The Rise and Fall of the 'Electronic': Strand Electric's Thyratron-based Stage Lighting Dimmer

David R. Bertenshaw, Version 1.0 13th March 2024

Abstract

Between the two world wars British theatre was very conservative, and despite technological lighting dimmer developments in Europe and the USA, continued to solely use large resistance dimmer switchboards. After the second world war, new American dimmers using thyratrons challenged this complacency in Strand Electric's management. Strand then also applied this technology by introducing a novel three valve, DC, phase control dimmer in 1949 called the 'Electronic'. The design offered two presets with dipless crossfading and obviated the need for an increased mains supply voltage to overcome valve loss. All other manufacturers used conventional two valve AC phase control arrangements, needing a boosted supply. Unfortunately the many drawbacks of Strand's approach and poor reliability led to a short market life of just five years.

This paper studies the incentives to its invention and the design and method of operation, together with its many problems which led to an early market withdrawal. Competitive products are also reviewed and the surprising pedigree of the inventor, James Templeton Wood, is revealed. Despite the difficulties, the Electronic provided accurate presetting of lighting levels to the British stage for the first time, thus many sales occurred with some systems remaining in service for over 20 years.

Dedicated to the memory of
Jennifer Kathleen Bertenshaw (1942–2023)

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1. Introduction

In the period between the two world wars (and afterwards) the major and in some respects dominant British theatre lighting supplier was the Strand Electric & Engineering Company Ltd. This company reflected the very insular attitude to theatrical development prevalent in Britain. Allardyce Nicoll (Nicoll 1928 (reprinted 1975)) lamented in 1928 '*the English theatre at the present time is almost completely stagnant…a darkness of outworn tradition hangs over the professional theatre*'. In consequence stage lighting control was dominated by simple resistance dimmers and large manual switchboards, ignoring the developments abroad in Germany and the USA where multi-presetting and load independent auto-transformer dimmers flourished.

This changed after the second world war, with an important British milestone in theatre lighting technology being Strand's 1949 introduction of electronic dimming using thyratron valves, permitting instant response, load independence and multiple presetting. The system was marketed as 'Strand Remote Control – Electronic Type' to discriminate it from the existing 'Strand Remote Control – Electro-magnetic Mechanical Type' (aka Light Console), but was commonly termed the 'Electronic' (1953d). The system was invented and electrically designed by James Templeton Wood, leading to both its inventor and the invention's common nickname, 'Woody'. It was peculiar in that it used three phase, half-wave, phase controlled rectification rather than the well-established single phase full-wave phase control. While this gave some advantages, it caused substantial problems resulting in its early demise in 1954.

There was little published about the design of the Electronic dimmer. The main sources are documents in the Strand/Bentham archives in the V&A Museum and the Backstage Heritage Collection (Theatrecrafts.com 2023), plus the salvaged desk, valve rack and records from Manchester Opera owned by Jim Laws (Laws 2018). Fortunately the V&A archive have copies of the (assumed) final version, while the Manchester records had incomplete but recoverable circuits from its era.

Rob Halliday published a short description of the system in 2018 (Halliday 2018). This paper extends that work with studies of its detail operation and flaws, how this particular design interacted with mains supplies, and its comparison with more conventional designs. An explanation of the special isolation transformers eventually needed is also provided, while an outline of Wood's life and surprising family history is appended.

2. The Problem of Presetting

The first electric stage lighting controls in the 1890s continued to emulate those of the preceding gas lighting systems, with a single control (now a rheostat) for each circuit. Consequently. even though the lighting could be suitably balanced for each scene, the levels for each light for that scene, the state plot, still had to be converted to the changes for each dimmer needed to proceed from scene to scene, the track plot (Bertenshaw 2023). Making all these changes simultaneously could require many operators if the changes were substantial. It was clear that ideally each scene's lighting levels should be capable of being preset in advance, but this was mechanically impossible with the early systems, where dimmers could only be simply locked to common shafts for combined operation. Strand's classic Grand Master system shown in Figure 1 was typical of this style.

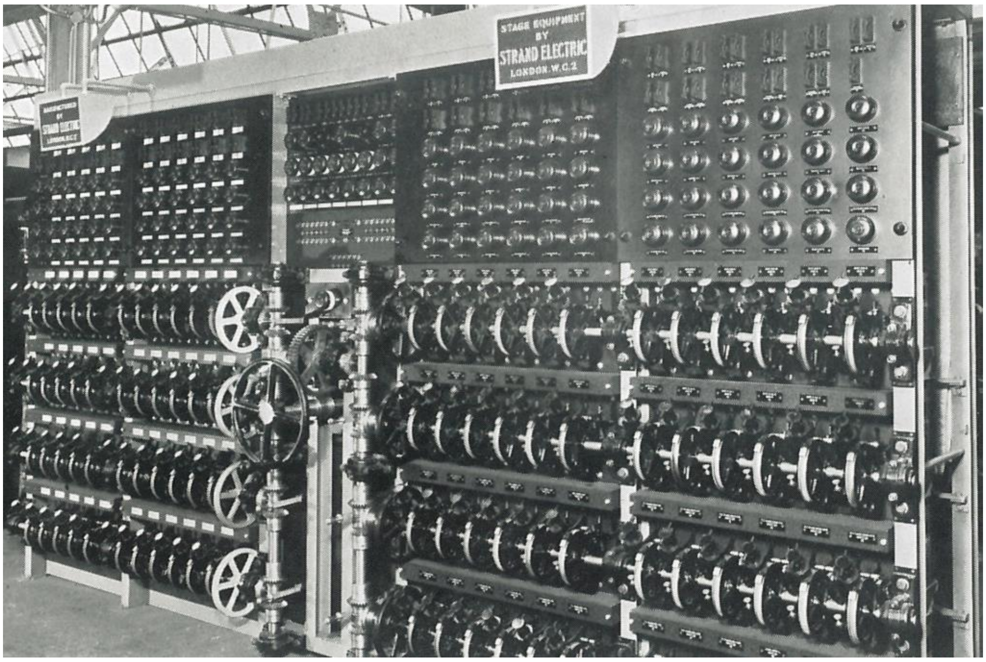

Figure 1. Strand Grand Master switchboard, 1930s (Theatrecrafts.com 2023)

The problem was first solved in 1926 by Siemens whose tracker-wire operated dimmers had small regulating handles that could be set to rotate in either direction for the same shaft rotation and cease movement at a presetable level (Thormann and Wahl 1936). This enabled a completely new scene to be preset and then presented simultaneously by one operator once the master shafts were turned. This was soon taken up by the other major German supplier AEG and thus presetable lighting controls[1] in the major theatres and opera houses became standard practice across much of continental Europe in the 1930s. Similarly in the USA, the invention of the thyratron permitted two preset electric control of saturable reactor dimmers in the 1929 General Electric (GE) Selsyn system (1929). Siemens in Germany also investigated the use of thyratrons in 1932 as an alternate to their Bordoni auto-transformer dimmers, but rejected them due to excessive losses (Jahn 1932).

Despite these clear advances in presetting overseas, the British stage continued to be dominated by simple switchboards, preferring tradition and economy over competence. Fredrick Bentham of Strand conceived and had manufactured his 'Light Console' in 1935 which also permitted one operator to control >200 lights. However this had no ability to preset levels; the operator could choose which circuits to raise and lower simultaneously, but then solely judged by eye when the right levels were reached. The first sale was not until 1940. This British insularity was endemic, even John Christie who worshipped German opera and imported Siemens Bordoni auto-transformer dimmers for his new 1934 Glyndebourne opera house, still used a simpler, British manufactured uni-directional preset control (Reid 1977). He thus lost Siemens' bidirectional presetting.

[1] Only ever two presets, the current state and next state.

3. The Rise and Fall of the 'Electronic' Dimmer

3.1. The challenge of Izenour

In 1945 Strand Electric was in poor shape like most British industry at the end of the war, with severe materials shortages. Demobilised staff were drifting back as the factory turned from war work back to theatre lighting equipment. One important aeronautical engineer, Morgan McLeod[2], who performed much of the T.A.T. design[3] during the war, stayed on as mechanical designer. The lighting dimmer product offerings were no different to the late 1930s, being manual Sunset and Grand Master (GM) resistance boards, plus Bentham's idiosyncratic Light Console remotely controlling Mansell clutch operated, resistance and transformer dimmers (1945). Strand's R&D at the time was a diffuse affair having various contributors, with the current leader, Frederick Bentham, confined to a sanatorium with tuberculosis by 1946 (Bentham 1992).

To rebuild sales, the redoubtable Theatre Sales Director, L. G. Applebee[4] embarked on a lecture tour of the USA, and sent back 15 letters of his findings (Bentham 1992). On 3rd May 1947 he wrote (Applebee 1947):

> *'Had a delightful day at Yale. Lunched with the Rowing Coaches and was shown all over the Sports Associate building… The main excitement is the Thyratron Board which is very, very near Bentham's Console, so near that I doubt we would ever sell one of ours against this... The Inventor, George Izenour, is full of enthusiasm as much as Bentham, and it has been put over on very good publicity.'*

This was very soon after Izenour's first Yale thyratron dimmer demonstration in April 1947, though it was not until October 1947 that an R&D meeting[5] under Strand's Managing Director (later Chairman) Jack Sheridan[6] authorised investigations into thyratron dimming (Bentham 1983). Post-war austerity limited investment thus it is notable that Strand dedicated considerable resources at this project. Though bed-bound, Bentham was kept informed and already lobbying for his version of design, asking for 'thyratron control (indirect)' to be investigated, being essentially motor-driven so could be controlled by his Light Console (Bentham 1948-50). Fortunately the sole engineer in Strand with any electronics experience (Wood) was over 200 miles away from Bentham, so was able to ignore his retrograde design strictures. Regardless Bentham did acknowledge something had to be done and despite his beloved Light Console, accepted that presetting finally needed to be offered. He later wrote (Bentham 1992):

> *'Strand simply had to have an electronic valve system to challenge George Izenour's; by now taken up by Century Lighting in New York, and that meant for the middle range, the majority of first class installations, the customer would have the choice of a preset type of control.'*

[2] Later to be the designer of the iconic Patt 23 and Patt 123 luminaires.
[3] Torpedo Attack Trainer, simulators used to train pilots, jointly manufactured by Link and Strand (Corry 1979)
[4] Joel Rubin of Kliegl considered Applebee as being at 'Prime Minister' level (Rubin 2017).
[5] This did not then include Wood or Percy Corry.
[6] Actual name John David Hatton Sheridan, commonly called Jack. He was son of the founder Phillip Sheridan.

3.2. Wood's three-phase idea

James Templeton Wood was an electrical engineer and trained RNVR officer in early radar systems (Dover and Europe), as described in the Appendix, but had probably not been involved in design engineering. On demobilisation he joined Strand as Assistant Manager to Percy Corry at Strand's Manchester Branch on 1st March 1946 (Bentham 1964). Corry, being a Strand director, was copied on the Applebee correspondence, which also described Applebee's visit to the Radio City Music Hall G.E. thyratron/saturable reactor console with five presets. Corry discussed this all with Wood, and they agreed something needed to be done (Wood 1974).

Wood recalled a naval design for a three-phase, half-wave, thyratron controlled radar power supply with DC output as a possible solution, rather than the single phase AC Izenour design. After much correspondence with Sheridan, Applebee and Bentham, permission was given to purchase valves for a one channel prototype. It was developed in the disused chapel (used for storage) next door to the Manchester factory and it worked (Bentham 1983). The detail design and operation are analysed in section 4.

The first prototype was taken to London for the R&D meeting on 9th March 1948 (Bentham 1983). This clearly encouraged everyone since Wood was instructed to complete a 6 channel prototype '*with all possible speed'*. Though Bentham was in hospital with TB, Corry and Wood were now attending the monthly R&D meetings which delegated McLeod to complete the mechanical design including faders and switches (Bentham 1983; Wood 1974). It is curious that at the March 1948 demonstration, the initial advantages foreseen did not include multiple presetting, though by June 1948 this was being publicly promoted (Bentham 1948). It was also decided to name the product 'Strand Electronic Control' though the brochure eventually called it 'Strand Remote Control - Electronic Type' (c1950).

The 6 channel, two preset prototype was completed as shown in Figure 2 and demonstrated in London to apparent satisfaction on 12th April 1948 (Bentham 1948-50). It was decided to manufacture a 36 way prototype, with 500 thyratron valves immediately ordered. Valves suitable for 4 kW loads were also identified and ordered. Though these were never marketed, some 4 kW circuits were supplied to the Royal Shakespeare Theatre, Stratford-upon-Avon. Reliability trials were initiated, involving both 3,000 hr continuous operation and repeated switching on/off. There is no record of problems from these tests.

Wood transferred to the London office by 1949 to complete the design and start promoting it. He did not join R&D (Bentham's domain) but was put under 'Sales Other', being all exports, however he remained involved in R&D work and decisions. McLeod in R&D designed the new one inch pitch preset faders and the (novel to Strand) sheet metal valve racks (Bentham 1983). The new design was announced in Tabs in 1949 (1949c) with a glowing endorsement by Basil Dean, though the scant photographs indicated it was still work in progress.

It may seem curious now to propose a DC output, but immediately post-war there were still a considerable number of DC supplied premises, including theatres, so was then a familiar technology[7]. Stratford-upon-Avon had a 230/460 V DC supply for its Grand Master dimmer system until replaced with AC for the new Electronic system in 1951 (Bentham 1972).

