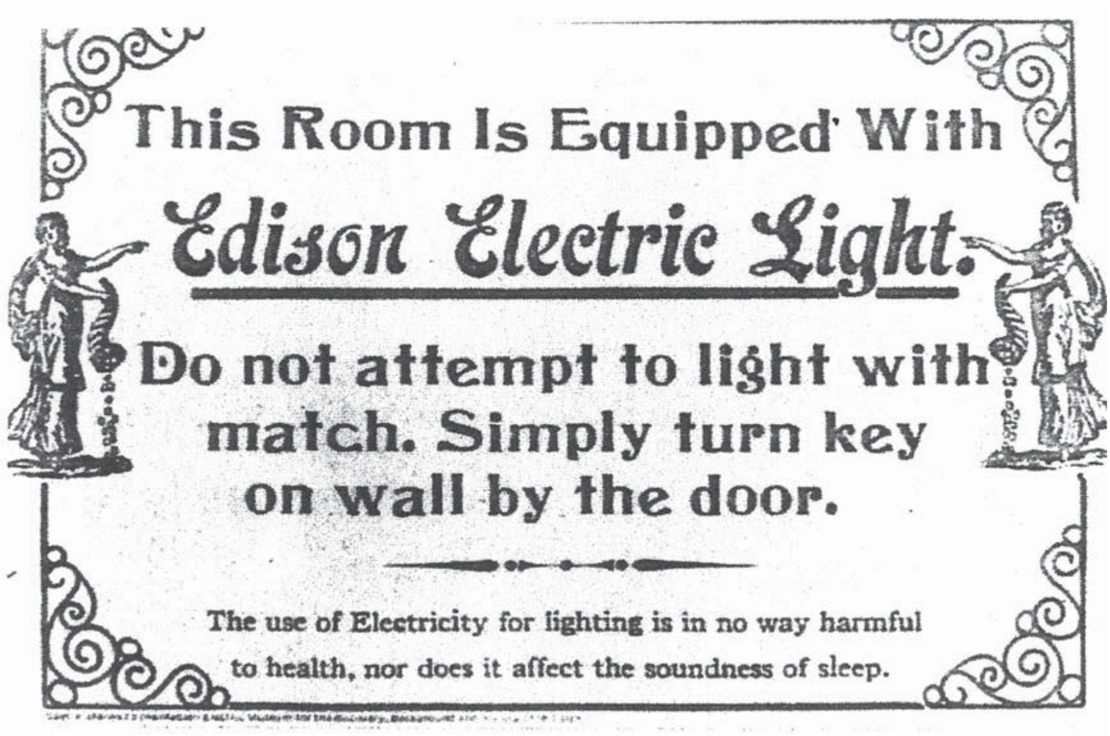
Men zal mij tegenwerpen: dat is altijd zo geweest, zo zit de wereld nu eenmaal in elkaar en het heeft in het verleden toch niet ontbroken aan mensen die kozen voor deze studie. Waarom deden ze dat? In de tijd dat ik aantrad als student in deze faculteit was de mensheid gefascineerd door de als bijna magisch ervaren prestaties van de jonge techniek. Nog nauwelijks bekomen van het ene wonder, diende zich alweer een volgend aan. Ik noemde al de telegraaf. Een volgend wonder was de telefoon. Inmiddels had elektrisch licht zijn intrede gedaan. Dan komt in de beginjaren van de twintigste eeuw de draadloze communicatie op gang, gevolgd door de radio-omroep. De maatschappelijke betekenis hiervan laat zich nauwelijks overschatten. Iemand als Hitler had dit goed door. Geen wonder dat hij ervoor ijverde het radiotoestel tot gemeengoed te maken. En het hield niet op. Televisie, radar, cybernetica... Het ging maar door. Als jongen met een beetje technische aanleg, wist je zeker dat je erbij wilde zijn. Toen ik aan mijn studie begon, merkte ik al gauw dat zeker de helft van mijn medestudenten hobbyist was en bezeten van de drang om meer te weten te komen en mee te doen. Echter, vandaag de dag is de fascinatie verdwenen. Het wordt volstrekt normaal gevonden dat je, terwijl je op het strand ligt te zonnen, je vriendje in Melbourne kan bellen en dat je in Kaapstad uit een willkeurige geldautomaat geld kunt pinnen. De enorme infrastructuur die achter al die verworvenheden ligt, is onzichtbaar. Het is er gewoon. Net zoals het gewoon gevonden wordt dat uit een klein zaadje een grote boom groeit. Dat leidt ook niet tot een run op de opleidingen in de botanie.

Conclusie: als je nu jongeren wilt interesseren voor een studie als elektrotechniek kun je geen beroep doen op de magie van het vak. De aanpak zal zakelijker moeten zijn en de status van de competente technicus meer in overeenstemming met zijn onmisbaarheid.

Dan nu de directe aanleiding tot dit symposium: honderd jaar Delftse opleiding tot elektrotechnisch ingenieur.

De start van deze opleiding valt samen met de verheffing van de Polytechnische School tot Technische Hogeschool met een universitaire status. Met de instelling van deze opleiding liep Nederland bepaald niet voorop. In landen als Duitsland en de Verenigde Staten bestonden zulke opleidingen al ruim twintig jaar. De nieuwe opleiding kon van meet af aan beschikken over een nieuw gebouw in neogothische stijl naar een kortdurende architectonische mode. De opleiding startte goed met een voor die tijd modern programma. Een vooraanstaand trekker was prof. Feldmann, die veel heeft betekend voor de elektrificatie van Nederland. De geschiedenis van de opleiding heeft ups en downs gekend. Na een goede start zwakte het elan in het tweede decennium af. Met name kwam onderwijs in de snel in betekenis toenemende communicatietechniek niet adequaat van de grond. In de dertiger jaren kwamen er, dankzij de inspanningen van mensen als Bähler en Elias vernieuwingen tot stand. Het bestek van deze voordracht biedt geen ruimte om de geschiedenis van de opleiding in detail te volgen. Wie zich hierin wil verdiepen raadplege het door de faculteit uitgegeven boek 'Spanning'. Na de oorlog brak er een periode aan van aanzienlijke groei, zowel in het aantal studenten als in de veelzijdigheid van het onderwijsaanbod. Toch bleef te lang een aanzienlijke werktuigbouwkundige component, met name in het propedeutisch curriculum domineren. Nawerking van een voorbije fase, waarin dit accent verdedigbaar was. Het heeft lang geduurd aleer het curriculum een adequate afspiegeling was van de actuele stand van de techniek.

Memorabel is de totstandkoming van een nieuw gebouw, dat nog altijd het tehuis is van de opleiding. Het werd offcieel in gebruik genomen in 1969. Een universitaire faculteit heeft tweeërlei opdracht: onderwijs en onderzoek. De tweede opdracht is vele decennia nauwelijks aan bod gekomen. Aan de onderwijsopdracht is, soms met enig horten en stoten, steeds in redelijke mate inhoud gegeven, zij het dat de grote autonomie van individuele docenten de efficiëncy van de aanpak soms wel in de weg zat. Gaandeweg werd die autonomie beteugeld, mede onder druk van de toenemende invloed van de studenten. Dit mag beschouwd worden als een vrucht van het democratiseringsproces, dat overigens weinig goeds heeft gebracht met zijn onvoorstelbaar inefficiënte vergadercultuur. Na omstreeks 1970 ontstond er een nieuw elan om te gaan streven naar onderzoek



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Bron: 'Geschiedenis van de techniek in Nederland', deel 3. Uitg. Stichting Historie der techniek, Walburg Pers.,1993.

op internationaal niveau. Eén van de instrumenten daartoe was het activeren van een promotiecultuur. Beperkte zich het aantal promoties tot circa 1970 tot gemiddeld minder dan één per jaar, in de negentiger jaren was dit aantal toegenomen tot circa 40 per jaar. De uitrusting van de laboratoria groeide naar een niveau dat naar internationale maatstaven de toets der kritiek kon doorstaan. Dit was te danken aan enerzijds forse investeringen van de zijde van de overheid en van de wetenschapsfondsen, waarvoor overigens stevig geknokt moest worden; anderzijds aan de aanzienlijke opbrengsten van samenwerking met industriële partners. Het resultaat mag er zijn. Een recente internationale studie, gepubliceerd in 'Electronic Engineering Times', plaatst Delft in een ranking van ingenieursopleidingen op de zevende plaats. In Europa staan alleen Cambridge en München hoger op deze ranglijst. We doen het blijkbaar niet zo slecht. Dat wisten we trouwens al uit de contacten met buitenlandse bedrijven die voor bepaalde specialisaties actief werven onder onze afgestudeerden. Handhaven van dit niveau gaat niet vanzelf. Het vereist voortdurende geconcentreerde inspanning. Daar gaat de faculteit voor.

Wat zal het tweede centennium brengen? De potentie van de toepassing van de elektrische verschijselen is nog lang niet uitgeput. Misschien zal een spreker bij gelegenheid van dit tweede centennium verkondigen dat het eerste centennium niet meer dan een prelude was. Een prima vooruitzicht.

De diode in historisch perspectief

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De honderdste verjaardag van het octrooi van Fleming op de vacuümdiode is een goede aanleiding voor aandacht aan de diode als basiselement in de elektronica. De diode is het oudste van de niet-lineaire elektronica elementen en daarmee wordt de introductie van de vacuümdiode vaak gezien als het begin van de discipline elektronica [1]. In feite ontstaat een dergelijk vakgebied echter gaande weg en het beste argument om de start van de elektronica te laten samenvallen met het diode octrooi is het scherp traceerbare moment van dit gebeuren. De oorsprong van de metaal-halfgeleider diode is door zijn vele verschijningsvormen veel minder duidelijk gemarkeerd maar ligt in feite ver voor 1900. De junctiediode (pn-overgang) volgt pas na de uitvinding van de transistor door Shockley, Brattain en Bardeen in 1947.

Vooral sinds de eerste geslaagde poging van Marconi met draadloze telgrafie over het Engels Kanaal in 1897, is er naarstig gezocht naar gevoelige en betrouwbare detectoren voor radiogolven. Het eerste octrooi voor een vorm van Radar dateert van 1904 [2]. Rond 1900 ontstaan er veel ideeën over toepassing van radiogolven en dat het begin van de elektronica daarmee geassocieerd wordt ligt alleszins voor de hand.

Het belang van de diode is hierbij groot, ook gezien het feit dat de elementaire diode terug te vinden is in de constructie van vrijwel alle andere niet-lineaire elektronische devices, ongeacht of we de elektronica met vacuümbuizen of de moderne halfgeleiderelektronica beschouwen. In beide gevallen is het meest eenvoudige versterker element (respectievelijk de triode en de transistor) samengesteld uit een of meer diodes. Daarnaast is de diode zelf ook in verschillende toepassingen uitgegroeid tot een zeer specifiek en krachtig device, zoals ook uit andere bijdragen, gewijd aan het thema diode, blijkt. Het is boeiend om bij de honderdste verjaardag van de vacuüm diode aandacht te schenken aan het historisch perspectief rondom de ontwikkelingen van dit basiselement.

Maatschappij en techniek

Na de ontdekking van de elektromagnetische inductie (Faraday 1831) deden de dynamo en de elektromotor hun intrede in de laatste helft van de 19^e eeuw. Dit leidde tot de tweede industriële revolutie. In Europa werd de elektrotechniek op grote schaal geïntroduceerd door Siemens (generatoren en elektromotoren in fabrieken, elektrische trams). In 1889 werd in Den Haag de eerste elektriciteitscentrale in Nederland geopend waarin acht dynamo's van Siemens elektriciteit produceerden. De Eerste Nederlandse Elektrische Tram Maatschappij liet de eerste Elektrische tram met bovenleiding lopen in 1898, maar in Den Haag liepen al sinds 1890 elektrische accu trams.

Dankzij de constructie van goede vacuümpompen komt er ook een maatschappij brede toepassing van de gloeilamp in zicht. De praktische gloeilamp met een redelijke brandduur van Edison stamt uit 1880 (US patent 223898) en is rondom de eeuwwisseling nog volop in ontwikkeling. Edison richtte een industrieel laboratorium (Menlo Parks) in en stichtte de Edison Electric Light Company in 1878 (in 1892 gefuseerd tot General Electric). In 1847 startte Siemens met de 'Telegraphen-Bauanstalt von Siemens & Halske' in Berlijn en 'Philips gloeilampen fabriek' werd opgericht in 1891.

Om snel een beeld van de techniekontwikkeling in deze periode te krijgen is een tabel met in het oog lopende octrooien uit de 19^e eeuw behulpzaam (tabel 1). De tabel is geenszins uitputtend, de onderwerpen zijn gekozen vanwege de beeldvorming in de ontwikkeling van de techniek.

Tabel 1. Octrooien 19e eeuw.

1837	Thomas Davenport	Electric motor
1839	Samuel Colt	Revolver
1840	Samuel F.B. Morse	Telegraph
1855	Isaac Singer	Sewing Machine
1869	Leigh Burton	Elec. resistance heater
1872	William Robinson	Elec. train signalling
1873	Louis Pasteur	Pasteurization
1873	Thomas Edison	Improved telegraph
1873	Louis Pasteur	Yeast process
1874	Alexander Graham Bell	Telephone
1879	Charles Brush	Carbon arc light
1880	Thomas Edison	Electric light
1884	George Eastman	Photographic film
1886	Elihu Thomson	Electric welding
1887	Carl Gassner	Dry cell battery
1888	Nikola Tesla	AC synchronous motor
1888	Nikola Tesla	Alternating current transmission
1888	Nikola Tesla	Electric distribution
1890	Nikola Tesla	Electric generator
1895	Rudolf Diesel	Diesel engine
1897	Guglielmo Marconi	Wireless telegraph
1900	Nikola Tesla	Wireless transmission of electric power

Het is ook interessant om enkele voorafgaande natuurkundige ontwikkelingen in bredere zin in het tijdsbeeld te plaatsen (tabel 2). De elektromagnetische wisselwerking en golfvoortplanting stonden volop in de belangstelling maar kennis en begrip van materialen kon nog niet worden verkregen door het ontbreken van een goed atoommodel. De EM-theorie was gebaseerd op golfvoortplanting in de ether, maar elektriciteit werd meestal als transport van geladen deeltjes gezien. Het is verbazingwekkend dat elektriciteit aan het eind van de 19e eeuw op zo grote industriële schaal technisch werd toegepast en benut, terwijl ze nog zo weinig begrepen was.

Tabel 2. Enkel grote natuurkundigen en hun bijdragen vóór 1900.

Gilbert	1544-1603	benoemt elektrostatische kracht (ηλετρον = barnsteen)
Coulomb	1736-1806	elektrische lading kwantificeerbaar (eenheid van lading) Coulombkracht
Watt	1736-1819	Stoommachine
Volta	1745-1827	depositie van lading bij elektrolyse, Voltacel
Ampère	1775-1836	onderlinge kracht stroomvoerende draden
Ørsted	1777-1851	wisselwerking tussen magneet en stroom (1820)
Ohm	1789-1854	eenheid van weerstand
Faraday	1791-1867	Materietransport bij elektrolyse (eenheid van capaciteit). Inductie (1831), elektrische en magnetische veldlijnen
Joule	1818-1889	stroomvoerende draad ontwikkelt warmte
Kirchhoff	1824-1887	serie en parallel stroomwetten
Maxwell	1831-1879	wiskundige formulering veldtheorie
Röntgen	1845-1923	Röntgenstralen, kristalstructuren (1901)
Lorentz	1853-1928	Lorentz-kracht; verwevenheid deeltjes-golven (1902)

Geïnspireerd door de beschikbaarheid van elektriciteit en de nieuwsgierigheid naar een goede verklaring, de mogelijkheid om vacuüm te pompen en door het succes van de gloeilamp werd er veel geëxperimenteerd met vacuümbuizen waarin spanningvoerende elektrodes waren ingebracht. Kathodestralen en Röntgenstraling werden ontdekt. Het elektron zelf kwam pas aan het eind van de 19e eeuw in beeld nadat Thomson in 1897, uit uitvoerige experimenten met kathodestralen had geconcludeerd dat deze stralen bestonden uit lichte, geladen deeltjes. Hij berekende de lading/massa verhouding van het elektron. Overigens hadden Zeeman en Lorentz enkele maanden eerder uit hun experimenten met spectraalverbreding onder invloed van magneetvelden ook geconcludeerd dat er een geladen deeltje met een massa 1600 maal kleiner dan die van een waterstofatoom in het spel moest zijn [3].

Na kracht en licht komt de communicatie aan bod. De wetten van Maxwell zijn geformuleerd in 1865 en radiogolven worden toegepast in de draadloze telegrafie. Voor de voortplanting van elektromagnetische golven wordt nog ether als noodzakelijk medium gedacht. Het etherprobleem wordt opgelost wanneer Einstein in 1905 publiceert dat de fysische wetten en de voortplanting van EM-golven onafhankelijk is van het inertiaal referentie stelsel.

Er was rond 1900 grote belangstelling voor de invoering van de draadloze telegrafie (Marconi, 1897) waarbij vooral behoefte was aan een gevoelige detector van elektromagnetische golven.

De vacuümdiode

Het gebrek aan natuurkundig inzicht in het verschijnsel elektriciteit kan verklaren waardoor de vacuümdiode pas in 1904 wordt geoctrooieerd, terwijl in en rondom de gloeilamp al veel eerder allerlei verschijnselen zoals kathodestralen waren waargenomen, die op emissie van geladen deeltjes wijzen. Eén van de vele octrooien van Edison [4] (Electrical Indicator, US patent nr. 307,031, 1884) beschrijft al gloeilampen waarin naast de twee stroomvoerende draden van het filament een derde elektrode is aangebracht waarmee metingen kunnen worden uitgevoerd die spanningsveranderingen over het filament aangeven. Dit staat bekend als het 'Edison Effect' en Edison noemde de buis, die ook werd gepatenteerd, 'electric indicator'. De toepassing als gelijkrichter werd daarbij echter niet onderkend. Ook de kathodestraalbuis was al langer bekend. De laatste decennia van de 19e eeuw werd veel met kathodestraalbuizen geëxperimenteerd o.a. door Hittorf, Crookes, Lenard, Röntgen, Braun en Thomson. Karl Ferdinand Braun construeerde in 1897 de eerste kathodestraalbuis waarmee hij afbeeldingen op een fluorescentie scherm kon maken. In 1905 ontving Philipp Eduard Anton Lenard zelfs de Nobelprijs van de Natuurkunde voor zijn werk op het gebied van kathodestralen.

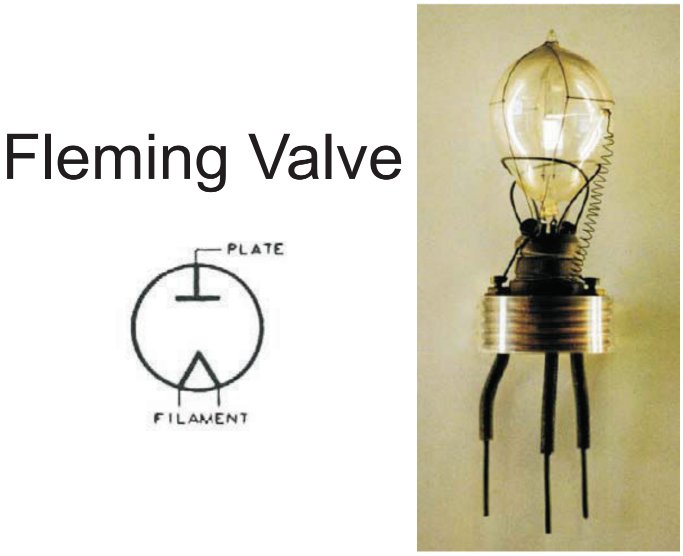
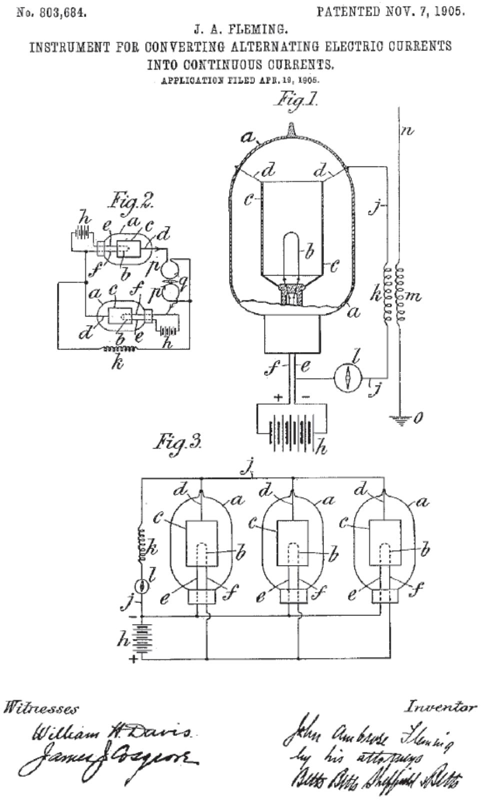


Fig.1 De vacuumdiode [5] zoals door Fleming in 1904 ontwikkeld

De vacuümdiode is in 1904 geoctrooieerd (toegekend in november 1905) door John Ambrose Fleming. Fleming (1848-1945) [1] was een Engelse ingenieur die aanzienlijk heeft bijgedragen aan de ontwikkeling van de elektronica, onder andere op het gebied van de fotometrie, elektrische metingen en draadloze telegrafie. Hij werd geboren in Lancaster en groeide op in Londen als zoon van een dominee. Na zijn studies aan het University College London en Cambridge University werd hij consultant voor Edison Electric Light Company en

Fig. 2. Schets bij het US octrooinummer 803,684 patented van Fleming "An Instrument For Converting Alternating Electrical Currents Into Continuous Currents", http://www.jmargolin.com/history/803684.pdf



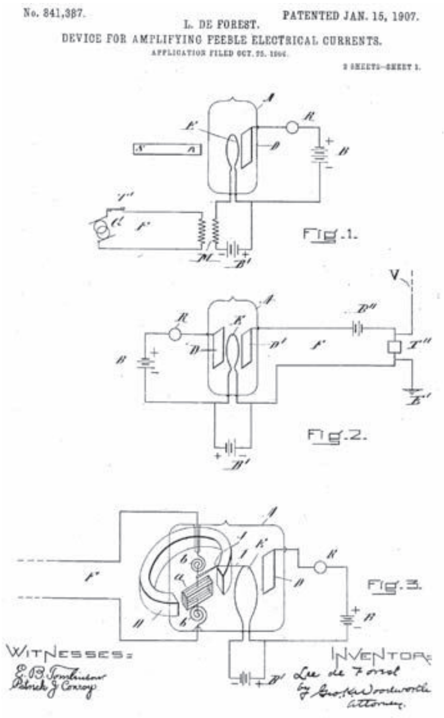


Fig. 3 Schets bij US octrooinummer 841,387, patented Jan. 15, 1907.
L. De Forest.' Device for Amplifying Feeble Electrical Currents'. application filed Oct. 25,1906.

later adviseur bij Marconi Wireless Telegraph Company. Van 1885 tot 1926 doceerde hij aan het University College Londen, waar hij, waarschijnlijk als eerste ter wereld, benoemd werd als hoogleraar Elektrotechniek.

Het octrooi van Fleming [5] (Fig.2), toegekend in 1905, beschrijft vooral de toepassing van het buizenelement als gelijkrichter. Flemings vacuüm diode buis bestaat uit een gloeidraad (kathode) en een koude anode. Uiteraard moest er nog een jarenlange ontwikkeling doorgemaakt worden om tot een goed produceerbaar en betrouwbaar element te komen. Als vervolg op Flemings diode komt Lee de Forest in 1906 met de uitvinding van de triode [6] (Fig.3), die hij Audion noemde. Hij plaatste tussen de kathode gloeidraad en de anode een draad gevouwen scherm, het rooster en kon daarmee de gevoeligheid van de diode als gelijkrichter verbeteren. De Forest had zelf nog niet in de gaten dat hij zijn triode als versterkerelement kon gebruiken.

Lee De Forest was een gewiekste zakenman. Hoewel hij van de werking van de triode niet veel had begrepen genereerde hij vele octrooien, voortbouwend op de triode. Er blijken ook veel patentgeschillen juridisch uitgevochten te worden en de commerciële toepassing wordt zelfs vertraagd door de octrooigeschillen tussen Fleming en De Forest.

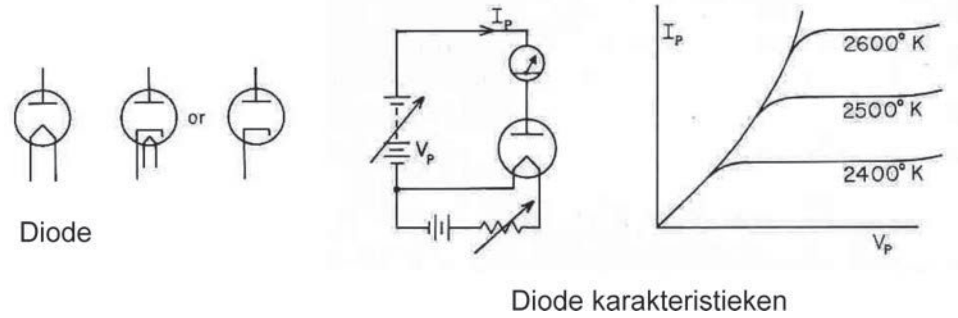
In Fig.4 zijn de meest gebruikte symbolen voor de vacuümdiode en de karakteristieken weergegeven. De emissiestroom J is de maximale emissiestroom per oppervlakte, waarbij W de uittree-energie van het kathodemateriaal is. De diodestroom in voorwaarts is in eerste instantie ruimteladings begrensd en is bij eenvoudige buisgeometrie een 3/2 macht van de anodespanning V_p.

De mogelijkheden van de triode als versterkerelement werden pas in 1911 door Edwin Armstrong onderkend en dit gaf een grote impuls aan de elektronica. De buizenelektronica is in de jaren zestig/zeventig van de vorige eeuw vrijwel geheel vervangen door de transistorelektronica en later de microelektronica. De buizentechniek heeft nog lang stand gehouden in de TV cameratechniek

Fig. 4 Symbolen en karakteristieken van een vacuümdiode

Thermische emissie (Richardson): $J = A_0 T^2 e^{W/kT}$

Diode stroom: $I = K V_p^{3/2}$



(Plumbicon). Een echte volhouder was de kathodestraalbuis in TV monitoren, waarvoor de vervanging door platte beeldschermen pas in deze (21ste) eeuw is doorgebroken.

Metaal-Halfgeleider diodes

Er werd eind 19^{e} eeuw niet alleen met vacuümbuizen geëxperimenteerd. Al in 1876 vindt Braun [7] dat een scherpe metaalpunt op loodglans (galena, loodsulfide) raadselachtige afwijkingen van de wet van Ohm en gelijkrichtende werking vertoont. Merkwaardigerwijs octrooieert hij deze bevinding niet. De constructie van een metaalnaald op een halfgeleidend mineraal wordt later 'cat-whisker' genoemd en zal veel gebruikt worden in detectiekringen voor radiosignalen. Braun gaat dit in 1899 toepassen als detector in zijn eigen telegrafie bedrijf TeleBraun (door fusie wordt dat Braun-Siemens en later Telefunken). Niet alleen bij loodglans maar ook bij selenide en diverse andere mineralen zoals zilversulfide, pyriet (ijzersulfide) en koperpyriet, en bij platinum elektroden in elektrolyt oplossingen werd gelijkrichtende werking geconstateerd. A.F. Khan schreef een lezenswaardig artikel over de vele halfgeleiderelementen die aan het eind van de 19^{e} eeuw werden onderzocht en gebruikt [8].

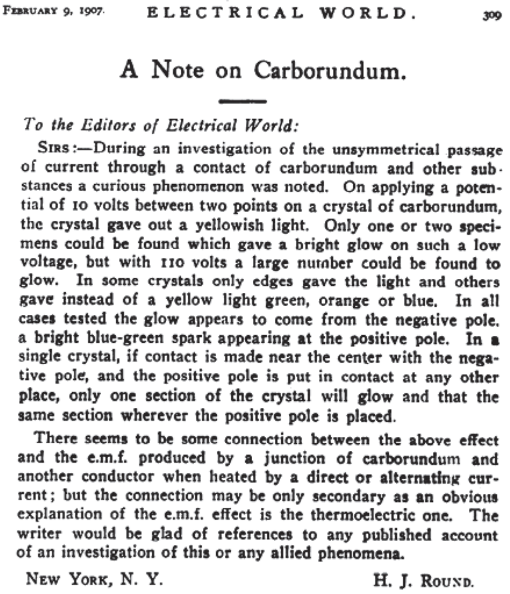
Van 1902 tot 1906 vond Pickard dat met siliciumkristallen, maar ook met ongeveer 250 verschillende mineralen, een gelijkrichtende functie verkregen kon worden, wanneer zij tussen metaalcontacten worden geklemd. In 1906 octrooieert hij een detector schakeling voor radiogolven [9] waarin een silicium puntcontactdiode als actief element is opgenomen. Pickard noemt dit een 'thermo-electric regenerative detector', maar hij onderkent wel de gelijkrichtende werking van dit device. We zien in deze periode vaker dat metaal halfgeleider contacten vanwege hun thermo-elektrische eigenschappen bestudeerd en gepatenteerd worden, waarbij de gelijkrichtende eigenschappen slechts terzijde worden vermeld. Eveneens in 1906 wordt een octrooi (US nr. 837,616) toegekend aan H.H.C. Dunwoody [10], getiteld Wireless Telegraph system, waarin o.a. een Silicium-Carbide puntcontact diode wordt beschreven. In zijn octrooi noemt hij dit een wave-response device. In een overzichtsartikel door H. Winfield in 1917 [11] worden 15 verschillende detector elementen voor de radiografie genoemd. Hieronder zijn de vacuümdiode en de triode, maar alle andere 13 elementen berusten op halfgeleidermineralen of elektrolyten. De vacuümbuizen bleken tot 1915 nog erg onbetrouwbaar maar daarna werden ze in professionele apparatuur steeds meer toegepast. Dit kon vooral doordat de fysica van de elektronenemissie al snel meer houvast gaf voor de optimalisatie van de vacuümbuis constructie en door de sterke verbetering van vacuüm technieken. Ook betere materiaalkeuzes voor de elektroden leidden tot bruikbare en betrouwbare buizen.

Hoewel de metaal-halfgeleider puntcontactdiode vooralsnog black magic was, werd hij in de beginperiode van draadloze communicatie veel meer toegepast dan de vacuümdiode. In 1927 octrooieert Grondahl een koper-koperoxide gelijkrichtend element [12] en de selenium gelijkrichter wordt in Duitsland door Siemens geïntroduceerd. Vanwege het feit dat zij grotere contactoppervlakken hebben dan puntcontactdiodes worden de koperoxide en selenium gelijkrichters vooral gebruikt voor vermogenstoepassingen zoals het opladen van accu's.