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[7] The last London theatre to convert to AC was Drury Lane which did not change to AC until 1954 (Applebee 1954). Film studios retained DC lighting supplies for decades later.

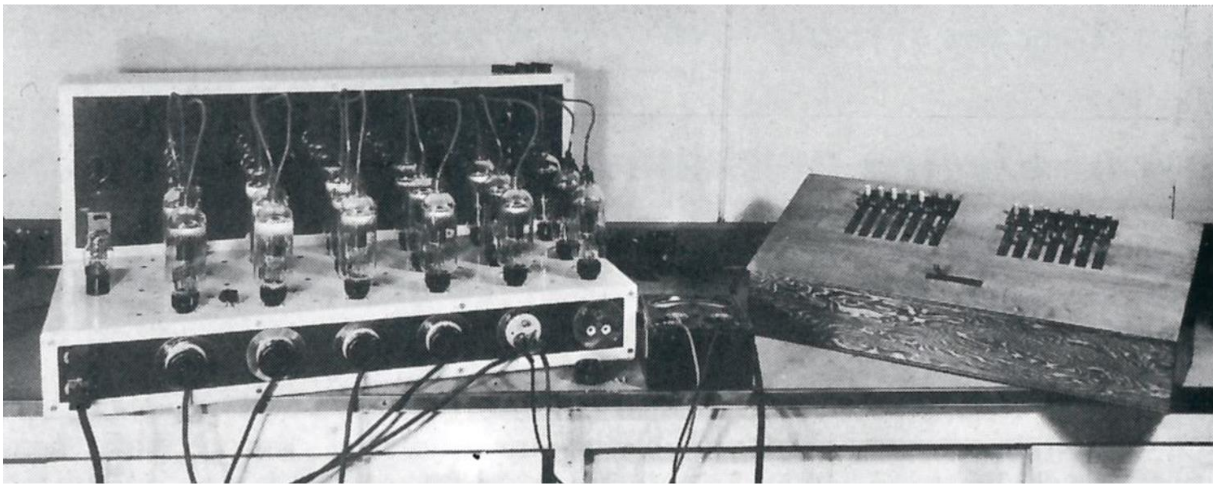

Figure 2. 6 channel Electronic prototype (Bentham 1983)

The functionality derived from several sources (Wood 1974). Wood knew from GM experience that full crossfading was vital. The compromise bi-directional shafts on GMs never worked well and '*used to tie people up in knots, still needing lots of extra operators'* Wood noted, despite the auto-release handle locks[8]. He had seen a better concept at Paramount Glasgow where a new Major Bell[9] 'X-Board' had bi-directional dimmer handle locks on the shafts, allowing proper crossfading with resistance dimmers. The rows of 12 faders came however from Applebee who still insisted on supporting four-colour mixing, while the independent switching scheme also closely followed the GM approach. Bentham (Bentham 1964) considered this was needed to '*to pacify the GM traditionalists'*. Bill Lorraine, who had recently joined Strand after working with Basil Dean, is reported to have also significantly contributed to the specification.

The first hint of what the layout might be comes from a Strand Manchester drawing in 1948 (1948c) in Figure 3, showing how the controls could be laid out for a 48 channel system. The master crossfader is shown with the row masters. Interestingly the preset masters and independent masters don't yet appear, although general and independent blackout grouping as on the GM exists. In a similarity to the GM, the central switches for each row that release that row from the crossfader is remarkably similar to the GM clutch arrangement.

[8] These only released at full and zero, not at any preset level,

[9] Major Bell was the cinema consultant to the Paramount Cinema chain (Bentham 1992)

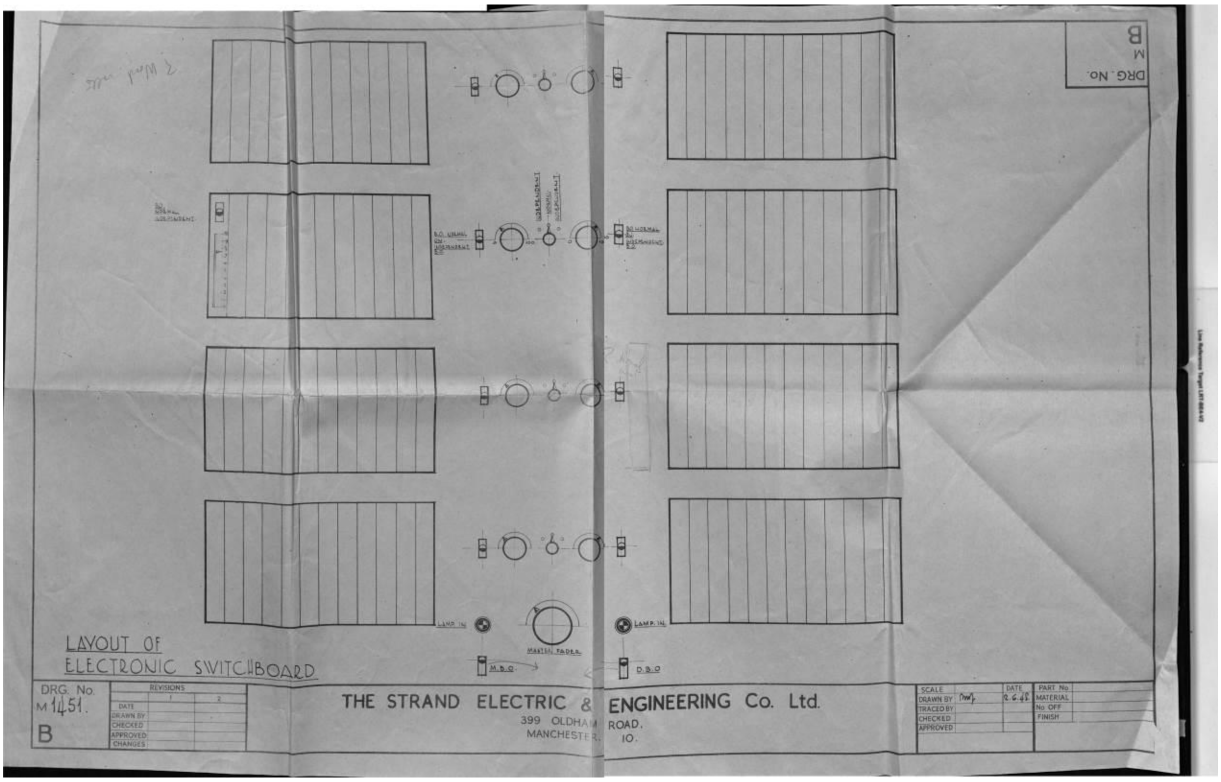

Figure 3. Layout of Electronic Switchboard, 1948 (1948c)

There is an interesting though somewhat contrived 1948 interview with George Devine[10] who considered the present crude methods of control *'reduce what should be an orchestration to the level of driving an Underground train'* (Devine 1948). He was thus asked to describe his ideal console. Not surprisingly he requested close-spaced, finger-strength, finely graduated controls, and proportional fading (he disliked shaft-action fading as often the wrong light goes out first). Ideally there should be four presets for major cues, but even three or two would be welcome. Sensitive hand-controlled mastering should be provided for cues less than 15 sec, plus motor assistance for longer. He looked forward to a console that permitted reproducing the plotted lighting sensitively with the action, but not in the sense of a *'long haired genius playing the lights just as his feelings take him.'* This endorsement was completed with a hint that such a console was to be launched very soon, but it is not clear if Devine's input had been sought earlier.

The pricing was mandated by Applebee who insisted that it could not be sold dearer than a GM, despite its manifest benefits, thus the target of £42.10.0 per way, inc. valves (Wood 1974). The fast/slow gearbox drive was most expensive item at over £1 per way, in a desk costed at £10 per way, and with valves at £15.15.0 per way (three valves) this left little for the rest. These prices however do not correlate with the William Bundy's sales accounts for the Old Vic in Table 1. Regardless, Wood claimed Strand made very decent profits (Wood 1974).

The claimed benefits of this new system were attractive. It offered two presets, each with two groups, dipless crossfade between the presets, instantaneous dimmer response, infinitely variable load, balanced three-phase supply, identical polarity outputs obviating any need to segregate differing phases between areas[11], and by comparison with other thyratron dimmers,

[10] At the time, Director of the Old Vic Theatre School.

[11] Mandatory 6 ft spacing was required between differing phase AC outlets in the UK in 1950 (1950d).

no need for a supply boost transformer. This was the first Strand dimmer system where precise lighting scenes could be reproduced every show, not dependent on the dexterity of the operator(s).

3.3. The Strand Patents

Shortly after the first R&D demonstration, the Electronic dimmer was identically patented in both the UK (Wood 1951b) and USA (Wood 1951a), both with an application priority of 15th April 1948 and granted in 1951. In both Wood was identified as the inventor, with the patent assigned to Strand. However in October 1948, Strand identified a prior art patent by a Mr. Clark dated six months earlier than theirs, which it purchased to protect Strand's application (Bentham 1948-50). This British patent is almost certainly that by Harold Clark applied for in 1947 and granted in Sept 1949 (Clark 1949). While it did not use thyratrons, its use of regular thermionic valves to dim theatrical stage lights[12] from control potentiometers could easily have permitted a challenge.

The patent recites as reason for the invention the 'virtually insurmountable' problems of obtaining compliance with the regulations requiring balanced phase loads and physical phase separation on stages[13]. As solution it proposed and claimed balanced three-phase rectification and DC outputs all of the same polarity.

3.4. Prototype and first sale to Reykjavik

A 48 channel demonstration system was installed in Strand's London demonstration theatre by March 1949. However there were no reported field trials, just a 36 channel demonstrator and the first sale to the new National Theatre in Reykjavik, Iceland in 1949 (Bundy 1983) through the local agent Bachman[14] (Bentham 1964). The design and control details continued to be adjusted through most of 1949, some in response to the Icelandic requirements. In August 1949, it was decided to limit the sales to between 24 and 144 channels (Bentham 1948-50).

After visiting Strand the Reykjavik National Theatre representatives ordered an Electronic system. However when the order arrived Strand didn't appreciate the small three-wire symbol on the power supply specification. The theatre supply was delta wired with no neutral, thus Strand had to additionally supply a delta-star, dimmer system transformer, costing £420 (Wood 1974; 1983).

Bundy (Bundy 1983) reports that this was all still so new, with drawings still being done, that the racks arrived late in 1949 only partly wired and the desk totally unwired. Bundy and Wood had to wire it all on site at night in secret from the client! It seems this was in reality the first field trial which opened in spring 1950. Strand was fortunate in that the later problems didn't occur there (or to a much lesser degree), both due to the dedicated supply transformer and well-ventilated dimmer room (Bundy 1983; Wood 1974).

Strand had also constructed a demonstration system illustrated in Figure 4, which was shown at the UNESCO International Theatre Institute (I.T.I.) exhibition and conference in Paris in

[12] The actual intention was by use of multiple differently tuned filters in the control to permit multitone radio remote control of a multiplicity of lights – anticipating DMX over wireless by 50 years!

[13] This curiously ignores the fact that for many years they had actually been surmounted on stages!

[14] Bachman was reportedly the only theatre electrician in Iceland (Bentham 1964).

June 1950. There was also a paper and presentation on the new system by Wood[15] (Wood 1950). This extolled the virtue of a presenting a balanced load across the three phases and not needing a boosted mains supply as required by Izenour. It however erred substantially on the declared valve current ratings and by declaring its efficiency to be comparable to Saturable Reactor (SR) dimmers. Wood didn't realise that a SR voltage drop is mostly reactive (hence lossless) and glossed over the issue that three valve filament losses occur continuously in every dimmer. Despite Strand's achievement in managing to place Hugh Cotterill as chair of the 'New Technical Developments' session and to get the 'Electronic-System' as subject matter, the extensive reports in Germany's Bühnentechnische Rundschau in 1950 failed to make more than a mention of it (1949d; 1950e; Unruh 1950).

Figure 4. Electronic 36 channel demonstrator at I.T.I. Paris, 1950 (Bundy 1983)

3.5. Sales roll in

After the I.T.I. conference sales continued steadily until 1954, plus the last in 1955 to the BBC at Riverside Studio 2 (Legge 1998). Images of typical installations are shown in Figure 5 to Figure 7 and Figure 15 to Figure 19.

The pricing of 144 channel Old Vic system shown in Table 1 is interesting, where Bundy reports just a 14% profit[16] (Bundy 1983). Bundy gives similar accounts for Kings, Edinburgh,

[15] ITI catalogued the paper as from M. J. Wood, which must have been a typographical error for Mr. J. Wood, since BTR reported the paper as from J. Wood (1950e).

[16] The costs were full ex-works prices. Thus 'Profit' thus still had to cover sales and management costs before a true profit could be declared.

Stratford and New Theatre, which all showed that the customers were sold the valves banks separately. The 100 dimmer system including a 300 outlet patch panel at BBC Riverside Studio 2 was initially quoted in 1955 at £10,036 excluding valves, followed by a reduction to £8,536 on deletion of transformers and switchgear (Strand Electric and Engineering Company Ltd 1955).

(£.s.d)	**Board**	**Valves**	**Total**
Selling price	£2,385. 00. 00	£2,025. 00. 00	£4,410. 00. 00
Cost price	-£2,263. 13. 08	-£1,488. 07. 06	
Profits	£121. 06. 04	£536. 12. 06	£657. 18. 10
less erection			-£53. 18. 03
less W. Bundy's expenses			-£2. 08. 00
less condensers			-£0. 04. 06
Total Profit			£601. 08. 01

Table 1. Old Vic sales breakdown (Bundy 1983)

The system was only sold up to a maximum of 144 ways, while Strand continued to promote Bentham's Light Console for larger installations, the largest at Drury Lane in 1950 of 216 ways (Applebee 1954). This was due to the influence of Bentham who considered that two presets would become inadequate above 144 ways yet disliked the multi-preset boards (5-10 presets) in the USA. Bentham justified this because the Electronic '*could not be used with console memory selection and mastering'* due to lack of inertia (Bentham 1964). He also pointedly described the Electronic as really only a one preset console, due to the other preset being occupied holding current levels (Bentham 1955 (revised 1957)). Regardless, Kliegl Strand's licensee in the USA routinely engineered 5 and 10 preset consoles to meet their market demand (Rubin 2017), while the BBC demanded and obtained 3 presets.

Real customers however saw accurate presetting as being of the greatest benefit (Bundy 1983). Despite the Bentham bias, Light Console sales were just 16 from 1935–1955, whereas the Electronic achieved over 30 sales in its 5 years of promotion and was the death knell for the Light Console (Legge 1998; Morgan 2005). By 1952, the Electronic product brochure (H.61 rev 8/52) listed 14 UK and 7 European installations current or in progress (1952c). The 28 installations that can be identified are given with their installation date where known in Table 2.

National Theatre, Reykjavik	1949/50
Tower Palace Theatre, Blackpool	1950
Grand Theatre, Blackpool	1951
Pavilion Theatre, Blackpool	1953
Old Vic, London	Autumn 1950
Royal Hall, Harrogate	1950
Pavilion, Bournemouth	1951
Criterion Theatre, London	
Kings Theatre, Edinburgh	1951
Kings Theatre, Glasgow	1952
The College, Cheltenham	1951
New Theatre, London	1951

Shakespeare Memorial Theatre, Stratford–upon-Avon (had some 4 kW dimmers)	Spring 1951
Theatre Royal, Hanley	1951
Battersea Theatre, Festival of Britain	Summer 1951 (temporary)
Opera House, Manchester	1951
Saville Theatre, London	1952
Crescent Theatre, Birmingham	1952
Stora Teatern, Norrköping (Moore 2018)	
Stora Teatern, Linköping (Moore 2018)	
Baden, Switzerland	
Zurich, Switzerland	
Växjö, Sweden	
St. Imier, Switzerland	
Interlaken, Switzerland	
Randers, Denmark	1952
Deventer, Netherlands (used Philips PL 57 thyratron)	1954
BBC Riverside Studio 2, London	1955
Australian demonstrator ?	1952

Table 2. Recorded Electronic system installations and date of installation

There was considerable published praise for the product with Richard Pilbrow at the Old Vic welcoming its simplicity (Pilbrow 2018b) and also commenting '*From a lighting design point of view, I loved the electronic; smooth transitions and complex level setting'* (Pilbrow 2018a). Smith at Stratford reported that *'the duplicate panel…is of immense value for saving time, as it is possible to set up the scene…and then plot it while the next scene is being set on the other panel. The cue is also there should the producer wish to go back to the previous scene.' (Peter Paget Smith 1950).* Basil Dean was also impressed, *'I have no hesitation in declaring this to be the most important advance in electrical equipment for the stage that has been made since 1939'* (1949c). The Times, referring to the New Theatre installation in 1950, noted that the control provided for *'the most delicate, intricate, and swift of effects to be controlled by one man'* (Morgan 2005). Their praise was short-lived however once they witnessed the opening night. Early installations were well publicised in the Strand Tabs journal as shown in Figure 6 to Figure 7.

Figure 5. Console and dimmer racks at Reykjavik (Strand Archive 1950; Theobald 1950)

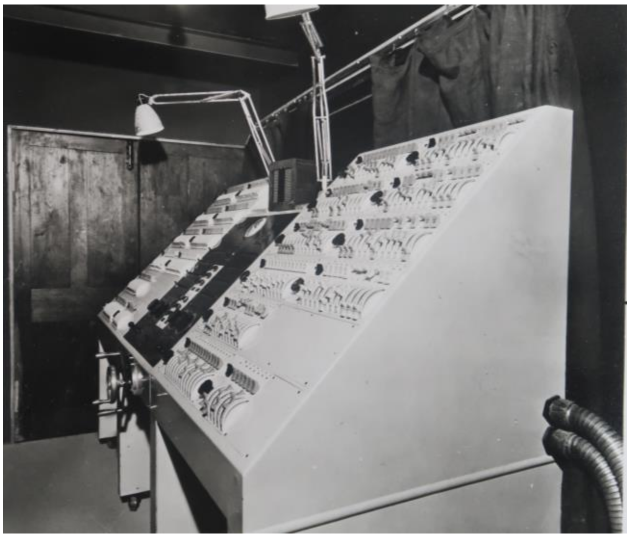

Figure 6. Console at Old Vic, London, 1950 (1950c)

Figure 7. Console at Stratford upon Avon, 1951 (Bentham 1972)

A licence was also granted to Kliegl in USA to compete with the Century/Izenour dimmer. It was sold as the 'Kliegtronic' dimmer rated at 6 kW per dimmer, shown advertised[17] in Figure 8 (1953c). This is reported to be due to the US lighting designer Abe Faber seeing the 1950 demonstration at I.T.I. and lobbying Kliegl. Wood travelled to New York several times to assist their implementation (Bentham 1964; Rubin 2018b). USA sales suffered due to the

[17] Curiously the advertisement showed 2.5 kW dimmers rather than 6 kW.

limitation of two presets, thus Rubin reported (Rubin 2014; 2018a) that local construction of 5 and 10 preset arrays was sometimes necessary. The dominance of the Izenour design in the USA limited the Kliegtronic sales.

Representative cubical of Kliegtronic Dimmer Bank with six 2.5 KW dimming circuits in a 24" cube.

Figure 8. Kliegtronic dimmer cubicle advertisement (1958)

3.6. Troubles mount

The dominant issues during the first two years appeared to be endless valve failures and related issues like flashing and sticking. By April 1950, Corry[18] wrote a ‘we must do something’ memo to Sheridan, stressing that recent ineffective fumbling at Blackpool Palace had shown that everyone, including Wood, appeared out of their depth, and was becoming obvious to the client (Corry 1950). Without resolution, he must cease sales. Blackpool Palace suffered very considerable problems, such that the second Blackpool system in the Grand Theatre was delayed until the problems were resolved. Of note is that the Palace dimmer room had a steam heating pipe in it exacerbating the overheating issues.

The installation at the Blackpool Palace did have supply transformer isolation but was wired in MICC cable, which gave ‘*extraordinary condenser effects’* (1952-54). Fuses liberally blew due to phase-phase shorts, a problem eventually solved by fitting anode resistances (Bentham 1983). A further problematic MICC installation reported was the Theatre Royal, Hanley in 1951. This produced ‘*instability’* in the console and an apparent ‘*mind of its own’* (Anderson 2018). However these issues must have been rapidly overcome since contemporary reports from Hanley talk of the ‘*state of the art electronic console…with 96 dimmers’* and of a successful opening night’s show and following winter programme (Neale 2011)[19].

[18] Corry had authority as he was Director of the Manchester branch for Strand as well as owning his own local theatre supply company ‘Watts and Corry’.
[19] Theatre attendance declined substantially after 1954 causing it to eventually change to Bingo in 1961.

The only theatre reported to have obtained an early replacement was London's New Theatre in 1955 (1955c). The true reason for the New Theatre replacement remain unclear; Bentham (Bentham 1992) considers that lamp sing and general unreliability was the cause, while Bundy (Bundy 1983) blames the dimmer's disastrous opening night of Hamlet in 1951 staring Alec Guinness, lit by Michael Northen (Northen 1997). Rehearsals had been plagued by dimmer problems, then on the first night the operator got totally out of step with the scenes for the first act, as well as several 'stickers' occurring[20]. The Times (1951c) reported the lighting system as 'suffering apparently from an attack of first night nerves'. The Stage (1951b) was much more critical of the lighting (and the acting):

> *'The lighting effects were very odd at the opening performance. It was a sound economical effect to play the battlement-scenes in a total black out…But where during one stage of the scene where Hamlet first sees his father's ghost, the too palpably bare stage was suddenly illuminated by a great light as though a modern occulting light-house was swinging its beam across the sky. No less curious was the device by which the King's face was spot-lit in the midst of an otherwise completely blacked-out stage at the end of the play-scene. Though some of the lighting eccentricities were doubtless due, as has been explained, to technical faults, the excuse can be scarcely advanced in this particular instance.'*

For at least the next three years, managing the problems of the Electronic was a dominant part of the R&D agenda. The Electronic's problems were routinely listed in R&D meetings (Bentham 1950+):

1. Loss of control of a valve (hence circuits would not switch fully off or on),
2. Overheating of valves,
3. Overheating of transformers,
4. Jumps and flat spots in dimming,
5. Change of lamp volts with load,
6. Change of lamp volts during cross over from main to pre-set panels and vice versa,
7. Overloading of valves,
8. Variation in anode current of 3 phases,
9. Unsuppressed surges,
10. Too high a value of grid resistance,
11. Surge on closing down,
12. Excessive dead travel of master potentiometers,
13. Fuses blowing.

In late 1952, when the Midlands Electricity Board refused permission to connect the Crescent Theatre, Birmingham, the awful truth dawned of the high DC currents imposed on the mains and the large neutral overloads, as discussed in section 9.4. Legal opinion was sought on Strand's liability which was deemed absolute. Strand had no choice but to offer to retrofit local transformers to all existing installations (unless already installed), and to supply neutral isolation transformers for new sales.

Despite many resolutions the Electronic's technical problems continued, eternally plagued with poor inefficiency, high maintenance costs and '*operational uncertainties'*. In particular, the realisation that each installation needed a dedicated transformer severely damaged the

[20] Bundy, who attended the performance, reports that he managed to reach the control room and correct the operator by the interval. Northen reports that he too raced to the operator after the first few cues went wrong and managed to get things on track by scene two, fearing this debacle would be the end of his career. It wasn't.

economics. Touring UK companies became very wary of it, with Foster at Blackpool (by then managing three systems) telling Bentham in 1954 *'Electronics are notorious among visiting companies, who want to use their own portables the moment the word is used.'* (1952-54).

Despite the system's problems, several sites achieved long service records, e.g. Reykjavik from 1950 until at least 1974 (Wood 1974), and Stratford from 1951 to 1971 (Bentham 1972). The sole recorded TV installation at BBC Riverside Studio 2 (BBC R2) operated from 1956 to 1968 (Kempton 2018). The records are also dominated by failures from UK installations despite 36% of sales being in Europe. Reykjavik's reliability was put down to it having its own supply transformer and good dimmer room ventilation.

The quiet changes made to the product leaflet from c1950 to 1952 show how the early blasé assumptions were steadily rolled back with experience (1952c; c1950). The initial boast that 'only' 80 W of valve loss per dimmer was much less with than resistance dimmers was removed, as was the need for 'no special ventilation', replaced by an ideal ambient of 80 °F, maximum 100 °F, and no cold draughts. Most critical was the initial complete lack of any electrical installation advice, replaced by introduction of a mandatory need for a supply isolation transformer. Users were further warned that the neutral conductor must be rated for the combined full load current and the phase conductors must be $1/\sqrt{3}$ sized rather than the usual 1/3. However Strand still erroneously thought in 1952 that, if fed by a delta/star transformer, the system was unity power factor.

3.7. Product withdrawn and replaced

The Strand R&D committee finally withdraw it from UK sale in January 1954 (Bentham 1983). This did not prevent the last sale to BBC Riverside Studio 2 of 96 ways in 1955. This was special with 120 V output and used the Zenon-filled XR1-6400 thyratron (1959) rather than mercury thyratrons. It too remained problematic despite Strand, Mullard and the BBC conducting tests on an initial three channel prototype (Nickels and Grubb 1957). The BBC also compounded their teething problems by choosing to buy the thyratrons themselves[21], thus Strand could and did wash their hands of any valve problems (Bentham 1992). The BBC Riverside Studio 2 report compares it with Riverside Studio 1 equipped with a System C using preset-able electro-mechanical dimmers, and concludes (Hersee and T 1957):

> *'By comparison with the electromagnetic clutch driven resistance and auto-transformer dimmers which have been installed in Riverside 1 as a further experiment, thyratrons do not show up well. Their advantage of a low space requirement is offset by the disadvantages listed above[22]. None of these seven criticisms can be levelled at the Riverside 1 installation.'*

The Electronic and Light Console products were replaced in 1955 by redesigned electro-mechanical preset dimmer system PR (replaced the Electronic in the New Theatre in 1955) and

[21] Since the BBC was doubtless buying many thousands of valves annually for maintenance, combined bulk purchase would have seemed a sensible economy. However much of Strand's profit came from the valve sales, so it was a disincentive to support. It seems from Bentham's description when visiting BBC R2 (Bentham 1992) of '*air hot with thyratron valves and thick with tobacco smoke and despondency*' that design problems were mostly left up to the BBC engineers to sort out for themselves. They were anyway probably better qualified than anyone in Strand – they even had oscilloscopes!

[22] Inefficiency, hum interference, lamp filament vibration, variations in dimmer law, interaction, fuse blowing and thyratron replacement cost.

with added memory grouping in systems C, CD and CD/W. By 1953 Strand was also offering Saturable Reactor dimmers with multiple presets for smaller installations.