Pas nadat Rutherford en Bohr hun atoommodellen hadden gepresenteerd nam de kennis over vastestoffen en halfgeleiders in de jaren dertig snel toe. Inmiddels slaagde men er ook in om halfgeleidermaterialen in steeds zuiverder samenstelling te synthetiseren, waardoor er een grotere reproduceerbaarheid ontstond. In 1931 publiceerde Wilson zijn theorie over ladingstransport in halfgeleiders en in 1938 kwam Walter Schottky met zijn diffusie theorie, waarmee hij ook de metaal-halfgeleiderdiode kon verklaren. T. Jenkins [13] geeft een aardig overzicht van de geschiedenis van halfgeleiderdevices. Het onderzoek aan metaal-halfgeleiderdiodes werd sterk bevorderd door de behoefte aan snelle detectoren voor de ontwikkeling van radar. In de dertiger jaren werd op verschillende, meest militaire, onderzoekcentra aan radar gewerkt om vijandige indringers te detecteren. Engeland had hierbij een voorsprong en de samenwerking met de VS en Canada op dit gebied is van grote invloed geweest op het verloop van de tweede wereldoorlog.

Behalve niet-lineaire stroom-spanningskarakteristieken aan halfgeleiderconstructies werden ook andere effecten ontdekt, getuige het volgende citaat uit 1907 [14] (zie figuur 5).

De geobserveerde luminescentie in siliciumcarbid kan beschouwd worden als de eerste beschrijving van een Light Emitting Diode (LED). Dus ook de



FEBRUARY 9, 1907. ELECTRICAL WORLD. 309

A Note on Carborundum.

To the Editors of Electrical World:

SIRS:—During an investigation of the unsymmetrical passage of current through a contact of carborundum and other substances a curious phenomenon was noted. On applying a potential of 10 volts between two points on a crystal of carborundum, the crystal gave out a yellowish light. Only one or two specimens could be found which gave a bright glow on such a low voltage, but with 110 volts a large number could be found to glow. In some crystals only edges gave the light and others gave instead of a yellow light green, orange or blue. In all cases tested the glow appears to come from the negative pole, a bright blue-green spark appearing at the positive pole. In a single crystal, if contact is made near the center with the negative pole, and the positive pole is put in contact at any other place, only one section of the crystal will glow and that the same section wherever the positive pole is placed.

There seems to be some connection between the above effect and the e.m.f. produced by a junction of carborundum and another conductor when heated by a direct or alternating current; but the connection may be only secondary as an obvious explanation of the e.m.f. effect is the thermoelectric one. The writer would be glad of references to any published account of an investigation of this or any allied phenomena.

NEW YORK, N. Y. H. J. ROUND.

Figuur 5

LED heeft bijna honderd jaar geleden al het licht gezien.

De junctie diode of pn-overgang

Pas na de ontdekking van de puntcontact transistor door Shockley, Brattain en Bardeen in 1947 nam de kennis en ontwikkeling van halfgeleiderdevices snel toe [15]. Na de tweede wereldoorlog werd op vele laboratoria onderzoek verricht om een versterkerelement in halfgeleidermateriaal te ontwikkelen. Na de ontdekking bij Bell Labs werden op vele fronten onderzoekprogramma's aangepast en productie van halfgeleiderdiodes en transistoren opgestart. Aanvankelijk was germanium het favoriete materiaal maar vooral na de komst van de Metaal Oxide Silicium transistor (Kahng en Atalla, 1959) [16] werd silicium op grote schaal het uitgangsmateriaal. Uiteindelijk biedt de pn-junctie een grote flexibiliteit waardoor een geweldige variatie aan toepassingen mogelijk wordt. Er kan geoptimaliseerd worden voor eigenschappen zoals: vermogen, snelheid, doorslagspanning, lichtgevoeligheid, zonnecel ed.

Fig.6 laat bekende representaties zien uit een hedendaags tekstboek [17].

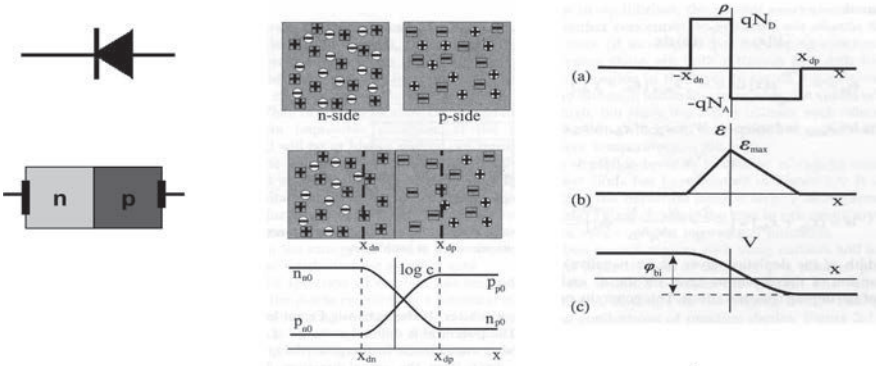
De stroom-spanningskarakteristiek van een junctiediode wordt gegeven door

$$j = j_n + j_p = gn_i^2\left[\frac{1}{N_A}\frac{D_n}{L_n} + \frac{1}{N_D}\frac{D_p}{L_p}\right]\left[\exp\left(\frac{qV_A}{kT}\right) - 1\right]$$

Het subscript n duidt op elektronen en p op gaten met D = diffusiecoëfficiënt, L = diffusieweglengte, N_A en N_D zijn respectievelijk de acceptor dotering van het p-type halfgeleider en de donordotering van het n-type materiaal, n_i is de concentratie van vrije elektronen in het intrinsieke halfgeleider materiaal en V_A is de aangelegde diode spanning. Uit deze formule kunnen we concluderen dat de I-V karakteristiek exponentieel en onafhankelijk is van de materiaalkeuze en doteringen, maar dat de voorfactor sterk afhankelijk is van de keuze van het halfgeleidermateriaal en de gekozen doteringen. Hiermee zijn de diode eigenschappen in grote mate toe te spitsen op de eisen die door de specifieke toepassingen (Fig.7) worden opgelegd.

Fig.8 laat een grafiek van de logI-V karakteristiek van verschillende diodetypes zien. De germaniumdiode 1N34A spant daarbij verreweg de kroon. Opvallend is dat de oude SiC diodes ook zeer goed presteren en dat de karakteristiek van de Fleming diode zeer matig is. De curves met code 6X4 t/m RCA UX200 zijn vacuümdiodes of triodes.

Fig.6 pn-overgang Symbolen; donor en acceptorconcentraties (grijs) en vrije ladingdragersconcentraties symbolisch weergegeven en op logaritmische schaal geplot; ruimtelading, veldsterkte en interne potentiaal in de ruimteladingslaag; in formule: de elektronenstroomdichtheid.



$$j_n = qD_n\frac{dn_p}{dx} + qn\mu_n E$$

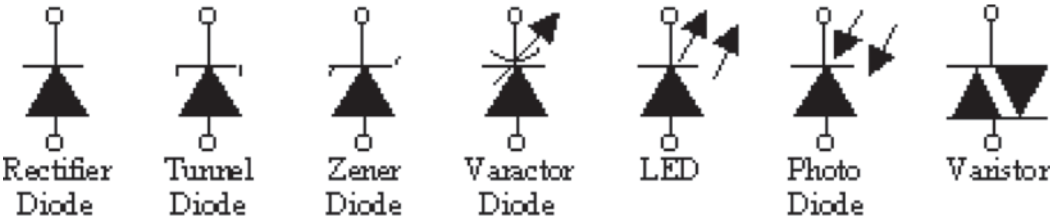


Fig.7 Een aantal specifieke diode symbolen voor diverse toepassingen.

Nawoord

De aanleiding voor een historische terugblik op de diode was de 100e verjaardag van het octrooi op de vacuümdiode. Hoewel de technologie van de buizenelektronica inmiddels volledig achterhaald is heeft zij er wel voor gezorgd dat tot de jaren 70 van de vorige eeuw, massacommunicatie beschikbaar kwam voor het grote publiek. Pas toen een goede materiaalbeheersing het mogelijk maakte om betrouwbare halfgeleidercomponenten te fabriceren kwam de grote evolutie van de microelektronica. De digitalisering tengevolge van de grote, en alom beschikbare, rekenkracht ligt aan de basis van onze huidige maatschappij.

De directe rol van de diode als gelijkrichter is daarbij van ondergeschikt belang geworden. Tenzij ze ten behoeve van een zeer specifieke toepassing uit bijzondere materialen zijn gemaakt of in bijzondere behuizing verpakt moeten worden, zullen diodes meestal onderdeel zijn van een geïntegreerde schakeling. Het gros van het aantal diodes is nodig als essentieel onderdeel van de transistor (BJT) of aansluitelektrode (MOST). Bekijken we de prijsontwikkeling van alle diodes (dus vooral als onderdeel van een transistor), dan is de prijs per diode gedaald van 1 US $ in 1968 tot 10^{-7} US $ in 2004.

Het aantal impliciete diodes dat in 2004 is geproduceerd bedraagt het astronomische getal van $2{\cdot}10^{18}$. Om een voorstelling bij deze hoeveelheid te krijgen: het betekent dat er per wereldburger 10 diodes per seconde worden gemaakt. In onze westerse wereld consumeren we een veelvoud hiervan per hoofd van de bevolking. Hoewel de vacuümdiode de elektronica heeft ingeluid is het duidelijk dat de microelektronica op basis van de halfgeleiderdiode verantwoordelijk is voor de gigantische ontwikkeling van alle communicatie en multimedia producten en netwerken die de maatschappij in de laatste decennia zo sterk hebben veranderd.

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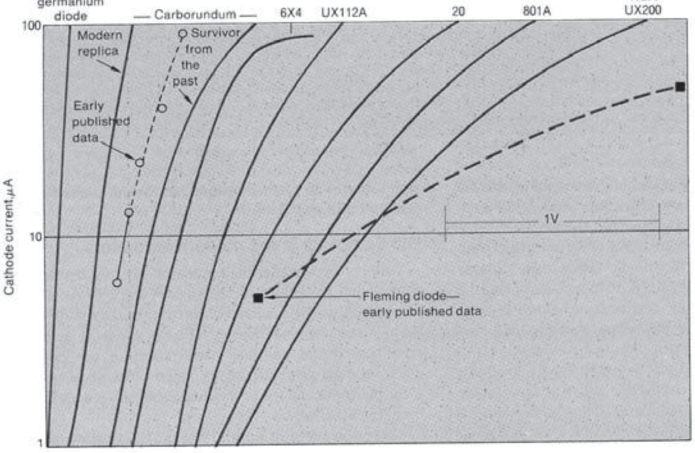
Fig.8 logI-V karakteristieken van diverse historische diode [18].



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Algemeen: Zoals al uit de referentie lijst blijkt, is bij de voorbereiding van de voordracht (en dit artikel) veelvuldig gebruikt gemaakt van het internet. Interessant is de site http://www.uspto.gov/ waarop alle US octrooien beschikbaar zijn, zij het dat de zoekfunctie voor octrooien verleend voor 1975 niet werkt en men alleen het octrooi kan opvragen met een bekend octrooinummer.

Intensief geraadpleegde interessante websites zijn o.a.:
http://www.uspto.gov/
http://www.jmargolin.com/history/trans.htm
http://www.acmi.net.au/AIC/TV_TL_COMP_2.html
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Reciprocity and EMC measurements

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Abstract: Reciprocity theorems for electrical networks and electromagnetic fields allow us to better understand the mechanisms that play a role in EMC measurements or to facilitate EMC measurements. This tutorial paper presents the theorems and their accompanying mathematical relations. Quite a number of rather simple but relevant examples demonstrate their usefulness in the field of transfer function and conversion measurements, antenna factors, radiated emission and immunity measurements, and shielding effectiveness.

1 Introduction

In 1928 the radio pioneer Stuart Ballantine wrote: "Among the tools of thought and artifices by which man forces his mind to give him more service, perhaps the most intensely useful are the simple mathematical rules of inversion known *as reciprocity theorems*" [1]. His words have not lost their meaning today. This paper aims to present reciprocity theorems useful in the field of EMC measurements in a tutorial way, that is limiting the theory to a level that allows a reasonable understanding of the relations used in the applications. We also present quite a number of rather simple applications to demonstrate the service given by these theorems.

The reciprocity theorems discussed here are in no way new and in a tutorial paper it can do no harm to mention several of the original (historical) publications, particularly since these publications offer the reader quite interesting discussions about the 'ins and outs' of these theorems. There are some famous names connected with the reciprocity theorems for use in experimental physics, in this case EMC measurements. In experimental physics, perhaps the earliest theorem is that about the reversibility of light rays, published in 1866 by Hermann von Helmholtz in his famous *Handbuch der Physiologischen Optik* [2]. This theorem springs to mind when considering the reciprocity of shielding effectiveness.

In 1877 Lord Rayleigh published his theorem dealing with electrical networks in his famous book *The Theory of Sound* [3]. This theorem is of importance when transfer functions (transfer impedance, filter attenuation, site attenuation, etc.) of linear passive networks have to be measured (Sections 2 and 3).

The reciprocity theorem for electromagnetic fields (Section 4) was formulated in 1895 by Hendrik Antoon Lorentz (Nobel Prize winner in 1905) [4, 5] and then seemingly almost forgotten for quite some time. Following Guglielmo Marconi's success in 1895 in demonstrating the possibility of sending and receiving signals using electromagnetic waves, radio communication research boomed. A reciprocity theorem for electromagnetic fields was very much needed, particularly to understand the behaviour of transmitting and receiving antennas. As 'Necessity is the Mother of Invention', John R. Carson of Bell Labs 're-invented' the theorem in 1924 [6] as did H. Pfrang in his Ph.D. thesis in Germany in 1925. Pfrang's results were used by his professor Arnold Sommerfeld in a publication in 1925 [7], where Sommerfeld also writes: "My friend M. von Laue (Nobel Prize winner in 1918, author's note) raised the surmise that this theorem could be found in the early work of H.A. Lorentz about electromagnetic waves. It indeed turned out that exactly 30 years ago Lorentz has published a beautiful and general theorem from which Pfrang's results can easily be derived." The 'connection' between the field reciprocity theorems formulated by Lorentz, Carson and Sommerfeld-Pfrang was made by Ballantine in 1928 [1].

Today, Lorentz's original publication is rather difficult to read since vector analysis had yet to be 'invented' in 1895, making his notation rather difficult to understand. In 1921, M. Abraham published his book *Theorie der Elektrizität* [8] the first chapter of which, written by A. Föppl, is devoted to vector analysis. It is most interesting to read Abraham's arguments in the introduction to his book of why vector analysis should be used in electromagnetic theory. Although the book was written in German, it is very clear from the many references made to this book that there was no language problem in the old days and, furthermore, that vector analysis was (and still is) a very useful tool, also used by Lorentz in his later publications [5]. Still, in the 1920's vector analysis was quite new and in [6] Carson writes in a foot note: "In the following proof it is necessary to assume a knowledge on the part of the reader of the elements of vector analysis; the notation is that employed by Abraham". Today the publications by Carson, Ballantine and Sommerfeld are quite readable if you bear in mind that in their days the system of units was not the same as our current system.

Ballantine, whose name lives on in the Stuart Ballantine Medal [9], published a most important application of the field reciprocity theorem [10], referring to important work carried out by Raymond M. Wilmotte [11] of the National Physics Laboratory in the U.K. (Section 5). As we will show below, this application leads to a hybrid reciprocity theorem that is of importance when considering antenna factors, radiated emission and immunity measurements, shielding effectiveness and uncertainties in EMC measurements (Section 6). Here the meaning of 'hybrid' is that, mathematically, the theorem is expressed in terms of voltage and current, on the one hand, and in electric and magnetic field components, on the other hand.

More recent literature on these reciprocity theorems can be found in [12, 15], for example, where due attention is given to the mathematics. A contemporary derivation of the hybrid reciprocity theorem used in this paper can be found in [16], for example. The material presented here was published earlier in Dutch, in a series of short articles in the journal of the Dutch EMC/ESD Society [17].