While 30+ sales of the Electronic in 5 years was a considerable advance on the 16 Light Consoles previously over 20 years, 190 of the replacement electro-mechanical systems (C, CD and PR) were sold in the next 5 years (Legge 1998). They were (for the entry level PR) cheaper, but also much more reliable and easily maintained by the theatres. The rapid rise of TV in the 1950s also ensured many extra sales to new TV studios.

In the USA Kliegl continued to market the related Kliegtronic until 1960 despite the arrival of the first 120 V thyristor dimmers[23] in 1958 (1960a; Rubin 2018a), selling in total about a 'couple of dozen' systems.

[23] The Century C-Core dimmer (1918-1999).

4. Thyratron Dimmer Technology

4.1. First use of thyratrons

The thyratron[24] is a type of thermionic valve invented in 1929 (Okamura 1994). It is constructed like a triode valve, with heated cathode, control grid and high voltage anode. However it also contains a small amount of gas which, when electron conduction starts, ionises and maintains the conduction. In the case of the UK Electronic dimmer the gas is mercury vaporised by the cathode heater. If the grid is held significantly negative to the cathode conduction is prevented. However once the grid-cathode voltage rises above about -5 V, conduction starts and the ionised mercury then maintains conduction regardless of the grid voltage. Conduction only stops when the anode voltage falls to zero, resetting the thyratron ready for the next cycle. Its operation as an electronic switch is comparable to the modern thyristor.

The thyratron was immediately used in stage lighting to control the input current of Saturable Reactor dimmers in the General Electric (GE) Selsyn system (1929), and first installed in the Chicago Civic Opera house in 1929 (Izenour 1988). The low control current permitted presetting, with probably the most famous installation being Radio City Music Hall, New York, with 320 dimmers and 5 presets, installed by GE in 1932 (Blalock 2017; Izenour 1988).

Thyratron controlled Saturable Reactor dimmers did not appear to find favour outside the USA. One notable exception in the UK was the British Thomson-Houston (BTH) system installed at the Odeon 'Super Cinema', Leicester Square, London in 1937 (1937d). BTH was a subsidiary of GE, and the BTH system was patented in the UK (Whiteley 1936). The installation was described in the trade press (1937)[25] and given that Wood was involved in 1930's cinema installations in Scotland, Tim Hatcher (Hatcher 2018) thinks it is very likely that Wood would have read about it and seen BTH publicity material (they also supplied projectors, amplifiers etc.). Wood however does not comment on it personally (Wood 1974). Certainly Bentham knew all about it, having written it up in detail by 1950 (Bentham 1950)[26].

The BTH Odeon system had 52 stage and 14 auditorium dimmers totalling 180 kW, with dual stage and projection room consoles, and two presets with a dipless master crossfader, something Wood would replicate after the war. However the design, illustrated in Figure 9, was unreliable and was replaced after only a few years by directly controlled dimmers (Hatcher 2018).

[24] The name is derived from the Greek *"thyra"* meaning a door.

[25] This cinema was by far the UK's most expensive and lavish; at £110 cost per seat to build it was 4x other cinemas. It could and did afford the best of everything.

[26] Strand supplied all the stage lighting equipment at this very prestigious venue, which Bentham still referred to by its previous Theatre name, the Alhambra.

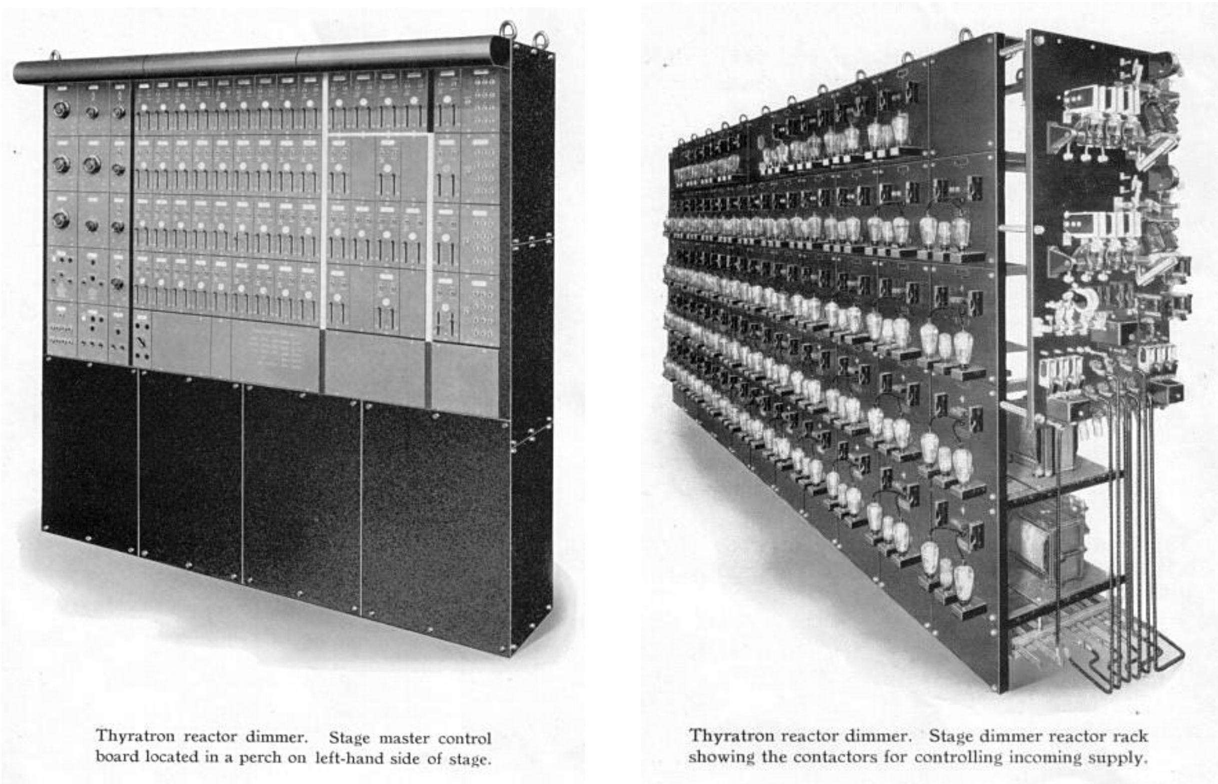

Figure 9. BTH 1937 Odeon thyratron reactor control board and dimmers (1937d)

4.2. The Izenour thyratron dimmer

While Izenour was probably the first to use thyratrons to directly dim stage lighting in an actual production in 1947[27], he was not the first inventor. The thyratron had already been patented as a theatre lighting dimmer by Brettel (Brettel 1941), whose US patent for two antiparallel thyratrons using phase control, was applied for in 1939. Izenour acknowledges this precedence and his 1941 discovery of it, in a footnote in his book (Izenour 1988). He then commits a fraud on the US Patent Office by failing to disclose it in his patent application of 28th August 1947 (Izenour 1949). (Brettel's patent was disclosed in Wood's US patent prior art.) Izenour's basic design is shown in Figure 11 and the first installation in Figure 44

4.3. The Strand Electronic three-valve thyratron dimmer

Thyratrons were used in many types of wartime radar sets to pulse modulate transmission and to regulate DC power supplies, in which Wood was trained. They were also common in DC motor drives, so would not have required much post-war invention.

The Strand Electronic dimmer is a system where three thyratron valves perform half-wave, phase-controlled rectification from the three-phase mains. The output is pulsed DC always of positive polarity. Since all three phases are used for half-wave rectification in each dimmer, the load is spread equally across the phases. However since all dimmers are the same polarity, the neutral return current is the DC rms sum of all the dimmer outputs, there is no contra-phase

[27] Izenour's dimmer development was in fact very long-winded, starting out in Yale in 1939 as a breadboard demonstrator to get funds to establish his theatre laboratory. A first prototype was installed in Yale in 1941, but before it could be completed the USA entered WW2, diverting Izenour to naval research work. This provided valuable training in professional engineering which only finished in 1946, enabling him to complete the Yale dimmer project in 1947.

cancellation. This requires the neutral supply conductor to be rated for a higher current than the phases, and the supplying transformer or utility service to be able to support large DC currents in both the phases and neutral. This was not formally appreciated by Strand until October 1952 (Bentham 1992).

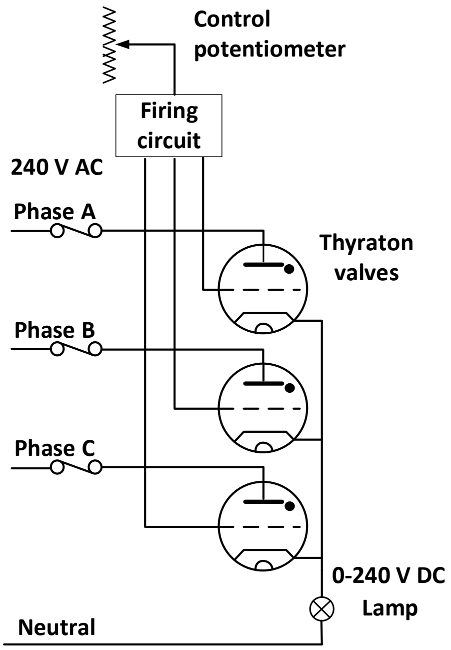

Figure 10. Wood's half-wave, three valve dimmer

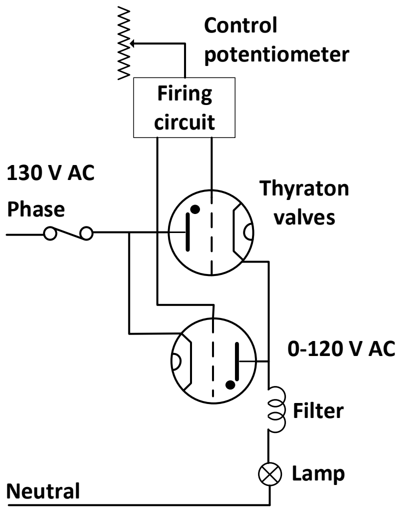

Figure 11. Izenour's full-wave, two valve dimmer

The Electronic's design is shown in Figure 10. Even though it uses three valves vs two valves in the antiparallel connection used by Izenour in Figure 11, it avoided the need for a system voltage booster transformer[28] needed by the two-valve design to offset the significant anode voltage drop. Its further lauded benefits were that the load is always balanced across the three phases, and the user has no need to separate outlets on the stage to prevent the risk of phase-to-phase, high voltage hazards. However it needed three fuses per dimmer (rather than one), any or all of which can fail.

Wood's design was also apparently due to the need to obtain 2 kW rating from whatever thyratrons existed rated at 240 V (Bentham 1992). This led to at least three valves being needed in parallel, suggesting the three-phase arrangement. The design further avoided the need for extra thermionic valve firing circuits as used by Izenour, but this was eventually found to be at the expense of drift and variation in firing due to unstable thyratron grid voltages.

One other possibility for this design's adoption is that Wood and Bentham were afraid that George Izenour had UK or European patent applications in progress to match his US patent and cast around for an alternate approach. Anderson reports that Bentham had wanted to use two antiparallel thyratrons for the BBC Riverside Studio 2 project in 1955, '*but was probably prevented by patents*' (Anderson 2017b). In practice there were no patent barriers in the UK or Europe. Strand eventually factored the Swiss Brown Boveri 'Thyralux' two thyratron dimmer (1954) for architectural lighting, and even offered the BBC 5 kW Thyralux dimmers for Riverside studio 2 (Strand Electric and Engineering Company Ltd 1955). However because

[28] However the Electronic was later discovered to still need a local supply isolation transformer.

Thyralux could not be multi-preset, the BBC eventually used motor-driven 5 kW resistance dimmers.

4.4. Modelled Waveforms of the Electronic thyratron dimmer

The Electronic Dimmer has been digitally modelled to determine its effect. For a 240/415 V three-phase main (UK standard in 1950) with 10 V anode drop in the thyratrons (Bentham 1958), full 180° conduction develops an output voltage of 275 Vrms. Consequently the dimmer must be limited to a certain maximum conduction angle (period of conduction per thyratron) to avoid over-volting luminaires. It requires a 111° conduction angle to achieve 240 Vrms output from the 3-phase rectification. Figure 12 shows the resultant dimmer output voltage waveform (conduction from 69° to 180°) over a 360° mains 50 Hz cycle (20 ms), with the input three phases shown dotted.

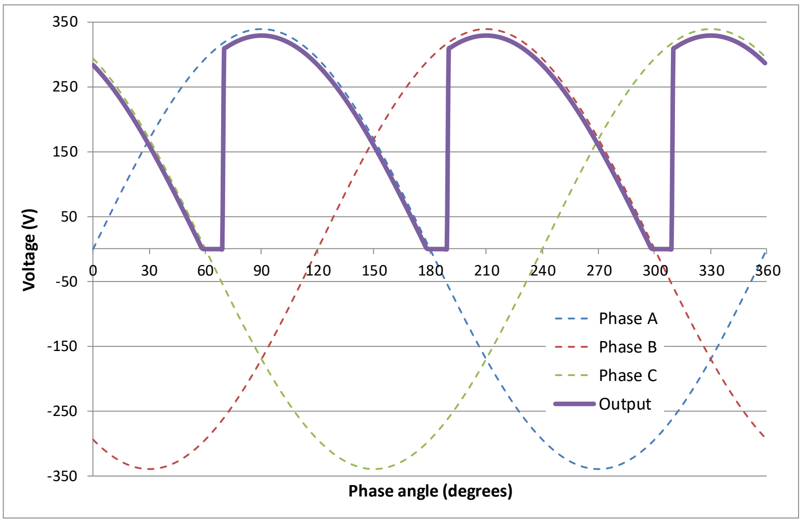

Figure 12. Dimmer output at full voltage (111° conduction)

From this it can be seen that even setting the dimmer to full 240 V output will not prevent lamp sing, there remains a ~300 V sudden voltage step at 150 Hz repetition rate. The only remedy is suitable rise-time chokes. Half output power (170 V rms) shown in Figure 13 and requiring a conduction angle of 78°, still causes a voltage step about the same amplitude, so lamp sing will remain a risk at all useful settings.

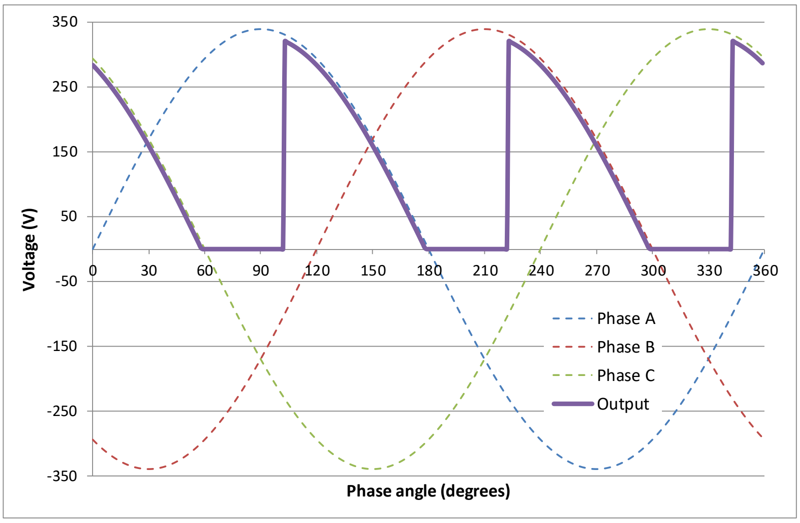

Figure 13. Dimmer output at half power (170 Vrms at 78° conduction)

One of the reported problems of the Electronic was ‘stickers’, being when a thyratron would turn on and remain on fully without being fired and the light stick on. To determine how problematic this might be, the thyratron is assumed to still turn off at zero-crossing else a phase-to-phase short would occur and fuses blow. If one phase (here phase A) does stick at full conduction when the dimmer is set at nominal 240 V output, the dimmer output rises to 253 V as shown in Figure 14. This is not a disastrous over-voltage as long as promptly corrected, and is eliminated by just reducing the control level to that which would have output 220 V. However the stuck dimmer never outputs less than 163 V even when the control is at zero, so will remain very evident.

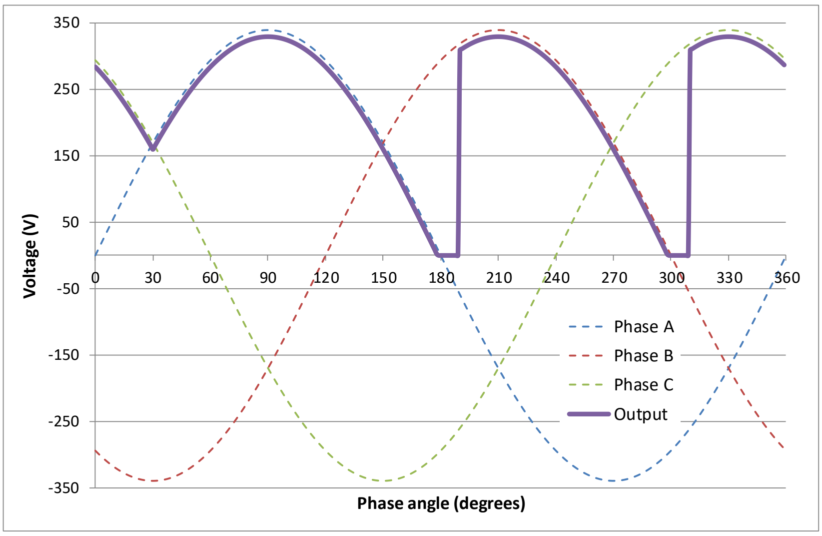

Figure 14. Dimmer output at full with phase A stuck on (253 Vrms)

5. Construction of the Electronic Dimmer System

5.1. General arangement

The system, termed the ‘Strand Remote Control - Electronic Type’ in sales literature, consisted of dimmer banks housed in a locked and ventilated dimmer room, and a separate control console situated ideally with a view of the stage (1953d). The thyratron dimmer banks had four dimmers per rail, giving up to 48 dimmers per double-sided, double-ended bank as illustrated in Figure 15. Each anode was fused with a re-wireable slide-lock fuse (later a HRC fuse). The centre section contained the control transformers and also the contracting area.

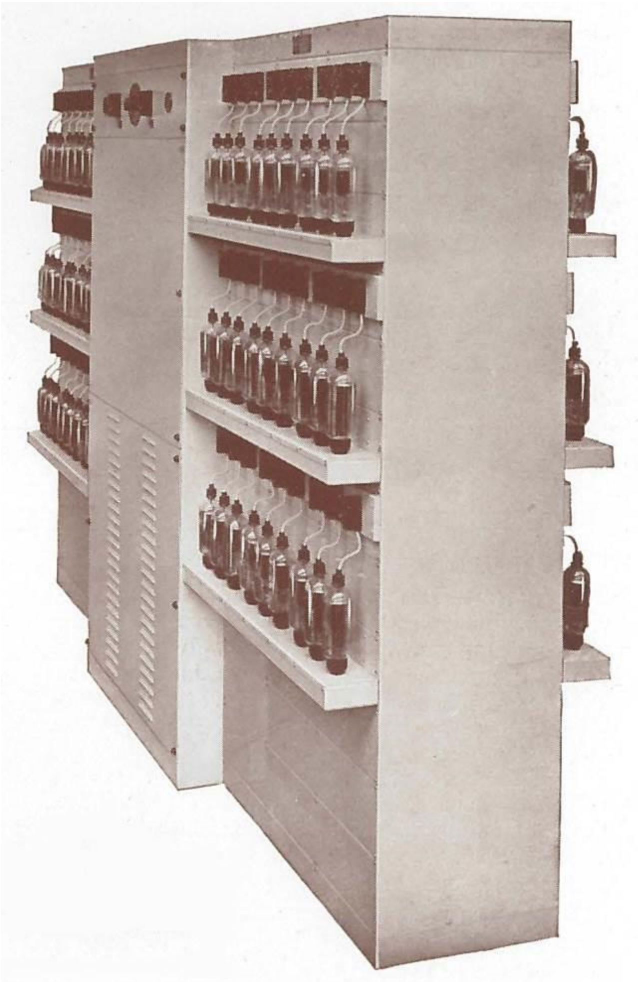

Figure 15. 36 dimmer Electronic thyratron bank publicity picture (1953d) (The bottom 4th row of valves is omitted in this early image)

Figure 16. Old Vic valve racks, 1950 (1950c)

The control console normally provided two preset wings, one either side of the centre master controls with the fast/slow crossfader handles, shown in Figure 17. The presets retained a local master for each group of 12 channels, with a complex switching system to allow some channels to be independent of the group masters and selected groups to be independent of the crossfader. Consoles could be angled to offer more convenient one-man operation as shown in Figure 18 from Manchester Opera House. The single flat tier of 6 rows of faders per presets led to the top rows being a challenge to reach, as can be imagined in Figure 17 and Figure 19.

The BBC R2 console shown in Figure 19 differed in that it had three presets interleaved across the two wings, thus dimmers 1-72 were on the lhs wing and 72-144 on the rhs wing (only 96 channels had dimmers, the rest were switched) (Bentham 1957). There were 3-way selection switches at either end of the master crossfader to choose the next preset. Both the crossfader and two preset masters were driven by the same Mansell clutch[29] and polarised relay motorised drive used for the 5 kW, clutch-driven, resistance dimmers, following small desk masters.

Figure 17. Standard Electronic two preset, 144 channel, control console installed at Reykjavik National Theatre (1953b; 1953d)

[29] The crossfader mechanical load needed double electromagnets to achieve reliable drive.

Figure 18. Angled two preset console from Manchester Opera House (Laws 2018)

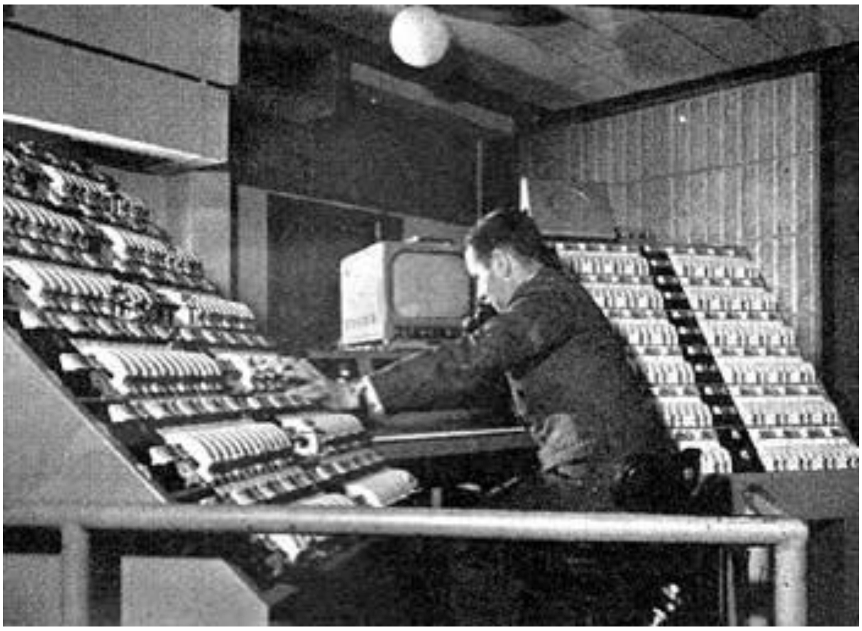

Figure 19. Three preset (interleaved) console at BBC R2 (Kempton 2018)

5.2. Rack construction

The Manchester Opera system (2018e) mostly still exists to investigate construction details. Standard dimmer racks are double-sided with the thyratrons external for easy service access and ventilation, shown in Figure 15. A maximum of 3 racks were sold for 144 ways. The insides of the side valve racks were mostly empty, containing only the grid transformers and the valve cooling system, plus probably the anode chokes in later racks.

The dimmers were all rated at 2 kW initially and for almost all sales. However in 1951 Stratford persuaded Strand to supply a number of 4 kW circuits, a pair of which were paralleled to support 8 kW (1952-54). Despite this, the limitation of 2 kW remained the official policy even by 1953 (1953d).

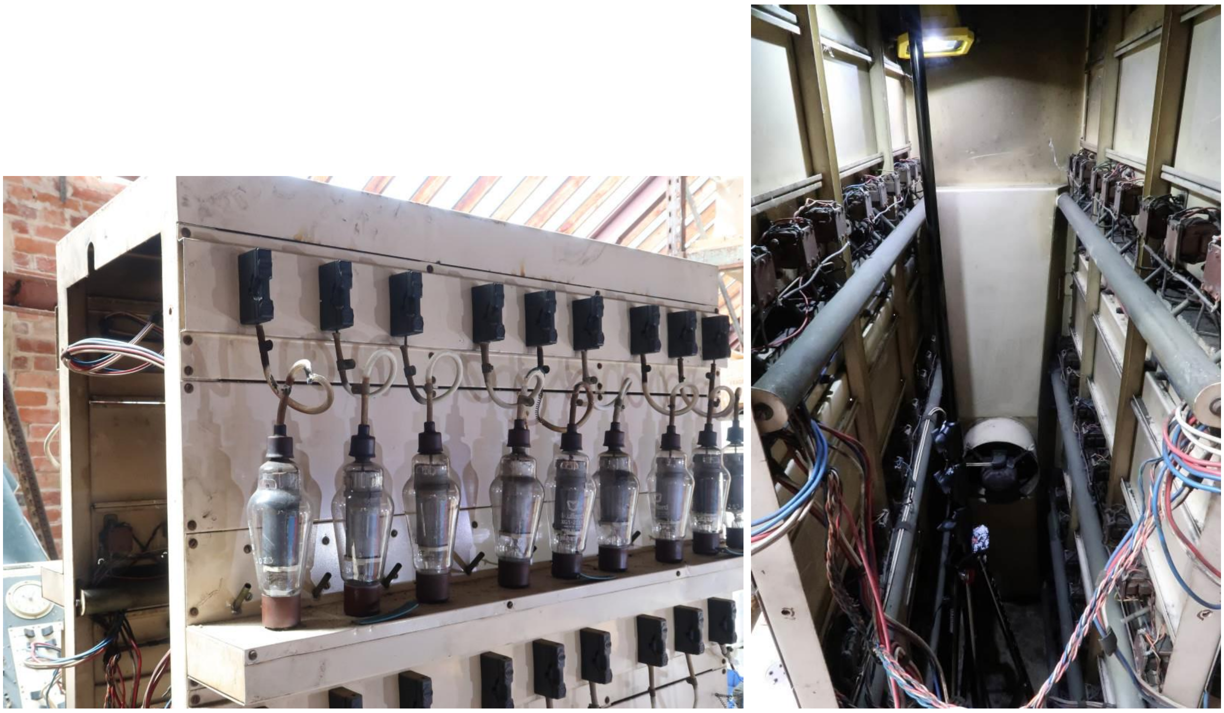

Figure 20. (left) View outside and (right) inside Manchester valve rack from centre

Valve cooling consists of a single fan-pressurized plenum at the cabinet ends feeding 4 ducts per side, each having small outlets directing cooling air near the valve bases in Figure 21. By this means a mercury condensation cool spot was maintained on each valve.