2 Kirchhoff networks

This section considers quasi-stationary linear passive electrical networks that do not contain devices that make use of the properties of magnetized ferrites, such as circulators. If electric and magnetic fields play a role, their action is contained in lumped elements and/or network parameters that describe field coupling such as the mutual inductance. In other words, we consider networks that obey the two Kirchhoff laws, so that in the remainder of this paper we will refer to these networks as Kirchhoff networks. The reciprocity theorem discussed here interrelates two states of one and the same Kirchhoff network, where the states are determined by the terminations of that network.

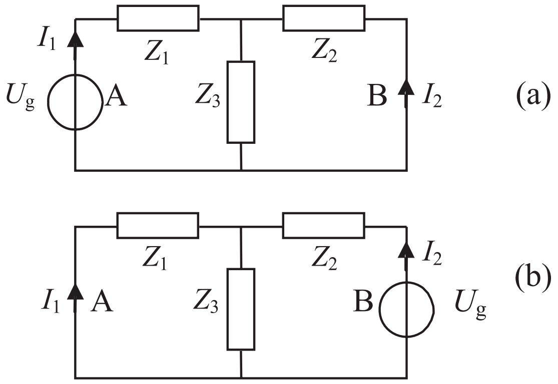


Fig.1 Network to illustrate the reciprocity theorem.
(a) e.m.f. U_g at A and current measurement at B,
(b) e.m.f. U_g at B and current measurement at A.

Lord Rayleigh, who formulated his reciprocity theorem rather generally in terms of forces and motions, presents various applications [3] and writes:

> "A further example may be taken from electricity. Let there be two circuits of insulated wire A and B and in their neighborhood any combination of wire circuits or solid conductors in communication with condensers. A periodic electromotive force in the circuit A will give rise to the same current in B as would be excited in A if the electromotive force operated in B".

This formulation hardly differs from that used today when introducing this reciprocity theorem, normally referring to the two circuits shown in Fig.1:

> 'If an e.m.f. U_g at the location A in a Kirchhoff network causes a current I_2^a to flow at point B in that network then a current $I_1^b = I_2^a$ will flow in point A after placing the e.m.f. U_g at the location B in that network.'

The superscripts a and b refer to the two states depicted in Figs. 1a and 1b. In more extended networks more than one e.m.f. may be present that also contribute to the current in the considered point. The theorem, however, only applies to that part of the current that is caused by the considered e.m.f.. It is very easy to verify that $I_1^b = I_2^a$ by calculating both currents. It then follows that

$$I_2^a = \frac{Z_3 U_g}{Z_1 Z_2 + Z_2 Z_3 + Z_3 Z_1} = I_1^b \qquad (1)$$

The given formulation of the reciprocity theorem is true enough but it is not very suited for use in further considerations. The step is therefore made to the general expression that describes the reciprocity of an N-port Kirchhoff network. As proven in [6, 18]

$$\sum_{k=1}^{N} U_k^a I_k^b = \sum_{k=1}^{N} U_k^b I_k^a \qquad (2)$$

where, again, the superscripts a and b correspond to two states that are determined by the terminations of the network and can be chosen arbitrarily within the conditions that apply. Equation (2) contains combinations of the voltages in one state (a or b) and the currents in the other state (b or a). As such, Eq.(2) has little to say. It only comes alive when N and the states a and b have been chosen. Before doing so, Eq.(2) is checked (not proven), in particular because the 'recipe' used shows great similarities with the one used in the derivation of the expression describing the reciprocity theorem for electromagnetic fields (see also Eq.(24)).

The most simple network is a one-port (N=1) formed by an impedance Z. In such a case Eq.(2) reduces to $U_1^a I_1^b = U_1^b I_1^a$ and the correctness of this equation can be verified in a rather trivial way. Assume in the a-state the voltage across Z is given by $U_1^a = Z I_1^a$, and in the b-state by $U_1^b = Z I_1^b$. The left and right hand member of the first equation are now multiplied by I_1^b so that $U_1^a I_1^b = Z I_1^a I_1^b$ and, equally, the second one by I_1^a so that $U_1^b I_1^a = Z I_1^b I_1^a$. Subtracting the second equation from the first one yields the relation being demonstrated: $U_1^a I_1^b = U_1^b I_1^a$.

To check the general expression, Eq.(2) is first written in vector/matrix form

$$[I^b]^T [U^a] = [I^b]^T [U^b] \qquad (3)$$

where the subscript T denotes the transposed matrix. In this notation, Ohm's law leads to $[U^a]=[Z][I^a]$ in the a-state and to $[U^b]=[Z][I^b]$ in the b-state. In a similar way as with the one-port, the first equation is multiplied by $[I^b]^T$ and the second one by $[I^a]^T$. The result of these multiplications is (note that the order of the terms is now always of importance)

$$[I^b]^T [U^a] = [I^b]^T [Z][I^a] \qquad (4a)$$

and

$$[I^a]^T [U^b] = [I^a]^T [Z][I^b] = \{[I^b]^T [Z]^T [I^a]\}^T \qquad (4b)$$

where in Eq.(4b) we have made use of the matrix property $[X]^T[Y]^T[Z]^T=\{[Z][Y][X]\}^T$. If $[Z]=[Z]^T$, as is the case in an N-port Kirchhoff network, Eq.(3) and hence Eq.(2) directly follow after subtracting Eq.(4b) from Eq.(4a).

3 Applications (1)

This section presents four examples that connect the reciprocity theorem for Kirchhoff networks to EMC-measurements. The examples pay particular attention to the transfer impedance, filter attenuation, the conversion of a differential-mode (DM) voltage into a common-mode (CM) current and to site attenuation. In all examples Fig.2 applies and N=2, but the applications are not limited to N=2. For example, if cross-talk between parallel lines is considered, N=3 or even higher may give useful information.
If N=2, Eq.(2) reduces to

$$U_1^a I_1^b + U_2^a I_2^b = U_1^b I_1^a + U_2^b I_2^a \qquad (5)$$

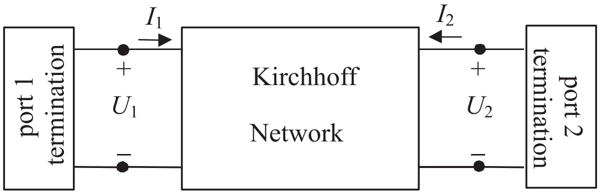
In fact in Fig.1 N=2 also applies. There $U_1^b = U_2^a = 0$ $U_1^a = U_2^b = U_g$ and substitution into Eq.(5) shows again that $I_1^b = I_2^a$.

3.1 Transfer impedance

The transfer impedance is the ratio of the voltage (e.m.f.) induced in a current loop by the current in another current loop. A typical example is the cable transfer impedance that characterizes the EMC behaviour of a cable (the cable 'leakage').

When applying Eq.(5), the termination at port 1 (see Fig.3) in the a-state is a current source of strength I_1^a and port 2 is open circuited, i.e. $I_2^a = 0$. In the b-state, a current source I_2^b terminates port 2 while port 1 is open circuited, i.e. $I_1^b = 0$. Hence, Eq.(5) reduces to $U_2^a I_2^b = U_1^b I_1^a$ or, expressed in the transfer impedances Z_{12} and Z_{21}

Fig.2 A two-port Kirchhoff network with a termination at each port that depends on the chosen application.



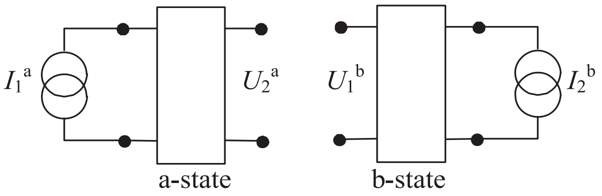


Fig.3 The two states when discussing the transfer impedance

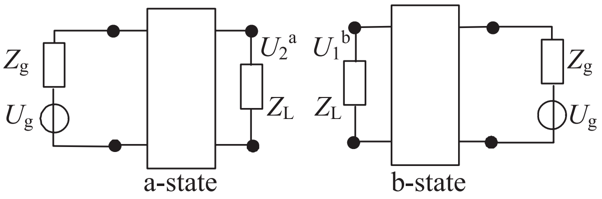
$$Z_{21} = \left.\frac{U_2^a}{I_1^a}\right|_{I_1^a=0} = \left.\frac{U_1^b}{I_2^b}\right|_{I_1^b=0} = Z_{12} \qquad (6)$$

So the cable transfer impedance is reciprocal if the cable behaves as a Kirchhoff network. The cable is always passive and is always linear at most practical signal levels, as long there is no magnetic material in the cable construction. If magnetic material is used, the current (e.g. the CM current on the cable) must be verified to make sure that it is so low that no saturation of the magnetic material results. When measuring the transfer impedance it is often very difficult, if not impossible, to sufficiently satisfy the condition $I_1^b = 0$ or $I_2^a = 0$ at high frequencies, so that the measurement result has to be corrected for this non-zero current effect. Section 6.7 on interference prediction demonstrates another application of the transfer impedance concept.

3.2 Filter attenuation

In the case of filter attenuation measurements, a source (e.m.f. U_g, internal impedance Z_g) is connected via a filter to the load impedance Z_L. A well known question related to filter attenuation is: 'Does it matter which of the filter ports is connected to the source and which port is connected to the load of that source?' If the filter itself is not purely symmetrical, the EMC engineer will answer that question with 'Yes', although he or she will not be able to demonstrate this using a 50Ω measuring system (generator and voltmeter having equal impedances, e.g. $Z_g=Z_L=50\Omega$). The latter can be verified as detailed below.

Fig.4 The two states when discussing the filter attenuation



Assume that in the a-state port 1 is terminated by the source and port 2 by the load, and the reverse termination holds in state b (see Fig.4). If U_0 is the voltage across Z_L in the absence of the filter, the filter attenuation $A^a = U_2^a / U_0$ in the a-state and $A^b = U_1^b / U_0$ in the b-state. So here it is relevant to consider the ratio $A^a / A^b = U_2^a / U_1^b$. At the terminations the following relations are valid

$$\begin{aligned} U_1^a &= U_g - I_1^a Z_g \\ U_2^b &= U_g - I_2^b Z_g \\ U_1^b &= -I_1^b Z_L \\ U_2^a &= -I_1^a Z_L \end{aligned} \qquad (7a\ 7d)$$

From Eqs.(7c) and (7d) it follows that $U_2^a / U_1^b = I_2^a / I_1^b$ and Eqs.(5) and (7) yield

$$\frac{A^a}{A^b} = \frac{I_2^a}{I_1^b} = \frac{I_1^a(Z_g - Z_L) - U_g}{I_2^b(Z_g - Z_L) - U_g} \qquad (8)$$

The attenuation will be independent of the choice of source port and load port if $A^a / A^b = 1$. In all other cases $A^a / A^b \neq 1$ and relative impedance values will determine the choice of the source and load port of the filter [19].

The condition $A^a / A^b = U_2^a / U_1^b = I_2^a / I_1^b = 1$ is met if $I_2^b = I_1^a$ and/or $Z_g = Z_L$. It is well known that the condition $I_2^a = I_1^b$, that simultaneously makes $I_2^a = I_1^b$, is met in the case of a purely symmetrical filter; the reciprocity theorem was not needed to demonstrate this. However, the condition $Z_g = Z_L$ resulting in $A^a / A^b = 1$ is sometimes overlooked as noted in Section 6.3. Moreover, it is this condition that explains why the engineer will measure no difference in the attenuation if source and load port are interchanged when using a 50Ω measuring system.

Of course, another path could also have been followed to arrive at the two conditions representing $A^a = A^b$. The Kirchhoff network can be characterized by a T-network and U_2^a / U_1^b can be expressed in the network impedances Z_1, Z_2 and Z_3 (see Fig.1). After straight forward calculations it then follows that

$$\frac{U_2^a}{U_1^b} = \frac{Z_2 Z_L + Z_1 Z_g + Z^2}{Z_1 Z_L + Z_2 Z_g + Z^2} \qquad (9)$$

where $Z^2 = Z_1Z_2 + Z_2Z_3 + Z_3Z_1 + Z_3Z_g + Z_gZ_L + Z_3Z_L$. The condition $Z_1 = Z_2$ then represents the purely symmetrical filter and, again, the condition $Z_g = Z_L$ represents the 50Ω measuring system.

3.3 DM/CM conversion

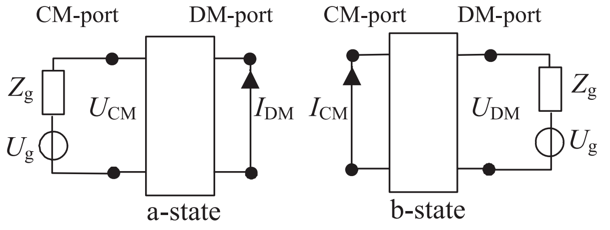
The application of a reciprocity theorem may change an unsuccessful measurement into a successful one. An example is the measurement of the conversion of a differential-mode (DM) voltage into a common-mode (CM) current to characterize the emission properties of a telephone subscriber line or a power line to which a digital-signal is applied. The DM voltage U_{DM} is supplied by the digital signal, and the resulting CM current I_{CM} is a direct measure of the radiated emission capability of such a line. This measure can be expressed in a conversion admittance $Y_{CM} = I_{CM}/U_{DM}$.

To measure this conversion over a certain frequency range, e.g. 0.1 MHz - 30 MHz, it seems rather obvious to apply a DM voltage to the line and to measure the resulting CM current. However, the line is also a relatively efficient receiving antenna and ambient fields will induce CM currents that may be of the same order of magnitude as the CM currents being measured, or possibly even larger. Another problem might be the correct measurement of a DM voltage at the higher end of the frequency range. Both problems can be circumvented by applying a CM voltage U_{CM} to the line and measuring the resulting DM current I_{DM}, i.e. by determining the conversion admittance $Y_{DM} = I_{DM}/U_{CM}$. The reciprocity theorem can now be used to find the condition leading to $Y_{CM} = Y_{DM}$.

The line being characterized can be considered as a two-port network where port 1 is the CM port and port 2 the DM port, see Fig.5. The following choice of terminations in the a- and b-state is now possible. In state a, representing the determination of Y_{DM}, port 1 is terminated by the voltage generator and a high impedance FET probe measures $U_1^a = U_{CM}$. Port 2 is short-circuited ($U_2^a = U_{DM} = 0$) and a current probe around the short circuit measures $I_2^a = I_{DM}$. In state b, representing the determination of Y_{CM}, port 2 is terminated by the generator and port 1 by the short circuit. In this case Eq.(5) reduces to $U_1^a I_1^b = U_2^b I_2^a$, so that

$$Y_{CM} = \frac{I_{CM}}{U_{DM}}\bigg|_{U_{CM}=0} = \frac{I_{DM}}{U_{CM}}\bigg|_{U_{DM}=0} = Y_{DM} \tag{10}$$

Fig.5 The two states when discussing the DM/CM conversion



A practical way of measuring Y_{DM} is to use Macfarlane's probe [20]. As described in [21], the CM voltage is applied to the CM input of the probe. The voltage is measured via a high impedance FET probe at this input and the current is measured in the short circuit between the probe's two DM terminals. Reference [21] also gives measured Y_{DM} data.

3.4 Site attenuation

Although only voltages and currents have been considered above, it does not mean that the reciprocity theorem does not apply if electric and magnetic fields play a role in the signal transfer. This should already be clear from the given examples, as field couplings play an important role in each of these examples.

Another example is the determination of the site attenuation in which the signal transfer between two antennas above a reflecting plane is considered. Fortunately, the signal transfer can be modelled into a passive two-port network [22] containing linear impedances as already described by Brown and King in 1934 [23]. Using a 50Ω measuring system, we can conclude from the discussion in Section 3.2 that it is not important which port is connected to the generator and which one to the receiver as long as the antennas have fixed positions. However, as noted in Section 6.2, this conclusion might not always be correct if the so-called normalized site attenuation is considered

4 Electromagnetic fields

This section considers the Lorentz reciprocity theorem interrelating the electromagnetic fields in two states that can occur in one and the same domain in space. Using Carson's formulation [24] and today's notation the reciprocity theorem for fields reads: "If $\boldsymbol{E}^a$, $\boldsymbol{H}^a$ are the field vectors due to a periodic disturbance from a source A_1 located at O_1 and $\boldsymbol{E}^b$, $\boldsymbol{H}^b$ are the corresponding field vectors due to a disturbance originating in A_2 from a source located at O_2, then

$$\int_{1+2} (\boldsymbol{E}^a \times \boldsymbol{H}^b)\cdot \mathrm{d}s = \int_{1+2} (\boldsymbol{E}^b \times \boldsymbol{H}^a)\cdot \mathrm{d}s \tag{11}$$

the surface integrals as indicated by the subscripts 1+2 being taken over closed surfaces 1 and 2 surrounding the sources A_1 and A_2 respectively."
Not directly given in [24] is the additional equality also following from the reciprocity considerations

$$\int_{1+2} (\boldsymbol{E}^{\mathrm{a}}\times\boldsymbol{J}^{\mathrm{b}})\cdot \mathrm{d}\nu = \int_{1+2} (\boldsymbol{E}^{\mathrm{b}}\times\boldsymbol{J}^{\mathrm{a}})\cdot\mathrm{d}\nu \qquad (12)$$

Where D is the volume containing the sources A_1 and A_2 represented by the source vectors $\boldsymbol{J}^{\mathrm{a}}$ and $\boldsymbol{J}^{\mathrm{b}}$, respectively. In Eq.(11) the surface of D is indicated by the subscripts 1+2. Equation (12) will be used in the derivation of the hybrid reciprocity theorem in Section 5. In applications it generally can be shown that Eq.(11) is valid so that by using Eq.(19) below, Eq.(12) is also valid.

So the theorem combines two field states (a and b), comparable to the discussed reciprocity theorem for an N-port Kirchhoff network. The derivation of Eqs. (11) and (12) starts from sets of two Maxwell's equations expressed in the frequency domain for the states a and b:

$$\begin{aligned}\operatorname{curl}\boldsymbol{E}^{\mathrm{b}} &= -j\omega\mu\boldsymbol{H}^{\mathrm{b}}\\ \operatorname{curl}\boldsymbol{H}^{\mathrm{b}} &= +j\omega\varepsilon\boldsymbol{E}^{\mathrm{b}}+\boldsymbol{J}^{\mathrm{b}}\end{aligned} \qquad (13a,b)$$

and

$$\begin{aligned}\operatorname{curl}\boldsymbol{E}^{\mathrm{a}} &= -j\omega\mu\boldsymbol{H}^{\mathrm{a}}\\ \operatorname{curl}\boldsymbol{H}^{\mathrm{a}} &= +j\omega\varepsilon\boldsymbol{E}^{\mathrm{a}}+\boldsymbol{J}^{\mathrm{a}}\end{aligned} \qquad (14a,b)$$

Now the trick is to remember the existence of the vector relation $\operatorname{div}(X \times Y) = Y \operatorname{curl}X - X \cdot \operatorname{curl}Y$ and to write

$$\operatorname{div}(\boldsymbol{E}^{\mathrm{a}}\times\boldsymbol{H}^{\mathrm{b}}) = \boldsymbol{H}^{\mathrm{b}}\cdot\operatorname{curl}\boldsymbol{E}^{\mathrm{a}} - \boldsymbol{E}^{\mathrm{a}}\cdot\operatorname{curl}\boldsymbol{H}^{\mathrm{b}} \qquad (15)$$

$$\operatorname{div}(\boldsymbol{E}^{\mathrm{b}}\times\boldsymbol{H}^{\mathrm{a}}) = \boldsymbol{H}^{\mathrm{a}}\cdot\operatorname{curl}\boldsymbol{E}^{\mathrm{b}} - \boldsymbol{E}^{\mathrm{b}}\cdot\operatorname{curl}\boldsymbol{H}^{\mathrm{a}} \qquad (16)$$

An expression for $\boldsymbol{H}^{\mathrm{b}} \cdot \operatorname{curl}\boldsymbol{E}^{\mathrm{a}}$ in Eq.(15) can be found by multiplying the left and right hand members of Eq.(13a) by $\boldsymbol{H}^{\mathrm{b}}$ (be careful with the order of the variables)

$$\boldsymbol{H}^{\mathrm{b}}\cdot\operatorname{curl}\boldsymbol{E}^{\mathrm{a}} = -j\omega\mu\boldsymbol{H}^{\mathrm{b}}\cdot\boldsymbol{H}^{\mathrm{a}} \qquad (17)$$

In a similar way, expressions can be found for the other terms on the right hand side of Eqs.(15) and (16) by multiplying Eqs.(13b), (14a) and (14b) by the proper vectors. After substitution of all resulting expressions in Eqs.(15) and (16) and subtracting the two final equations, we find that

$$\operatorname{div}(\boldsymbol{E}^{\mathrm{a}}\times\boldsymbol{H}^{\mathrm{b}} - \boldsymbol{E}^{\mathrm{b}}\times\boldsymbol{H}^{\mathrm{a}}) = \boldsymbol{E}^{\mathrm{b}}\cdot\boldsymbol{J}^{\mathrm{a}} - \boldsymbol{E}^{\mathrm{a}}\cdot\boldsymbol{J}^{\mathrm{b}} \qquad (18)$$

This equation, in which the ω-terms no longer appear, is sometimes called the local form of the reciprocity theorem. To find the general form, Eq.(18) has to be integrated over the volume D containing all sources represented by $\boldsymbol{J}^{\mathrm{a}}$ and $\boldsymbol{J}^{\mathrm{b}}$, yielding

$$\begin{aligned}&\int_D \operatorname{div}(\boldsymbol{E}^{\mathrm{a}}\times\boldsymbol{H}^{\mathrm{b}} - \boldsymbol{E}^{\mathrm{b}}\times\boldsymbol{H}^{\mathrm{a}})\cdot\mathrm{d}\nu =\\ &\int_S (\boldsymbol{E}^{\mathrm{a}}\times\boldsymbol{H}^{\mathrm{b}} - \boldsymbol{E}^{\mathrm{b}}\times\boldsymbol{H}^{\mathrm{a}})\cdot\mathrm{d}s =\\ &\int_D (\boldsymbol{E}^{\mathrm{b}}\cdot\boldsymbol{J}^{\mathrm{a}} - \boldsymbol{E}^{\mathrm{a}}\cdot\boldsymbol{J}^{\mathrm{b}})\cdot\mathrm{d}\nu\end{aligned} \qquad (19)$$

We had to expect an integration as the Maxwell equations consider field derivatives whereas an expression for the fields is needed. The most left hand member of Eq.(19) has been converted from an integral over a volume D into an integral over the surface S of D by applying Gauss's theorem. This action also 'removes' the div operation. Equation (19) is the general form of the Lorentz reciprocity theorem, a form that can even be extended [14], although this extension is not needed in the context of this paper.

If the fields propagate in isotropic media, it can be shown that the outcome of the integrals in Eq.(19) is equal to zero (a value given by Lorentz who considered the propagation properties of light). Increase the volume D to a volume D_1 such that its surface S_1 is at a distance

a) much larger than the wavelength λ of the considered fields (far-field condition), and
b) so large that the fields of the sources A_1 and A_2 can be assumed to originate from a single point source, so that at S_1 the fields have the same direction of propagation.

In the far-field (condition a), the field propagates as a plane or quasi-plane wave so that the E- and the H-vector of the field are perpendicular to each other and have a constant ratio, $\eta = \sqrt{(\mu/\varepsilon)}$, the wave impedance (377Ω in air). In vector notation the latter means that $\nu\times\boldsymbol{E} = \eta\boldsymbol{H}$, where ν is the unit vector perpendicular to the plane formed by $\boldsymbol{E}$ and $\boldsymbol{H}$. The vector ν represents the direction of propagation, which is at S_1 the same for the fields emitted by A_1 and A_2 (condition b). After application of this relation to $\boldsymbol{E}^{\mathrm{a}} \times \boldsymbol{H}^{\mathrm{b}}$ and to $\boldsymbol{E}^{\mathrm{b}} \times \boldsymbol{H}^{\mathrm{a}}$ and after application of the vector relation
$X\times(Y\times Z) = Y\cdot(X\cdot Z) - Z(X\cdot Y)$ we find that

$$\boldsymbol{E}^{\mathrm{a}}\times\boldsymbol{H}^{\mathrm{b}} = \boldsymbol{E}^{\mathrm{b}}\times\boldsymbol{H}^{\mathrm{a}} = \eta(\boldsymbol{E}^{\mathrm{b}}\cdot\boldsymbol{E}^{\mathrm{a}}) \qquad (20)$$

so that $\boldsymbol{E}^{\mathrm{a}} \times \boldsymbol{H}^{\mathrm{b}} - \boldsymbol{E}^{\mathrm{b}} \times \boldsymbol{H}^{\mathrm{a}} = 0$ and, consequently, the integrals in Eq.(19) are equal to zero and Eqs.(11) and (12) given at the start of this section automatically follow for D_1 with S_1. Reducing D_1 to the original volume D will not change the outcome of the integrals in Eq.(12) as there are no sources in the space between S and S_1. Hence Eq.(12) is also valid for D and, consequently, also Eq.(11) holds for S.

5. The hybrid reciprocity theorem

The experimentalist can only humbly lift his hat at the mathematical fireworks presented in Section 4 and then pass to the order of the day. An application is what is needed to catch his or her interest. As mentioned in the introduction, a very useful application was already given in 1929 by Ballantine [10], referring to the work of Wilmotte [11].This application, resulting in the hybrid reciprocity theorem, can also be found in Section 4.5 of a more recent textbook [16]. The theorem gives an expression for the voltage U_{i} induced by an incident field E^{i} in an antenna or structure acting as an antenna, e.g. an EUT (Equipment Under Test) and its connected cables.

First of all, two wire antennas A_1 and A_2 are considered (see Fig.6) contained in the volume D with surface S. Each wire antenna consists of two wire elements, separated by a small gap of width w_1 and w_2 respectively, that determines the distance between the two terminals (each connected to a wire element) of the antenna. The wire antennas of total length L_1 and L_2 are assumed to be electrically thin and perfectly conducting. The widths $\{w_1,w_2\}<<\{L_1,L_2\}$ are so small that a quasi-stationary approach is allowed at the gaps, i.e. it is assumed that the time derivative in Faraday's law can be taken equal to zero. In other words: the wire elements may be connected to a Kirchhoff network.

Fig.6 The states (a) transmission and (b) reception. The dashed lines indicate parts that need not necessarily be accessible.

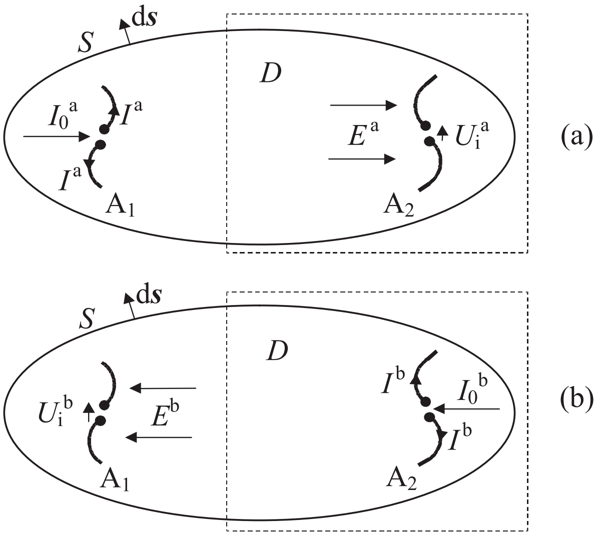


Figure 6a depicts the a-state: A_1 is the transmitting antenna to which a current source of strength I_0^{a} is connected. This results in a current distribution I^{a} over A_1, and an incident field E^{a} at the location of A_2. The open circuit voltage induced in the latter antenna is $U_{\mathrm{i}}^{\mathrm{a}}$. The b-state is considered in Fig.6b: a current source I_0^{b} is connected to the terminals of A_2, creating a E^{b} at the location of A_1, in which antenna an open circuit voltage $U_{\mathrm{i}}^{\mathrm{b}}$ is induced. The task now is to derive an expression for $U_{\mathrm{i}}^{\mathrm{b}}$.

If we realize that within the volume D the current can only flow on the wire elements, $\boldsymbol{J}\mathrm{d}v$ in Eq.(12) can be replaced by $I(l)\mathrm{d}\boldsymbol{l}$. The current $I(l)$ is the current (perfect conductor) uniformly distributed over the infinitesimal wire segment $\mathrm{d}\boldsymbol{l}$ at the position l along the wire element. The segment has a certain orientation with respect to the incident field, so $\mathrm{d}\boldsymbol{l}$ is a vector. Moreover, the volume integral in Eq.(12) now changes into a line integral, so that comparable to Eq.(5)

$$\begin{aligned}\int_{L_1+w_1} I^{\mathrm{a}}(l)\boldsymbol{E}^{\mathrm{b}} \cdot \mathrm{d}\boldsymbol{l} + \int_{L_2+w_2} I^{\mathrm{a}}(l)\boldsymbol{E}^{\mathrm{b}} \cdot \mathrm{d}\boldsymbol{l} &= \\ \int_{L_1+w_1} I^{\mathrm{b}}(l)\boldsymbol{E}^{\mathrm{a}} \cdot \mathrm{d}\boldsymbol{l} + \int_{L_2+w_2} I^{\mathrm{b}}(l)\boldsymbol{E}^{\mathrm{a}} \cdot \mathrm{d}\boldsymbol{l}\end{aligned} \qquad (21)$$

The outcome of the integrals over L_1 and L_2 equals zero because the dot product $\boldsymbol{E} \cdot \mathrm{d}\boldsymbol{l}$ is zero since this dot product represents the tangential field. In a perfect conductor the internal E-field is always zero and the boundary condition states that also the E-field just outside the conductor, so the tangential field, is zero. What is left are the integrals over w_1 and w_2. In the left hand member of Eq.(21) the integral over w_2 equals zero because the port of A_2 is open and, hence, the current is zero. Similarly, in the right hand member of Eq.(21) the integral over w_1 equals zero. Because at the gaps the quasi-static approach is allowed, $\boldsymbol{E} \cdot \mathrm{d}\boldsymbol{l}$ is the voltage over a gap and Eq.(21) reduces to

$$I_0^{\mathrm{a}} U_{\mathrm{i}}^{\mathrm{b}} = I_0^{\mathrm{b}} U_{\mathrm{i}}^{\mathrm{a}} \qquad (22)$$

This result would also have been found when applying the generalized Rayleigh theorem to the two port system of the two antennas with the chosen load conditions. So this example nicely demonstrates a connection between the theorems of Lorentz and Rayleigh. In a general approach, it can be shown that under certain conditions the reciprocity theorem for the Kirchhoff networks, Eq.(2) can be derived from the Lorentz reciprocity theorem and the following relation holds [14, 15]

$$\int_S (\boldsymbol{E}^{\mathrm{a}} \times \boldsymbol{H}^{\mathrm{b}} - \boldsymbol{E}^{\mathrm{b}} \times \boldsymbol{H}^{\mathrm{a}}) \cdot \mathrm{d}\boldsymbol{s} = \sum_{\mathrm{k}=1}^{\mathrm{N}} (U_{\mathrm{k}}^{\mathrm{a}} I_{\mathrm{k}}^{\mathrm{b}} - U_{\mathrm{k}}^{\mathrm{b}} I_{\mathrm{k}}^{\mathrm{a}}) = 0 \qquad (23)$$

This means that there is a direct link between the Maxwell equations and the reciprocity theorem for Kirchhoff networks and that we no longer have to think in terms of electrical forces and motions, as was common in Rayleigh's days.