Figure 21. (left) Rear of valve rail showing grid transformers and (right) cooling ducts to valve bases

The rack centre section was not recovered from Manchester, and must have contained the main contactors, phase shift transformers, valve heater transformers, RFI capacitors plus control and load terminals. This early system did not have had any dimmer filter chokes, the valve racks had no provision for them and the centre rack was much too small for 48 chokes in addition to the above. Chokes to reduce lamp sing were not apparently fitted until 1954.

The only extra chokes noted in the literature intended to mitigate lamp sing were fitted by the BBC at Riverside 2. These consisted of 0.55 mH, 17 A air-cored chokes complete with 4 μF paper capacitors, retrofitted in separate cases of 24 ways (B.B.C. 1956).

The valve anodes were originally directly connected by fuses to the phase supplies but by March 1950 changed initially to include 1 Ω then later than year 2 Ω resistors to reduce cold-lamp inrush and prevent the major damage phase-phase shorts caused (Bentham 1948-50;

Bundy 1983). The initial 1 Ω resistors were fitted inside the racks until their dissipation was found to damage the wiring. The 2 Ω anode resistances were coiled resistance wire inside glass fibre sleeving[30] between anode cap and fuse. The per-phase rms current for 2 kW at 240 V is 4.8 A (8.33 A load current divided by $\sqrt{3}$ not 3)[31], thus each anode resistor will be dissipating 46 W at full load. This loss is almost double the heater loss and comparable to the valve voltage drop loss. While these resistors are not shown in the initial publicity images such as Figure 15, they are clearly visible on the 1950 Old Vic installation in Figure 16.

The temperatures generated in these anode resistors is massive, since they are very small for the dissipation. In a test simulating a 2 kW dimmer load (4.8 A rms) the outside glass sleeve reached 350 °C (by thermocouple) within 150 seconds. Even at only 1 kW it reached 152 °C. The central resistive core is clearly visible in the IR image in Figure 22 (the IR camera range was limited to 150 °C), where it can also be seen the lead into the fuse-holder reaches 41 °C above ambient. The extra heating imposed on the valve cap is also significant at 34 °C above ambient. Bentham found a 40 °C rise, which was contributing to valve cap failures (1952-54). The consequent damage to the glass sleeves is also very evident in Figure 20 (a).

Figure 22. IR image of anode lead carrying 4.81 A rms

It is clear that in 1950 this high loss was not appreciated, since Wood declared that three valves sharing the current over three phases would simply take a third each, allowing the valve's average rating of 2.5 A to be accommodated (Wood 1950). From the viewpoint of the valve rating, he was correct. The thyratron anode heating is affected by the anode voltage drop,

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[30] On test 40 cm of 0.8 mm dia. wire measured at 0.446 Ω resistance (R), thus resistivity (ρ) = $R \times Area / Length$ = $0.446 \times 0.16 \times 10^{-6} \times \pi / 0.4$ = 5.6×10^{-7} Ωm, indicating the wire is probably Manganin or Constantin material.

[31] This non-intuitive fact is due to the non-overlapping nature of the current pulses. The three phases deliver their power to the load in 3 separate pulses per mains cycle. Since they are identically proportions of the mains cycle, they will be identical powers, and since the power in the load is the cycle integral of the power in the three pulses, each pulse will provide 1/3 of the total load power. The power developed in a resistive load R (i.e. lamp) by its rms total current I_L is $I_L{}^2R$, thus if the rms current of each phase is I_P then the power delivered by each pulse is $I_P{}^2R$. This means that $3I_P{}^2R = I_L{}^2R$ thus $I_P = 1/\sqrt{3}\, I_L$.

which is caused by an electronic space charge effect. This causes a constant voltage to develop rather than constant resistance, thus the valve dissipation follows the average current and not the rms current. At full 240 V output, the per-valve average current is just 2.4 A thus within the valve rating. It is the more important rms measure that is 73% greater.

The anode fuses are declared as 15 A on the first rack drawing, but recorded in 1950 as being 29 SWG by Wood who declared they would blow at 2.5 kW load (1949a; Bentham 1948-50). The 1950 I.E.E Regulations 12th edition Table 21 for semi-enclosed fuses rates 29 SWG wire (0.0136”) at 10 A operation (1950d). From Manchester they were rewireable slide-lock type fitted with a wire gauge of 27 SWG rated about 12 A. Why such a high rating was used is unknown, when ~7 A would have offered better protection, however ‘fuse blowing’ was a frequent complaint so pushing the rating up would be a natural tendency.

It was also reported that for phase to phase shorts *‘the holders would sometimes blow right off the panel’* (Bundy 1983). Further the use of open fuse wire meant in the case of a severe fusing event, vapourised metal was sprayed around, and by 1950 shorts between fuse bases and the panel were being reported from Iceland and Blackpool (Bentham 1948-50). Later builds used HRC cartridge fuses and holders that better survived and protected the valves against phase-phase shorts.

The rack had controls for power off/warm-up/operate and a 5% step tap-changer switch to adjust the 5 V valve heater voltage, monitored on a panel voltmeter. This needed to be manually regulated within +/-10% limits. It appears the operator was expected to monitor this routinely.

5.3. Desk construction

The desk is constructed in two wings for the two presets, with centre master controls, as shown in Figure 17 and Figure 18. The channels are laid out in rows of 12. The channel faders are an integrated plug-in moulding for wire-wound fader winding and control switch as shown in Figure 23. The averaging output resistor is fitted to the fader and visible in the centre.

As can be seen in the example, a fair amount of dirt can drop down the lever slots and accumulate on the strips. The wiper is a single open sliding contact onto a wire-wound resistance strip and is likely to have suffered from some degree of intermittency due to dirt build-up (later similar Strand fader designs used multiple wiper contacts).

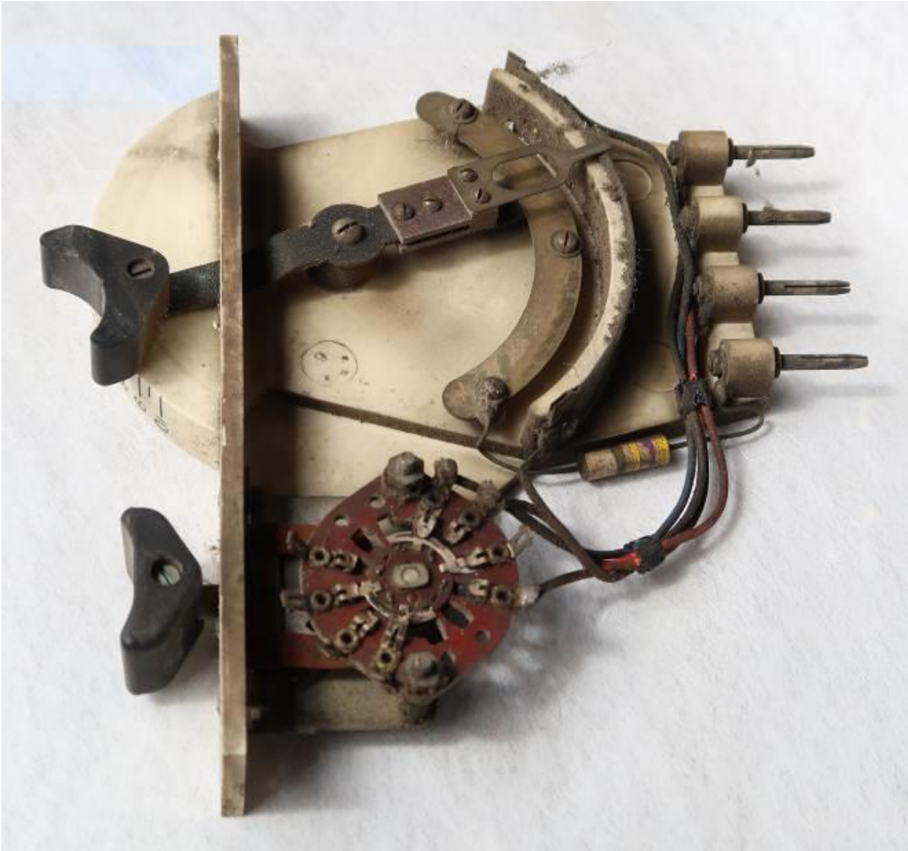

Figure 23. Channel fader with switch

Each row of 12 channels has a rotary row master potentiometer shown on front and reverse in Figure 24. Of note for both channel faders and row masters is that the zero setting is offset. On the channel fader it is about 16% of the full range, while on the row master it is over 22%. These substantial offsets are assumed to ensure that there is a reliable off region for the dimmers to accommodate valve parameter variance and drift with age. The greater offset on the row master is probably to compensate for the resistive loading of the channel faders on the row master potentiometer. This offset was not present on the prototype image in 1949 (1949c), indicating possibly that the tendency for the extinction voltage on the thyratrons to drift with time/aging was not initially appreciated.

An indicator light[32] shows if that row is live controlling lights. This indicates when the crossfader has activated this preset or when this preset/row has been set to 'hold'.

[32] 50 V Post Office wedge design with series resistor.

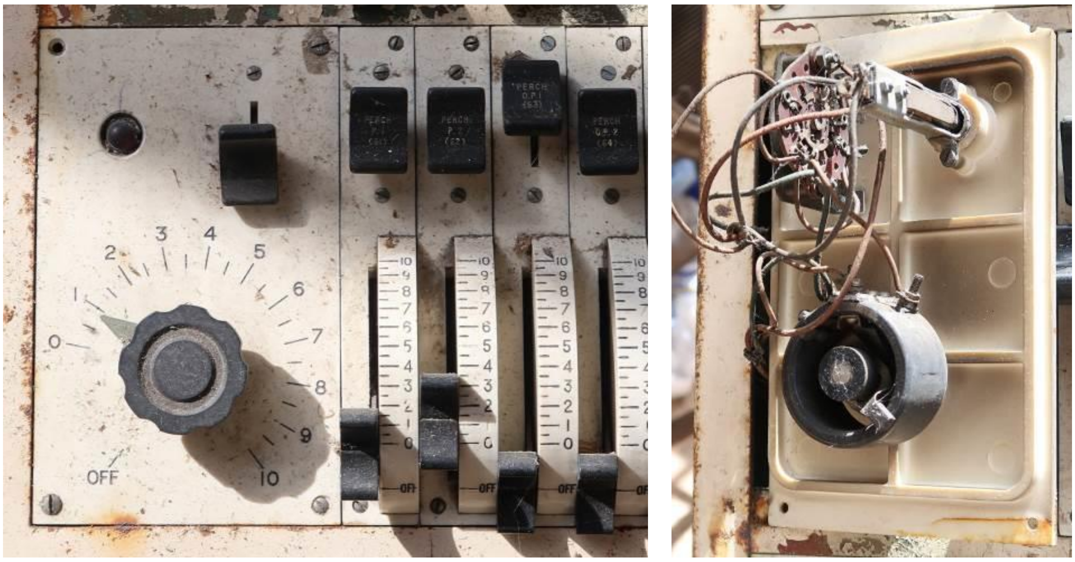

Figure 24. (left) Row master control front and (right) rear

Each preset has a Main master and Independent (Ind) master potentiometer mounted on the centre control panel, shown in Figure 26 with front and rear views. The Main preset master is a dual 1 kΩ potentiometer, shared alternately across the rows. The Ind. preset master is a single 500 Ω potentiometer for all rows, its lower power capacity presumably due to less expected circuit load. Neither potentiometer ratings are recorded. Of note here is that the scales do not have any zero offset.

Also on the centre panel are the left and right preset Blackout (BO) switches and the Dead Blackout (DBO) switch. In the middle are the channel Hold switches, one per 12 channel row. The remaining controls are all auxiliary controls for the Manchester Opera lighting specials.

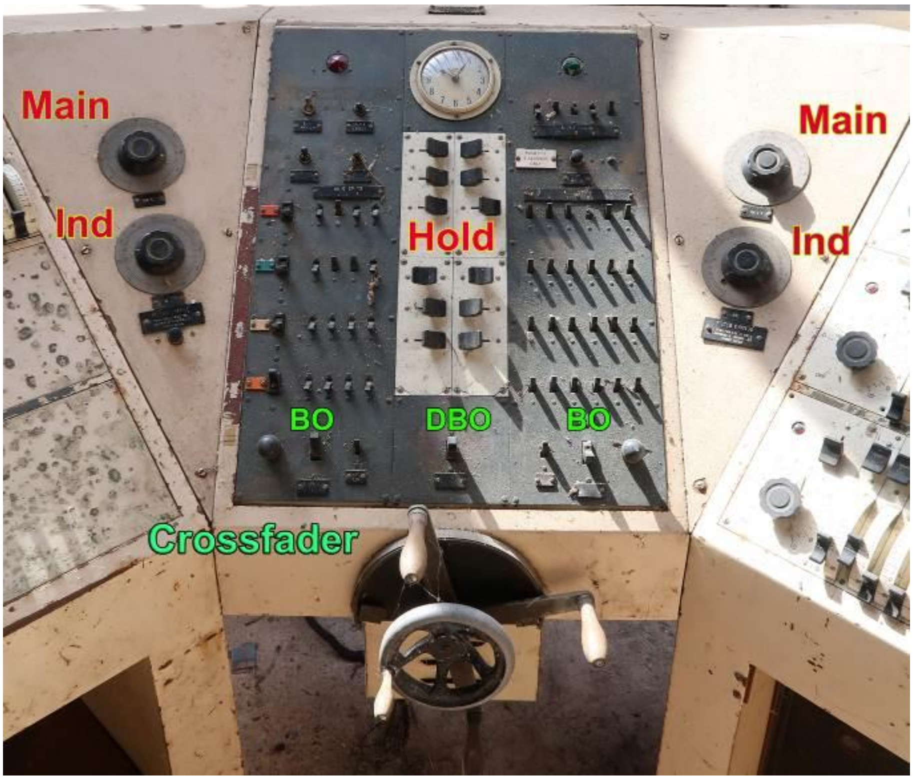

Figure 25. Master panel with identified controls

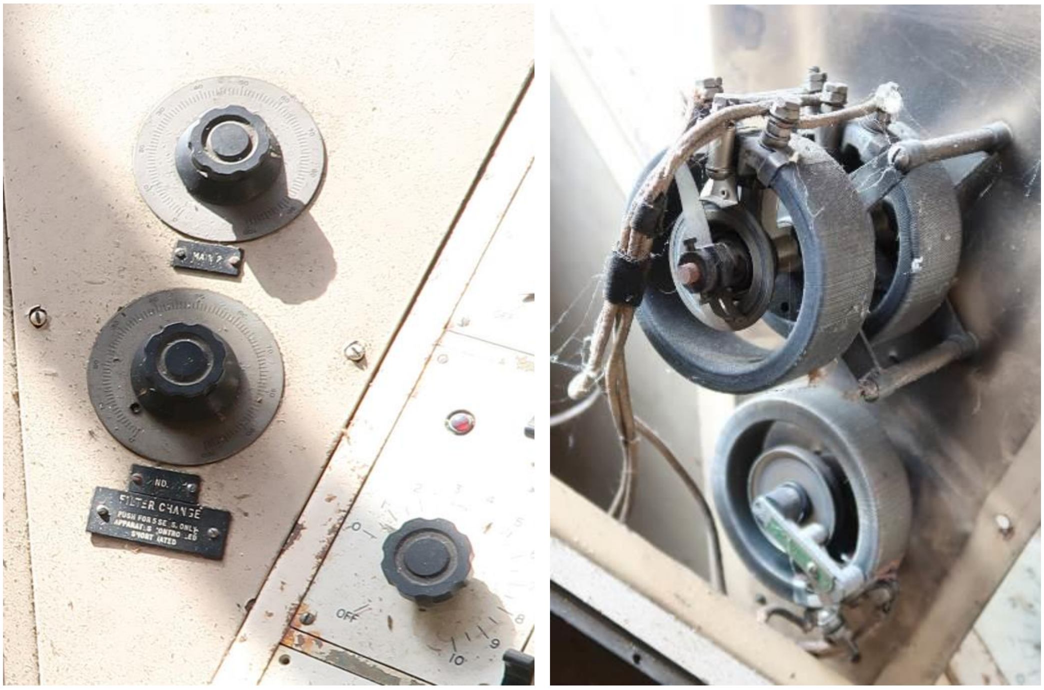

Figure 26. Master panel Main and Ind. potentiometers (front and rear)

Figure 27. Interior of master panel with setup adjustments

5.4. The crossfader

The crossfader is the heart of the machine. It establishes the voltage rails on the preset that is active. It is composed of a ganged pair of 100 Ω, 300 W potentiometers, chain-driven from a dual speed manual action. The centre handle drives the crossfader via a ~20:1 reduction gearbox, while the outer handles directly drive the crossfader, overriding a slipping clutch. The gearbox is mounted inside the centre console near the front as shown in Figure 27, with the potentiometers mounted in a casing underneath in Figure 28 (a) and (b).

Figure 28. (left) Crossfader housing and (right) internal potentiometers

The heat dissipated by these would have been significant. With ~100 V master rails, the total dissipation would have been a continuous 200 W.

5.5. Operation of the desk controls

The system, while basically a simple two-preset control, still contained some peculiarities. Firstly the channels are always arranged in rows of 12. This does not follow any stage layout, but as noted seems solely to emulate older GM boards (1930-40s?). Each GM shaft had its own handle for local operation, thus similarly each row has a Row Master control. Channels can be switched to the Row and Panel Master, off or independent (Ind.) of the Row and Panel Master. The switch is centre off, so changing this selection on a live preset will cause a dip.

Each Row Master also has a switch that can select if all channels are controlled by the Preset Master regardless of the channel switches, off, or those channels on Ind. are controlled by the Preset Ind. Master. Since the Preset BO switch only blacks out the channels on the Preset Master, this also allows those channels selected to Ind. and whose Row master is also set to Ind. to escape the preset BO. Again this switch is centre off, so changing this selection on a live preset will also cause a dip.

The Crossfader decides which preset is live and thus controlling the dimmers. However each row of 12 channels can be switched by Hold switches in the centre control panel. In the switch's centre position, the Crossfader masters them as normal. If Hold is switched either left or right, the left or right row of preset faders are made permanently live with the Crossfader ineffective for them. Thus groups of 12 channels can be isolated for manual operation while crossfading scenes on the remaining channels[33].

Three blackout (BO) switches are fitted, two Preset BO as described above and a dead blackout (DBO). This not only switches off all the channel fader power irrespective of Ind. and Hold settings, but also trips the main rack contactors[34]. One assumes this last action is to ensure that any malfunctioning 'stickers' were also forcibly turned off!

[33] It would have been a great improvement if the Ind. selection had allowed arbitrary selection of any group of channels to be isolated from the crossfader.

[34] DBO by main contactor was quite normal for larger resistance boards. It did not depower the valve heaters so immediate operation could be resumed.

6. Electronic Design of the Electronic Dimmer

6.1. Initial genesis

While Wood was the key electronic designer, it would be wrong to think of him working alone in his ‘garret’ (in reality an empty chapel/storeroom next door to the Manchester works). Correspondence between Wood and Bentham[35] indicates that this was very much a collaborative effort between them, and some detail was being discussed clandestinely, bypassing the usual R&D meetings for example to avoid *‘being told what to do by McKenzie’*. (Wood 1948). Wood was also by no means full time on design, he was originally employed on Sales for Scotland and still had to find time between trips for the R&D.

The initial concept seemed to have been confused as Applebee didn’t explain to Wood that while Yale was a DC site, it had an AC dimmer supply (Wood 1948). Wood then suggested the simple two-valve antiparallel arrangement in January 1948, however by March 1948, this had changed to the final three-valve design (Bentham 1948). Wood also discussed with Bentham detail blackout functions and organisation of the preset masters and lobbied for the production detailing to be done in the works to get their co-operation. Once the design moved to London and the first installation was completed, Wood was again sent out on sales trips. The product’s long troubleshooting period then become an R&D committee task using Wood as a consultant with Bentham often playing a more major part than Wood.

6.2. Control desk channel faders, master and crossfade operation

Using information from the final Strand drawings, a single channel, two preset basic circuit is shown in Figure 29. This shows the three levels of mastering offered in the standard Electronic, the crossfader, the preset master and the row master, plus the three thyratron valves and their firing circuits. The power supplies, master switching and filament transformers are omitted for clarity.

[35] Unfortunately we only have copies of Wood’s letters, Bentham’s replies are missing.

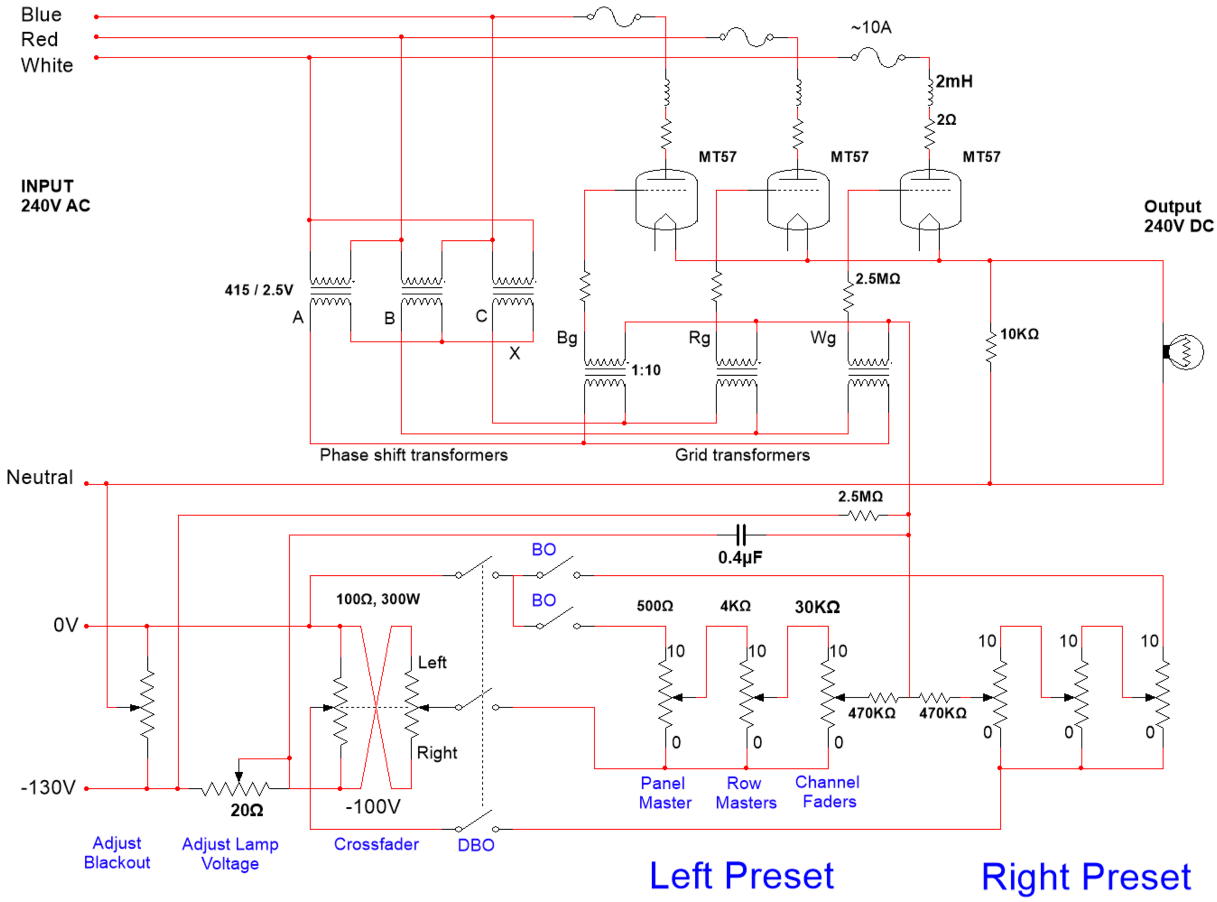

Figure 29. Single channel Electronic Control circuit (Mk2 – C1809)

The desk's DC control voltage is developed by the two preset potentiometers (Channel Faders) whose outputs are averaged by two 470 kΩ resistors. The presets in turn are optionally mastered by Row Masters and Preset Panel Masters, then overall mastered by the ganged twin Crossfader. The averaging effect of the two 470 kΩ resistors causes the common drive point for the dimmers to be dipless on a crossfade between presets. The common point for each dimmer also has a 2.5 MΩ resistor to -130 V to ensure the dimmers are biased off in case of control disconnection and Blackout and Dead Blackout (BO/DBO).

After the 'Adjust Lamp Voltage' rheostat, the master rail voltage supplies are approximately 100 V DC and adjustable for maximum output, giving a net -50 V (off) to 0 V (full) control range after the preset averaging resistors into the grid transformers. The whole DC supply is offset to neutral with the 'Adjust Blackout' potentiometer to set the blackout bias on all the control signals, thus the resultant control signal varies from about -40 V to +10 V with respect to neutral and the thyratron cathodes.

The design is unusual in that the inactive preset is crossfaded or switched (Hold) to 0 V, being full output. Since one or other preset is always active, it is the effect of the active preset that has its -100 V rails energised that 'pulls down' the control voltage on any dimmer set less than 100%. This has the advantage that any failure of control (e.g. open-circuit potentiometer wiper or switch) cannot lead to a control signal greater than 100% and over-volt a luminaire.

There is also a damping capacitor of 0.4 µF (initially 0.2 µF) after the averaging resistors, which adds a 50 ms time constant to the control signal changes, and is connected to the –ve master rail to minimise inter-channel interaction. The purpose is to add turn-on delay to limit lamp-surge currents, since the cold filament surges on 2 kW lamps can exceed the valve rating. A much larger delay of 300 ms was fitted to the Strand BBC Riverside 2, whose manual describes it as '*offering the required switching delay*'.

The console uses a 230 V AC adjustable supply taken from a variac in one valve rack. The AC supply is then rectified and smoothed with a large inductor in the rack and capacitors mounted in the desk to give about 130 V DC. Since this supply is unregulated, it will vary with load and mains voltage. The total load of crossfader and faders is about 3 A, thus dissipating ~400 W in the desk. Bundy (Bundy 1983) reports that desk ventilation fans had to be retro-fitted to keep it cool.

The crossfader needs to be a pair of low resistance (and thus high power) potentiometers to avoid being excessively loaded by up to 144 dimmer potentiometers. In consequence it had a large lever for direct operation, and a geared slow-motion drive. At BBC Riverside Studio 2 it was mounted on and driven by the same magnetic-clutched motor drive shaft that operated the 5 kW resistance dimmers.