Unfortunately, due to the 'problem' of the tangential field being equal to zero, the above approach does not lead to an expression for $U_{\mathrm{i}}^{\mathrm{b}}$. To circumvent this problem only antenna A_1 in Fig.(6) is considered and the volume *D* with surface *S* is taken around A_1 only. Antenna A_2 is assumed to be placed at such a large distance from A_1, that a field emitted by A_2 arrives at *S* as a (quasi) plane wave. The restriction to a plane wave is not a serious one because an incident field that is not a plane wave can always written as a sum of plane waves. By performing somewhat lengthy but straight forward calculations it can be shown that also in this case Eq.(11) holds and, consequently, Eq.(12). Using the same load conditions as in the previous example, Eq.(12) reduces to

$$\int_{L_1 + w_1} I^{\mathrm{a}}(l)\boldsymbol{E}^{\mathrm{b}} \cdot \mathrm{d}\boldsymbol{l} = \int_{L_1 + w_1} I^{\mathrm{b}}(l)\boldsymbol{E}^{\mathrm{a}} \cdot \mathrm{d}\boldsymbol{l} \qquad (24)$$

In the a-state, A_1 is the transmitting antenna so that the right hand member of Eq.(24) equals zero: the integral over L_1 equals zero because $\boldsymbol{E}^{\mathrm{a}} \cdot \mathrm{d}\boldsymbol{l} = 0$ and the integral over w_1 is zero because in the b-state the antenna port is open. To get rid of the $\boldsymbol{E} \cdot \mathrm{d}\boldsymbol{l} = 0$ problem, in the b-state antenna A_1 is removed but the integration is carried out over the path originally occupied by A_1. As a result, the integral over L_1 in the left hand member of Eq.(24) is not equal to zero because there is no conductor present. This approach can be made plausible by noting that the condition 'tangential field equal to zero' can be interpreted as follows [16]. An incident field $\boldsymbol{E}^{\mathrm{b}}$ induces in a wire segment $\mathrm{d}\boldsymbol{l}$ a current that creates a scattered field Es such that at the segment surface the field is exactly equal to zero. Now, if all wire segments are replaced by field sources for which $\boldsymbol{E}^{\mathrm{s}}\,\mathrm{d}\boldsymbol{l} = -\boldsymbol{E}^{\mathrm{b}} \cdot \mathrm{d}\boldsymbol{l}$, the wire antenna is no longer present but the field distribution outside the original location of A_1 is not changed. The left hand member of Eq.(24) can now be written as

$$I_0 U_{\mathrm{i}} = \int_{L_1} I^{\mathrm{t}}(l)\boldsymbol{E}^{\mathrm{i}} \cdot \mathrm{d}\boldsymbol{l} \qquad (25)$$

Since the transmission and reception of electromagnetic waves is of interest in EMC field measurements, the superscript t of transmission is used in I^{t} in stead of a, and the superscript i of incident is used in $\boldsymbol{E}^{\mathrm{i}}$ in stead of b. Furthermore, I_0^{a} has been replace by I_0 and $U_{\mathrm{i}}^{\mathrm{b}}$ by U_{i}. This relation given by Ballantine and derived from the Lorentz reciprocity theorem clearly demonstrates the hybrid character mentioned in the introduction.

Some general observations can be made from Eq.(25):

a) Of the fields, only the *incident* field counts, i.e. the field that is present in the absence of the antenna!
b) The equation only contains parameters that apply to antenna A_1 or to the location of A_1. No information is needed about 'where is antenna A_2 causing the incident field E^{i}´, or about 'what happens in antenna A_2´. This is indicated schematically in Fig.6 by the dashed lines.
c) Up to this point we have tacitly assumed that in principal all ports of the network are accessible for (simultaneous) connection of terminations (of measuring equipment). Equation (25) can look at a situation in which only one port is accessible.
d) The equation meets the demands of an experimentalist who is never able to directly measure the field strength. He or she always needs a conversion of a field strength quantity into a quantity that can be measured via conduction.
e) Equation (25) can also be written as

$$U_{\mathrm{i}} = \int_{L_1} \frac{I^{\mathrm{t}}(l)}{I_0}\boldsymbol{E}^{\mathrm{i}} \cdot \mathrm{d}\boldsymbol{l} \qquad (26)$$

so that $I_{\mathrm{t}}(l)/I_0$ can be considered to be the normalized current distribution in the transmitting state that weighs the contributions of incident field in the receiving state.

6 Applications (2)

This section presents a number of simple applications of Eq.(25) or Eq.(26), dealing with the antenna factor, radiated immunity measurements and shielding. Interesting and rigorously treated applications of Eq.(23) can be found in [15, 25]. Only in simple cases can the integral in Eq.(25) or Eq.(26) be solved analytically; an example is given in Section 6.1. However, the other examples will show that quite useful information is made available without solving the integral.

6.1 The λ/2-dipole

A very simple application of Eq.(26) follows if we calculate the voltage induced in a λ/2-dipole in free space. As can be found in all current text books on antennas and was verified experimentally by Wilmotte in 1927 [26], the current distribution in the transmitting state of this antenna is half a sine wave. If the incident field is a plane wave of strength E^i with its polarization parallel to the wire elements, the well known expression for the induced voltage follows from Eq.(26):

$$U_i = \frac{E^i}{I_0} \int_{-\lambda/4}^{\lambda/4} I_0 \sin\left(\frac{2\pi}{\lambda}\left(\frac{\lambda}{4} - l\right)\right) \mathrm{d}l = \frac{\lambda}{\pi} E^i \qquad (27)$$

If Z_m is the effective load impedance and Z_a the internal impedance of the λ/2-dipole antenna, the voltage U_m measured by the receiver is given by

$$U_m = \frac{Z_m}{Z_m + Z_a} \frac{\lambda}{\pi} E^i \qquad (28)$$

and if $E^i = E_c^i$ is the field strength during calibration of this antenna, its antenna factor F_A is given by

$$F_A = \frac{\pi (Z_m + Z_a)}{\lambda Z_m} \qquad (29)$$

By stating ´Z_m is the effective load impedance of the antenna' and not ´Z_m is the input impedance of the receiver', the properties of the antenna balun are assumed to be taken into account.

Seibersdorf, for example, is a supplier of a set of 27 λ/2-dipole antennas suitable for performing the validation of an antenna calibration test site as described by CISPR/A [27]. For these antennas $Z_m = 100\ \Omega$, and the free space value of $Z_a = 73\ \Omega$. Inserting these values in Eq.(29) results in F_A values that differ less than 0.1 dB from the theoretical values supplied by Seibersdorf (maybe, Seibersdorf also used Eq.(29)).

6.2 The antenna factor F_A

This section should clarify which parameters play a role in the determination of the antenna factor and what the consequences are in radiated emission measurements, measurement uncertainty and normalized site attenuation measurements.

By definition, the measured field strength $E_m = F_A U_m$, so the antenna factor can be written as

$$F_A = \frac{Z_m + Z_{a,c}}{Z_m} \frac{1}{\int_L (I_c^t(l)/I_0) \boldsymbol{E}_c^i \cdot d\boldsymbol{l}} \qquad (30)$$

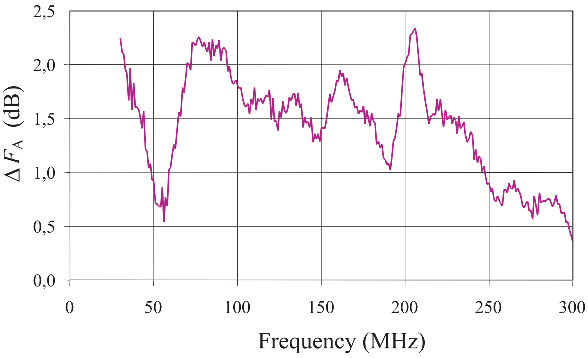
The antenna factor therefore depends on 3 variables determined by the *calibration set-up*, in Eq.(30) indicated by the subscript c,

1) The antenna impedance $Z_{a,c}$,
2) The normalized current distribution $I_c^t(l)/I_0$, and
3) The outcome of the dot-product $\boldsymbol{E}_c^i \cdot \mathrm{d}\boldsymbol{l}$ along the wire elements.

Officially, Z_m also plays a part but as a result of standardization of measuring equipment this parameter normally does not change. As a consequence, if in a radiated emission measurement one or more of these three variables differ from the values during calibration, the antenna factor is *unknown* or, at least, the confidence margin of the antenna factor might be much larger than the one quoted in the calibration report. In discussions about the standardization of radiated emission tests, the first variable (the antenna impedance) has often been considered, but not the other two variables.

The normalized current distribution depends on the interaction of the antenna with its environment during its actual use (calibration or radiated emission test). Of course, the outcome of the integral depends on the incident-field distribution which, however, is not specified in a radiated emission compliance test. The wire elements of a receiving antenna automatically 'integrate' over the field distribution whether the measurement is carried out on an open area test site, or in a semi or a fully

Fig 7. The difference $\Delta F_A = F_A(ANSI/3m) - F_A(Free\text{-}Space)$ between the antenna factors of a log-biconical antenna derived from the two calibration reports



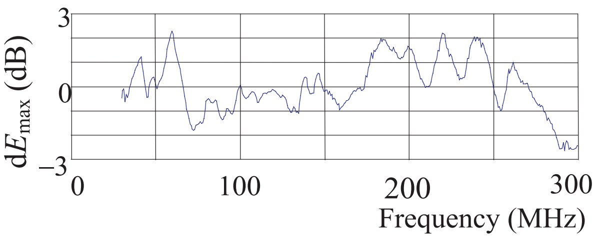
anechoic room. Consequently, antennas with different shapes will have different induced voltages, even if the incident field is a plane wave.

The combined effect of all three variables comes to the fore in the first example. Figure 7 shows the difference ΔF_A between the ANSI(3m) antenna factor and the free-space antenna factor of one and the same log-biconical antenna, as determined by a UKAS accredited company.

We can also conclude from the above that the linearized model used in documents on EMC measurement instrumentation uncertainties [28, 29] cannot be justified. Moreover, the uncertainty in the antenna factor during calibration has little in common with the uncertainty in the antenna factor during an actual radiated emission test. In the normalized site attenuation measurement method the result of the site attenuation measurement is normalized to the antenna factors, after which the result is compared to a theoretically predicted result. This method is formally only correct if it can be demonstrated that the antenna factors used are valid during the conditions of the site attenuation measurement.

As a second example, Fig.8 shows the difference dE_{max} when in the CISPR/A radiated emission round robin test (RRT) the field-strength emitted by the battery operated tightly specified EUT (a rod antenna above a small ground plane) was firstly measured using a biconical antenna and secondly by using a log-biconical antenna [30]. When replacing the receiving antenna, care was taken that the remaining part of the set-up was not changed. Only the prescribed measurement distance was adjusted by moving the receiving antenna. In this example, the effect of integrating over different parts of the incident field distribution comes to the fore very clear. This effect was also found in the statistical evaluation of the RRT field strength measurement results using the tightly specified EUT [30].

Fig.8 Measured field strength difference dE_{max} (dB) after a biconical antenna has been replaced by a log-biconical antenna



When using a log-biconical antenna, the effective measurement distance changes with frequency, and it has sometimes been suggested that is possible to correct for this effect. From the theory above, it will be clear that such a correction is only possible if the complete actual incident-field distribution is known and accounted for in the correction factor.

6.3 Probe calibration in a TEM cell

Field probes are often calibrated in a TEM-cell. However, the practical use of these probes is generally outside such a cell. So the current distribution in the t-state, and, consequently, the antenna factor, may be different in cases where the probe is not as close to the metal plates as it is inside the TEM-cell. It seems that this aspect was overlooked in [31]. It might therefore be one of the reasons for the limited agreement between measurement results obtained in the TEM cell and those obtained outside that cell. In addition, the authors in [31] claim that the reciprocity of the TEM cell was verified experimentally. In that experiment, a first transfer function was measured after connecting the signal generator to the probe acting as transmitting antenna inside the cell and the measuring receiver to one of the cell terminals. A second transfer function was measured after reversing the connections, i.e. after connecting the generator to the cell terminal and the measuring receiver to the probe. They then conclude that reciprocity has been demonstrated as the two transfer functions differed by less than 1 dB. However, for trivial reasons the TEM cell was a linear passive device and, hence, was reciprocal. The discussions in Section 3.2 then indicate that the experiment only demonstrated that the ratio of the output impedance of the generator and the input impedance of the measuring receiver was smaller than 1 dB. If a 50Ω generator and a 75Ω measuring receiver would have been used, for example, that ratio would most likely have been different and the authors would have discovered that their method needed an additional consideration. Reciprocity does not always mean 'equal values' of the chosen measurands.

Another application of the reciprocity theorem involving a TEM cell is given in [32].

6.4 Radiated immunity, E^i

In a radiated immunity test, it is the induced voltage that may cause malfunctioning of the EUT. Equation (26) clearly indicates that this voltage is determined by the incident field *and* by the normalized current distribution. In this section, aspects of the incident field are considered and in Section 6.5 aspects of the current distribution are considered.

The incident field is the field that would be present in absence of the EUT plus its attached cables acting as an antenna. Consequently, the specified field strength in a radiated immunity test is normally measured and adjusted before the placement of the EUT using a small probe (negligible interaction with the field source). It is not correct to measure the specified field strength using a small probe near the EUT, because that probe measures the field *incident to the probe*. The latter field may significantly differ from the incident field experienced by the EUT, as it is the combination of the wanted field and the field reflected from the EUT. The field incident to the probe might even be almost zero if the desired test field and the reflected field are in anti-phase.

After placement of the EUT we need to verify that the incident field as such has not changed as a result of a possible strong interaction between the EUT and the source of the field. Such an effect may be observed by comparing the forward power measured via a directional coupler, in the connection between the generator and antenna emitting the test field during the previously mentioned field adjustment, with the power measured after the placement of the EUT. If the forward power has changed, the desired incident field has changed. A first correction is to adjust the generator output to a level that results in the original forward power. However, from the hybrid theorem it follows that this adjustment does not need to be 100% correct, as the field distribution during the field adjustment and that after placement of the EUT need not be the same.

6.5 Radiated immunity, $I^t(l)/I_0$

Equation (26) also indicates that the normalized current distribution in the t-state is of importance. Since that distribution is the weighting function of the voltage contributions induced by the incident field, resonances in that distribution may be noticed in the disturbance signal induced in the cable attached to an EUT. An example is given in Fig.9, where the maximum (max), average (avg) and the minimum (min) value of the measured induced CM-current are plotted as a function of the frequency of the homogeneous incident field with a strength of 1 V/m. Eight EUTs taken from a class of electrically small EUTs were tested [21].

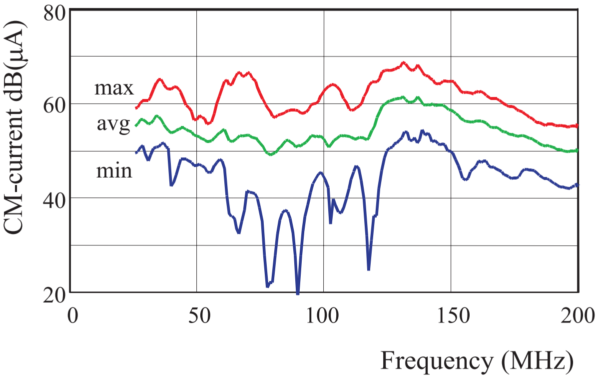


Fig.9 The induced common-mode current measured close to an electrically small EUT in the cable attached to that EUT, when illuminated by a field of 1 V/m (8 EUTs)

Although the average value is about 55 dBμA (a value close to the rule of thumb for these EUTs: 1 mA per V/m), the curve labelled 'min' indicates that resonances may cause a minimum in the induced current, so that the considered EUT is hardly tested for immunity around the resonance frequencies. In other words, a uniform and constant incident field does not guarantee that the EUT is tested with a constant actual disturbance signal (here represented by the CM current). In addition, we should expect the resonance frequencies to shift when the layout of the cables is changed. If it had been possible to let the EUT act as a transmitter, the resonances would also have been found, comparable to the resonances of a rod antenna.

In the case of an interference complaint in which a product is insufficiently immune to EM fields, it is not always possible to solve the problem at the location where the product is used. The disturbance field strength at that location is measured and the product is taken to the test lab to carry out a radiated immunity test with that field strength. However, if the CM current distribution on the cables attached to that product differs significantly in the test situation from that at the complaint location, the test might not cover the actual complaint. So it is advisable to measure not only the field strength at the complaint location, but also the CM current on the attached cables (close to the product) and to verify whether these currents are (more or less) the same in the test house.

6.6 Shielding

This section addresses the frequently asked question 'If a shield attenuates the field emanating from circuits inside that shield by an amount of X dB, are these circuits then also shielded by an amount of X dB for fields generated outside that shield?' We can illustrate the reasoning behind the answer by the following rather simple configuration, that allows the use of simple analytical relations. Rigorous approaches based on the Lorentz theorem can be found in [25, 33]. In Section 6.7 the results are also used in an example of interference prediction.

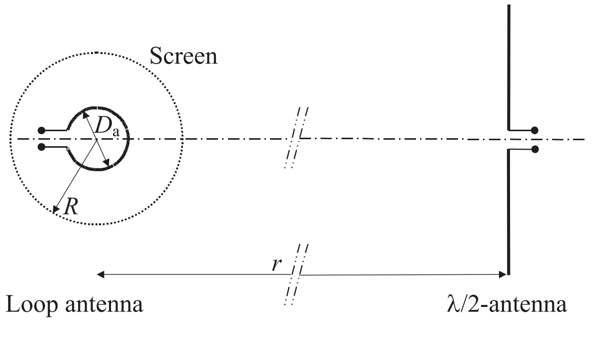
A tuned λ/2 dipole is located at a distance r in the far-field of a small loop antenna, as shown in Fig.10. Both antennas are located in free space so that antenna coupling and reflections do not play a role. A signal source $\{U_g, R_g\}$ can be connected to the loop antenna, and a voltmeter (input impedance $R_v = R_g$) can be connected to the λ/2 dipole (internal impedance Z_a), and vice versa. The area of the loop antenna $A = \pi D_a^2/4$ and the internal impedance of that antenna is Z_l. The orientation of both antennas is such that an optimal signal transfer results.

If the source is connected to the loop antenna and the voltmeter to the λ/2 dipole, the voltmeter reading U_{v1} in the absence of the screen will be given by

$$U_{v1} = \frac{\lambda R_g}{\pi(R_g + Z_a)} \cdot \frac{Z_0 k^2 A U_a}{4\pi(R_g + Z)} \qquad (31)$$

where $\lambda R_g/\{\pi(R_g + Z_a)\}$ is the voltmeter reading in the case of an incident field given by the second part of the right hand member of Eq.(31), (also see Eq. (28)). In that part, $AU_g/(R_g + Z_l)$ is the magnetic dipole moment of the loop antenna, Z_0 the far-field wave impedance and $k = 2\pi/\lambda$. Next, a spherical screen of radius R, $D_a/2 << R << \{r, \lambda/2\pi\}$, is put around the loop antenna such that the loop is in its center. The screen is assumed to be in the near field of the loop. Now the voltmeter reading is U_{v2} and, consequently, the shielding effectiveness $S_H = U_{v1}/U_{v2}$. Because the sphere also acts as a magnetic dipole [25], U_{v2} is also described by Eq.(31), although the magnetic dipole moment is now a factor S_H smaller.

Fig.10 Schematic drawing for use in the application of the reciprocity theorems



The next step is to connect the generator to the λ/2 dipole and the voltmeter to the loop antenna. In the absence of the screen U_{v3} is measured and in the presence of that screen U_{v4} is measured. The voltage U_{v3} is given by

$$U_{v3} = \frac{\mu_0 \omega A R_g}{(R_g + Z)} \cdot \frac{2U_g}{4\pi(R_g + Z_a)} \qquad (32)$$

where $R_g/(R_g + Z_l)$ gives the voltage division of the voltage $\mu_0 \omega AH$ induced by the incident H-field. That field is given by the second part of the right hand member of Eq.(32), and is easily understood when remembering that in the far-field the E-field of a center fed tuned λ/2 dipole is given by $E = 60I/r = 2Z_0/(4\pi r)$ so that $H = 2I/(4\pi r)$ and where I is the current entering the antenna.

Using the relations $Z_0 = \sqrt{(\mu_0 / \varepsilon_0)}$ and $f \cdot \lambda = c = 1/\sqrt{(\mu_0 \varepsilon_0)}$ we can easily verify that $U_{v1} = U_{v3}$. This is not a surprising result, since the equivalent network between the ports of the two antennas is a Kirchhoff network, which means that the associated reciprocity theorem directly gives the answer $U_{v1} = U_{v3}$ (see Eq.(8)) using $Z_g = Z_L = R_g$. However, because the screen is also linear and passive, the same theorem shows that $U_{v2} = U_{v4}$, and a simple calculation like the one above to demonstrate this result is not possible. The last statement is particularly true because the dipole field arrives as a plane wave at the screen, while the screen is in the near-field region of the loop antenna. A knowledgeable in the theory may be able to show that the Helmholtz theorem about the reversibility of light rays [2] is applicable in the described situation.

In this example the actual shielding effectiveness is determined by that of the screen in the near-field of the loop antenna. This effectiveness is generally much lower, e.g. 40 dB, than that for a plane wave generated outside the screen. The example stresses the fact that the shielding effectiveness is not entirely a property of the shield. It is a property of the shield plus the antennas or antenna structures playing a role in the disturbance signal transfer.

In conclusion, the reciprocity theorems give conditions under which the shielding effectiveness is reciprocal, and the results are certainly applicable in the case of in-band interference. In the case of out-of-band disturbances acting on non-linear devices such as transistors, the theorems are not formally applicable. However, it is still possible to follow the given path to estimate the magnitude of the induced signals and to consider the consequences of those signals afterwards [33].

6.7 Interference prediction

The results obtained in Section 6.6 can be applied to interference prediction. As an example, the following application considers the unwanted signal induced by a distant broadcasting transmitter in the antenna of Magnetic Resonance Imaging (MRI) equipment used in hospitals.

In the early days of the use of MRI equipment, hospitals did not like to have large Faraday cages around the equipment. As broadcasting transmitters could emit strong fields at the in-band frequencies of the MRI equipment, the following question arose 'Is it possible to carry out field strength measurements at the location where the MRI equipment is planned to be used *before* the placement of that equipment and to predict the level of the disturbance signal induced in the MRI antenna?' The answer was 'Yes, and with a reasonable degree of confidence'. The following three steps had to be followed to find the answer. Figure 10 is again applicable: the MRI antenna is the loop antenna and the $\lambda/2$ dipole is the antenna of the broadcasting transmitter, (normally a $\lambda/4$ antenna above the earth acting as a ground plane). Simple mathematical relations illustrate the estimate of the maximum voltage $U_{\mathrm{i,max}}$ that could be induced in the loop antenna.

Step 1: Connect a signal source $\{U_{\mathrm{g}}, R_{\mathrm{g}}\}$ to the MRI antenna located at its normal-use position inside the MRI equipment, so that all interactions are properly taken into account because the normal-use current distribution is to be approached. Set the frequency of this source to that of the (strong) broadcasting field to be expected in the hospital. Measure at a distance r_1 in the far-field of the MRI equipment the field pattern $E_1(\varphi)$, $0° \leq \varphi \leq 360°$, emitted by the MRI antenna and measure the current I_0^{t} flowing into the loop antenna. This is a measurement that can be carried out on the manufacturers premises!

Step 2: Determine the maximum E_{max} of $E_1(\varphi)$ and assume that the MRI equipment emits this field in the direction of the $\lambda/2$ dipole at a distance r from the equipment (worst case). This field is proportional to I_0^{t}, so $E_{\mathrm{max}} = \alpha_{\mathrm{max}} I_0^{\mathrm{t}}$ and the incident field for the $\lambda/2$ dipole $E^{\mathrm{t}} = (\alpha r_1 I_0^{\mathrm{t}})/r$. Application of the hybrid reciprocity theorem then gives the voltage induced in the $\lambda/2$ dipole: $U_{\mathrm{i},\lambda/2} = (\alpha_{\mathrm{max}} \lambda r_1 I_0^{\mathrm{t}})/(\pi r)$, (see Eq.(27)). Consequently, the transfer impedance Z_{tr} between the loop antenna and the $\lambda/2$ dipole is given by

$$Z_{\mathrm{tr}} = \frac{\alpha_{\mathrm{max}} \lambda r_1}{\pi r} \tag{33}$$

and in the given situation Z_{tr} is reciprocal.

Step 3: During operation of the broadcasting transmitter, the input current to its antenna is I_0^{r} and that current can be determined from the field strength E^{r} measured at the location where the MRI equipment is to be installed, by using the well known relation $E^{\mathrm{r}} = 60 I_0^{\mathrm{r}}/r$. Using Eq.(33), the estimate of the maximum voltage $U_{\mathrm{i,max}}$ induced by the broadcasting transmitter in the loop antenna is given by

$$U_{\mathrm{i,max}} = Z_{\mathrm{tr}} I_0^{\mathrm{r}} = \frac{\alpha_{\mathrm{max}} \lambda r_1}{60\pi} E^{\mathrm{t}} \tag{34}$$

By comparing this voltage with the level allowed to operate the MRI equipment sufficiently free of interference, a decision can be made about whether or not a Faraday cage is needed and, if it is, how much attenuation that cage should present.

If in step 1 it is not possible to properly carry out far-field measurements, near-field measurements may be carried out at a number of distances, say 3, from which an equivalent magnetic dipole moment can be deduced for further use in the prediction calculations.

Summary

In this paper we have discussed the reciprocity theorem interrelating two states of one and the same Kirchhoff network (linear passive network) as determined by the terminations of that network. We have given applications improving the understanding of transfer impedance, filter and site attenuation measurements. In addition, we have used the theorem to facilitate a DM voltage to CM current conversion measurement.

We discussed the reciprocity theorem interrelating the electromagnetic fields in two states that can occur in one and the same domain in space, and from this theorem we derived the hybrid reciprocity theorem. The latter theorem was applied to a tuned λ/2 dipole, to the measurement of antenna factors, to probe calibration in a TEM cell and the uncertainties associated with these measurements. We also used the hybrid reciprocity theorem to discuss aspects of radiated immunity measurements.

Finally, we used the reciprocity the reciprocity theorems in a discussion about the reciprocity of the shielding effectiveness and in a simple method to estimate the interference potential of a field (at in-band frequencies) incident on an antenna.

Acknowledgements

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Aan dit staaltje van hoogwaardig technisch kunnen worden wij in Huizen alleen nog herinnerd door de namen 'Zenderwijk', PHOHI flat/winkelcentrum en de lokale omroep PHOHI. De nieuwe rotonde op de Gooilandweg/Randweg is dé locatie voor het 12 meter hoge stalen model van de Korte Golf antennes (de oorspronkelijke hoogte van deze zendmasten was 60 meter).

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The Salvage of the 'Kursk'

Alexander Bakker and Lars Walder
Book abstract by H.J. Visser

This article is based on the book 'The Salvage of the 'Kursk'', by Alexander Bakker and Lars Walder, 2003, SMIT, Rotterdam (ISBN:90-9017034-0). The publisher permitted the use of the contents of this book, which is kindly acknowledged by NERG.

The Sinking

The submarine 'Kursk' sailed from the port of Vidiayevo on the morning of Thursday 10 August 2000. The 'Kursk' had 118 people on board for this journey; 111 crew members, five officers from the headquarters of the Submarine Division of the Northern Fleet and two specialists on torpedo weapons, one of them being a civilian.

The 'Kursk' was heading for firing a training torpedo on Saturday 12 August and, after completion of the torpedo launch, to report to the Commander of the Northern Fleet. Since such a report had not been received in the evening of that day, the Commander of the Northern Fleet, Admiral Popov, ordered to start a search & rescue operation.

As we know now, that Saturday morning two hydrodynamic blows had been recorded by several ships min the area of the exercise. The two explosions were most probably due to an accident with an experimental torpedo and resulted in the sinking of the 'Kursk'.

On Sunday morning, the position of the sunken 'Kursk' was found by sonar aboard the cruiser 'Mikhail Rudnitsky'. The twenty ships and vessels, sent on a rescue operation by the Commander of the Northern Fleet, failed in their rescuing attempts, as they had not been given the right equipment. As a result of an agreement with NATO a specially adapted British rescue submarine set sail from a Norwegian port on 17 August 2000 and arrived at the 'Kursk' on 20 August, but was unable to open the escape hatches of the sunken submarine. After repeated attempts, Norwegian divers, however, succeeded in opening the lower cover of the air lock hatch of the 'Kursk', only to discover that the lower section had completely filled up with water. On this day it was officially

Figure 1: The showpiece of the Russian navy in the bay at Murmansk

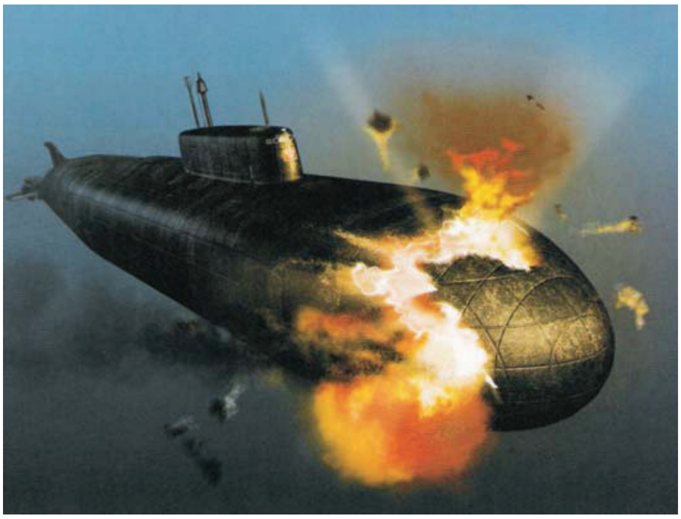


Figure 2: The explosion occurred in the foremost compartment, where the torpedoes were stored. The depth the sub was at prevented the shockwave from forcing its way out of the sub; instead, most of the force of the blast traveled through the vessel's interior, causing devastation.

reported that all people aboard the 'Kursk' had died. Later, in October, 12 bodies were recovered from the sunken 'Kursk'.

In the spring of 2001, two Dutch companies started to work on the salvage of the 'Kursk'. They were Mammoet, a company specializing in lifting work and SMIT, the towage and salvage company. The salvage operation was a race against the clock, where the changeable weather conditions in the Barents Sea were the salvor's greatest enemy. The Russian President Putin personally had taken the decision about the submarine lifting, putting a deadline on the end of 2001. The salvage contract was not signed until May 2001, which gave the salvors just five months to successfully complete this extremely complex operation. Five months, since the Barents Sea's stormy season starts in October.

Figure 3: The precise location of the sunken 'Kursk': 69°7'00"North, 37°34'25"East.

The Contract

On Monday 14 August the news of the sinking of the 'Kursk'already reached SMIT in Rotterdam. Although SMIT did not have the specialized equipment needed to open the hatches on the 'Kursk', SMIT's services were offered to Rubin, the Russian navy's design bureau in St. Petersburg. In the meantime SMIT continued gathering information on the 'Kursk'.

In Brussels in the early autumn of 2000, the Kursk Foundation was set up, headed by the former Dutch Defense Minister Wim van Eekelen and the former Russian Foreign Minister Alexander Bessmertnykh. The foundation was concerned about possible environmental consequences of the disaster in the Barents Sea caused by the nuclear reactors on board the 'Kursk' and worked hard to obtain both international cooperation in this matter and the necessary funds.

SMIT wanted to undertake the risky salvage operation using 'proven technology' and 'just hoist up' the 'Kursk'. This approach required the deployment of Heerema's semi-submersible crane vessel 'Thialf', that however could not and was not permitted to sail with a load in its rigging. To overcome this problem, the lifting cables would have to be fed straight down through a large barge. Thus, the 'Kursk' would be hoisted and pulled against the underside of the barge and be held there.

This plan was approved by Rubin and in December 2000, consortium negotiations, involving SMIT, Heerema and American Company Halliburton, started for the salvage assignment. The aim was to carry out the salvage operation in August 2001.

When, in mid-April 2001, it appeared that the consortium that SMIT belonged to could not carry out the salvage operation during 2001, simly because the necessary equipment could not be available in time, Rubin summoned the Mammoet director, in secrecy, to St. Petersburg.
After discussing options with his engineers, the Mammoet director informed Rubin that, as far as Mammoet was concerned, the salvage operation could still be carried out in 2001. On 16 May, SMIT's consortium was informed that it had lost the contract because it could no longer carry out the salvage operation in 2001.

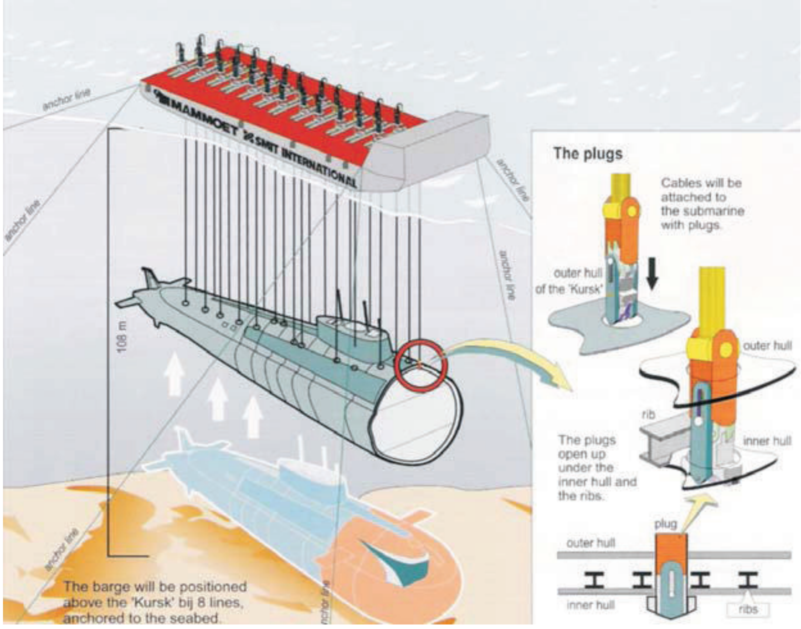


Figure 4   Depiction of the lifting plan. A barge equipped with 26 lifting units is to raise the 'Kursk' horizontally to the surface. The lifting cables are attached to the frames using large grippers (plugs). This requires the cutting of holes in the sub's exterior and interior shells.

Upon finding out who actually won the contract, SMIT director Nico Buis called Mammoet director Frans van Seumeren. The message from Rotterdam was: 'Congratulations, but you can't do it alone'.
The very next day negotiations at the Mammoet headquarters in De Meern resulted by evening in a 50:50 joint venture between Mammoet and SMIT to salvage the 'Kursk'. SMIT was to be responsible for the nautical part of the operation; Mammoet being responsible for the lifting.

The Preparatory Stage

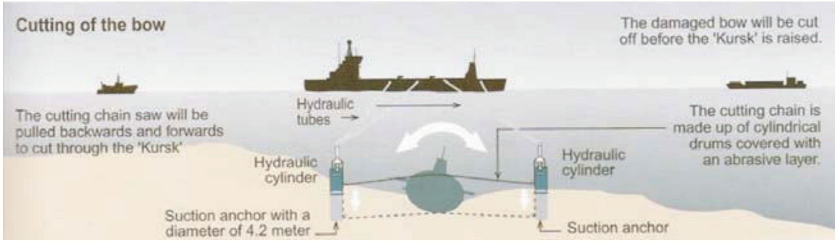
The salvor's plan involved using a large single barge, on which the strandjacks (lifting jacks), complete with sea swell compensation units had to be fitted. Lifting cables had to be fed straight down through the barge and part of the underside of the barge itself had to be cut away to make room for the 'Kursk's' conning towers.
On top of all that, accommodations for about 50 salvage workers had to be placed on the deck of the barge.

Besides the problem of constructing the equipment for the salvage operation, another problem was formed by the foremost compartment of the 'Kursk', which was badly damaged. After all this was where the torpedoes, which had probably all exploded, were located. The Russian authorities insisted and in the end the salvors also decided that the submarine's nose had to be sawn off.

In the little time left for preparation, the salvors had to face the problem of constructing the necessary equipment, getting all the parts delivered in time and going through the excessive amount of paperwork.

In respect of the technology to be deployed, only the strandjacks were familiar territory. But soon the lifting cables generated a problem: Were do you store 26 bundles each consisting of 54 cables that are 150 metres long? The original plan to simply store the bundles on deck was abandoned in favour of the plan to coil the cables on spools.

Figure 5: Before lifting can commence, the badly damaged bow has to be cut off. SMIT designs a special cutting wire for this job that is to be placed over the nose and 'saw' its way through it and down to the seabed.



The basic idea for using grippers (plugs) came from the Rubin engineers. These grippers, that had to meet very tight specifications, were designed and manufactured by Huisman-Itrec in Schiedam (NL). When the Russians, after the testing of the first two grippers, approved for follow-up production, they were informed that the rest of the 26 grippers were as good as ready. Time pressure had made it imperative to start the manufacturing process for the remaining 24 grippers immediately.

To saw off the foremost compartment of the 'Kursk', a new system, only tested two weeks before the sinking of the 'Kursk', was chosen to be used. In this new system, a chain or cable is wrapped in sleeves made from joined pieces of ultra-hard steel. For the sawing off of the 'Kursk's' nose, the decision was taken to go for large suction anchors on opposite sides of the 'Kursk' to guide the sawing cable. The driving mechanisms were finally decided to be hydraulic cylinders mounted on top of the suction anchors. With the aid of all suppliers, components that would normally take eight months to deliver were ready in just a couple of weeks.

The joint venture with SMIT also involved the deployment of the barge 'Giant 4'. This semi-submersible 140 metre long and 36 metre wide barge was - till then - used for loading material onto its deck. For this job, however, the load was to be held under the barge. This meant that the 'Giant 4' had to be extensively rebuilt. At the Shipdock shipyard in Amsterdam for weeks on end, hundreds of people worked extremely hard on the conversion. Large pieces of steel were cut away from the floor to make room for the 'Kursk' conning towers. A hole was cut to the size of 30.6 metres by 8.44 metres. About 2000 tonnes of steel were added at various points to strengthen the structure in compensation for this hole.

In addition, so-called saddles were fixed to the floor of the 'Giant 4', against which the 'Kursk' would be held once it had been hoisted up.

Furthermore, 26 conduits were drilled straight down through the barge, through which the lifting cables would be fed. On top of these, the lifting units were placed: each consisting of a platform holding the five-metre high cylinders of the swell compensation system and the strandjacks, and on top of the latter the cable spools.

During the salvage operation itself, about 50 people would be at work on board the 'Giant 4'.

Figure 6: A large hole is bored in the underside of the 'Giant 4' to completely accommodate the conning tower of the 'Kursk'. The hole measures 32 metres by 9 metres.

Since the vessel had no accommodation itself, for this operation the deck of the barge was filled with containers containing berths, a 'canteen' and a galley. Huge tanks containing drinking water were also fitted on the deck. Other containers placed on deck contained liquid nitrogen for the swell compensation system as well as all kind of auxiliary equipment. For insurance and classification purposes mainly, every piece of equipment had to be described in detail.

Although the strandjacks were familiar territory, the use of 26 of them at the same time formed a problem. A lot of them had been engaged for other jobs and in the end three quarters of the 26 jacks required were manufactured especially for this job at Hysdrospex in Hengelo (NL).

The existing computer equipment could be used to control 20 strandjacks (good for a total capacity of 18,000 tonnes). Rubin insisted to have 26 lifting units, based on the fact that the submarine hull damaged by explosions might not withstand the pulling force of a strandjack. Luckily, a second control unit with software that allowed the two computers to work together could be supplied.

Although it appeared that all safety systems on board of the 'Kursk' had worked properly and that both nuclear reactors had been shut down automatically, a strict nuclear safety plan had been devised. The nuclear component also made it difficult to obtain insurance cover for the entire operation. In the end it was a consortium of Russian insurers for nuclear related policies that provided necessary cover.

The Salvage Operation

On 6 July, DSND Subsea Ltd., which was hired for the diving activities, sent the Norwegian diving ship 'Mayo' from Aberdeen to the Barents Sea. On the spot, the Scottish divers, assisted by Russian navy divers, who have specific know-how about Russian weapons, and SMIT's own divers flushed away the mud, cleared away all of the pieces of wreckage and other junk and started cutting the first two of the 26 holes in the hull of the 'Kursk'. The divers worked around the clock, in three teams, each shift lasting six hours. In order to avoid the time-consuming process of decompression after every dive, the salvage team used the so-called saturation technique, whereby the diving teams breathe a mixture of oxygen and helium. This allowed the divers to remain as much as 28 days under the same pressurized conditions, followed by a four-day decompression period. The divers descended from the 'Mayo' to the wreckage of the 'Kursk' in a diving bell. Two divers carried out the work, while a third one remained behind in the diving bell as their 'protector'.

The drilling of the first two holes was problematic, due to the eight centimeters thick rubber cladding of the hull, which was intended to reduce sonar noise. The problem was eventually solved by removing the cladding with thermal lances.

Components for the saw arrived at the port of Kirkenes in Norway from all over Europe. Within a week, the entire unit was constructed there and computer operating programmes had been written or modified. The first 'dry' tests revealed however that the sleeves on the sawing cables were not up to scratch. All 1500 saw sleeves were sent back to Rotterdam for modification. A second test, carried out a week later, proved to be more successful.

Figure 9: The 'Giant 4' under bright lights. The operation proceeded round the clock, as time was of the essence.

The two huge suction anchors had already been suspended under the barge 'AMT Carrier' before it was towed to the Barents Sea on 20 August. Each anchor was more than 12 metres high and had a diameter of three and a half metres. With the addition of the cylinder fitted on top, each complete unit was over 26 metres high and weighed 85 tonnes. As soon as the 'AMT Carrier' arrived and was positioned above the 'Kursk', the anchors were lowered to a depth of more than one hundred metres. Although in just a few hours, 20 percent of the hull was being sawn, the snapping of a hoisting cable caused tha salvors to run into some delay for the first time.

When the first compartment of the 'Kursk' had been sawn off, the ocean-going tug 'SmitWijs Singapore' towed the 'Giant 4' from the port of Kirkenes to the 'Kursk's' location. In the meantime the divers worked flat out to clean the 26 holes in the submarine's hull.

At the beginning of the final week of September, the lifting barge was in place over the 'Kursk'. The salvors needed three to five consecutive days of good weather to attach the 26 lifting cables to the 'Kursk' and lift it. Unfortunately it turned out that the weather conditions were not only changeable but also unpredictable. Depressions delayed the attachment of the lifting cables. At one point, a new depression, suspected to bring really severe weather, made the salvors even consider releasing the 'Giant 4' from its anchors and allowing it to seek shelter along the coast, a decision that would have made the whole operation hanging by a thread. It was decided though to leave the 'Giant 4' were it was.

It was already October when the first lifting cable was attached to the 'Kursk'. After six cables had been attached successfully, another period of seriously bad weather was forecasted. Luckily, just as unexpectedly as they appeared, the depressions disappeared and the weather prospects became positive. The operation to attach the lifting cables started going smoothly and on the evening of Sunday 7 October (When the first American bombs fell on Afghanistan) the signal was given to start the lifting operation.

A problem was that no one knew how much the 'Kursk' actually weighed in its damaged condition. It was not clear if the submarine had completely filled up with water or if it still contained a lot of air. It was also unsure how the vessel's centre of gravity would behave if the rear was lifted first or if the body of water in the 'Kursk' started sliding. It was not just a question of freeing the 'Kursk' but also of keeping it under control once it had been freed.

However, after just four hours of pulling, the 'Kursk' came free. On Monday morning 8 October, the 'Kursk' was in a state of suspension, six metres above the seabed and safe in the arms of the 'Giant 4's' hoist.

The Journey Home

With the 'Kursk' freed from the seabed, the 'Giant 4' was uncoupled from its anchors completely. At the speed of ten metres per hour the 'Kursk' was raised until it was tight under the lifting barge. While the lifting was still in progress, the barge course was being set for Murmansk, towed by the tug 'SmitWijs Singapore'. It was unsure at that time whether the submarine's conning towers would actually fit into the opening cut for them in the underside of the 'Gaint 4' and also whether the 'saddles' fitted under the lifting barge would fit properly. It was an enormous relief for all those concerned when the 'Kursk' was pulled tight up against the underside of the 'Giant 4' and everything turned out to be all right.

With the raising of the 'Kursk' from the seabed the salvage operation had not been completed, as the 'Kursk 'still had to be transported to a huge dock at the Russian village Roslyakov. Because the combination of the 'Giant 4' and 'Kursk' lied to deep in the water to enter the sunken dock, they had to be hoisted up together using two auxiliary barges specially built for this purpose. These two barges, the 'Mar' and the 'Gon' were not as stable as people would like. In fact, the 'Mar', which was the first to be submersed and positioned halfway under the 'Giant 4' was almost lost.

At dawn on Sunday 21 October, the 'Kursk' together with the 'Giant 4', borne by the two auxiliary barges, began the final section of 'the journey home' to the dock.

At the dock, 200 tonnes of equipment were quickly hoisted of the deck of the 'Giant 4' and 400 tonnes of ballast water were pumped overboard since it turned out that the combination of the 'Giant 4' and 'Kursk' and auxiliary barges was still too low in the water.

The next day, the 'Giant 4', this time without the 'Kursk' floated out of the dock on the two auxiliary barges. As soon as they had left the dock, the captain of the 'Giant 4', Piet Sinke, gathered all remaining salvors on the quarterdeck of the 'Giant 4' for a brief speech and a moment of silencem, a gesture very much appreciated by the Russians.

The 'Mar' and the 'Gon' were disconnected without any problem and barely a week later, the 'Giant 4', towed by the 'SmitWijs Singapore', arrived in the Norwegain port of Kirkenes. Upon arrival the crew was flown back to The Netherlands, a fresh crew would pilote the 'Giant 4' home.

At the end of November 2001, the Dutch salvage crews were welcomed to the Kremlin by President Putin with all honours. In their own country, the Dutch Minister of Transport and Public Works Netelenbos honoured the salvors by awarding them the Michiel de Ruyter medal.

Figure 10: The whole floating hulk is so high in the water that it can be manoeuvred into the dock, where the 'Kursk' is carefully positioned on supports.