The use of master resistance potentiometers will lead to uncertain mid settings as the load on each varies. For the crossfader on 144 channels, its effective output resistance at mid setting of 25 Ω per preset, is loaded with a 500 Ω Preset master, 333 Ω of Row masters and 208 Ω of Channel faders, total load = 101 Ω. At midpoint in a crossfade, this load would cause a 10% error in the expected voltage, leading to both presets being a bit higher than expected. Thus crossfades probably had a slight boost in the middle, visually sometimes useful when changing from one scene to another. Further if a lot of channels on one preset were switched off the masters, the change in DC load on the power supply between presets could cause visible level changes on other channels.

6.3. Thyratron racks circuit

The initial design in drawing M1402 before production is shown in Figure 30, developed before transfer for production in London (1948b). This diagram appears to also be the source drawing for the patents and was probably the essence of the prototype shown in Figure 2 (though this had no preset masters or BO switches).

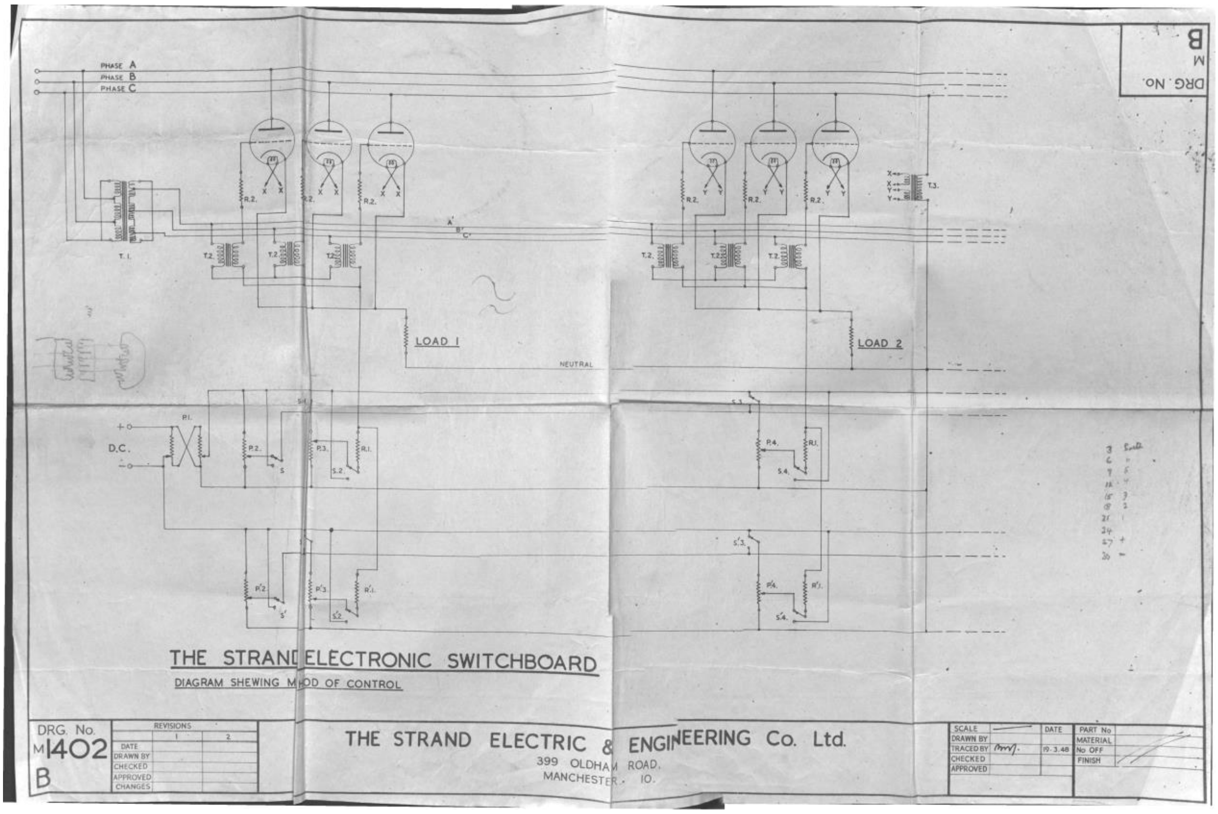

Figure 30. The Strand Electronic Switchboard M1402 (1948b)

The assumed first production version was B1378 from 1949 shown in Figure 34, which had valve fuses and the three-phase, phase-shift transformer replaced by a delta-star connection of individual transformers and delta connection of the grid transformers (1949a).

Due to the many modifications made to the detail rack design from field experience, two further versions were drawn, with several of the earlier installations updated to the final 1951 version to resolve reliability versions. The three rack drawings are given in B1378 (1949a) shown in Figure 34, second C1738 (1950b) shown in Figure 35 (reconstituted from recovered Manchester Opera house documentation) and final C1809 (1951a) shown in Figure 36.

While C1738 had 2 Ω anode resistors fitted by 1950, the final rack drawing C1809 had significant differences by 1954. The valve bases changed from British 5 pin to USA 4 pin, the phase shift transformer connections changed (though still gave 60° delay as drawn) and 2 mH air-cored chokes are now fitted in each anode connection. This choke detail design is unknown, but since it was air-cored and must withstand ~5 A rms per valve at full, its dimensions are governed by simple electromagnetics. Thus it would be comparable to an example Intertek design (2018c). This is 107 x 123 x 88 mm and even though only 0.16 Ω in resistance, would still dissipate 4 W at full output; it may have had to be bigger still to minimise self-heating. The drawing indicates these were mounted on or behind the fuse panels.

The output of each dimmer eventually had a 10 kΩ resistive load (dissipating another 6 W at full output) added to stabilise on no-load, possibly to obviate the MICC problems? The grid delay capacitor also increased from 0.2 to 0.4 μF to reduce current surges on cold 2 kW loads. This capacitor and the co-joined 2.5 MΩ resistors are now connected to different negative console power supplies to reduce inter-circuit interference.

The standard Electronic used mercury MT57 thyratrons (also numbered XGI-2500) rated at up to 1 kV and 6.4 A (1952a; c1952b; Bentham 1958). As described in Section 4, the thyratron valves pass a controlled proportion of each phase to a common cathode circuit, which is connected to the lamp load and back to neutral. The thyratron valves trigger above a small negative grid-cathode voltage (between -6 V to 0 V), and this voltage is used to time the firing point.

The firing circuit for each thyratron grid as drawn takes the three-phase star supply and makes a delta-star transformation in the phase shift transformers. This results in a 30° lagging shift. The grid transformers are then connected in delta across the phase shift transformers, resulting in a second 30° lagging shift, totalling 60°. This provides a signal lagging each phase by 60°. This however cannot be correct and is discussed further in section 7.1. All the literature and patents describe operation with a 90° lagging control signal, so it is presumed the 'Phase Shift Transformers' had special windings or more complex magnetic construction.

The approximately 70 V peak-peak transformer AC voltage is then offset by about -40 V DC (at off) negative control voltage with respect to neutral, to ensure that the grid never reaches firing voltage. This control voltage is then reduced by the action of the live preset fader. Once the peak of the negatively biased grid voltage AC waveform reaches ~0 V, the thyratron will just fire at the minimum conduction angle of a few degrees. An increasing (less negative) control voltage thus progressively advances the time at which the grid reaches the firing threshold increasing the conduction angle. This is illustrated in Figure 31 for a low control signal with conduction angle of 30° and in Figure 32 at 111° for full output. The control voltage varies from about -35 V for start of conduction to about +15 V for full output firing at the maximum conduction angle of 111°. However these are idealised values, and a study modelling the more likely operation is given in section 7.

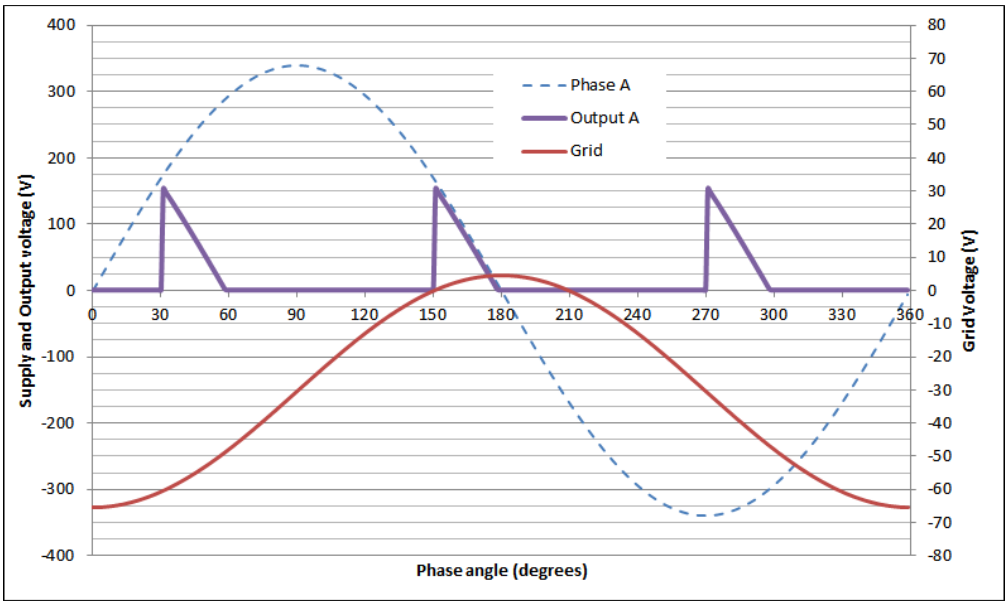

Figure 31. Grid voltage and output waveform to trigger at 30° conduction, 44 Vrms output

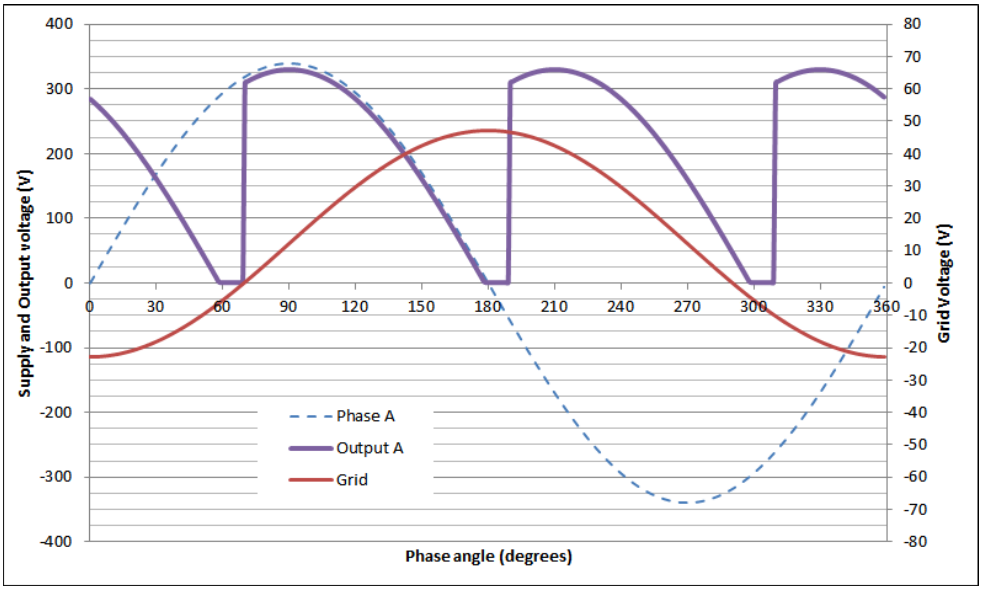

Figure 32. Grid voltage and output waveform with full control to trigger at 111° conduction, 240 Vrms output

The BBC R2 system used larger xenon-filled XR1-6400 thyratrons which necessitated some amount of redesign. The BBC Report (Hersee and T 1957) notes that a 0.001 uF capacitor needed to be connected between each grid and cathode to prevent 'erratic firing' and specifies a 4 µF grid delay capacitor (1957b). Since the fader averaging resistors were here reduced to 150 kΩ, this gave a 300 ms time constant to the desk response, needed to protect the thyratrons from excessive lamp surge current damage. The grid resistors were also only 150 kΩ rather than the standard 2.5 MΩ. The Report also notes that once fired, each thyratron grid feeds current back into the control system via its now relatively low value grid resistor, changing voltages and causing shifts in the firing of other dimmers. A large smoothing capacitor of 250 uF on the DC supply 'Blackout' adjustment was added to minimise this tendency.

The Strand BBC Riverside Technical Description (L.W.L (Leonard Wiggett Leggett?) 1958) unequivocally states a 90° firing delay, however the delta-star-delta phase shift transformer circuit in its Fig. 2, again indicates only a 60° lag. Refuting that is a hand-written correction stating the primary is a star connection which would achieve 90°. Further the draft version of the Description shows the same star-star-delta arrangement, plus the input transformers were only rated at 120 V, thus incapable of delta connection across 208 V (1957b). Finally the BBC's report also clearly states there was a 90° firing lag, and since the BBC spent much time with oscilloscopes investigating misfiring and control interaction, it seems impossible that they would have missed such an obvious difference (Hersee and T 1957).

6.4. Measurement and setup challenges

The use of chopped waveforms presented Strand with serious unexpected and probably unknown measurement issues. The heating effect of a voltage or current, on a lamp filament or supply conductor, is measured by the rms value of the waveform, not mean. However many DC bench meters were moving-coil type which only read the mean or average value of a varying signal. Moving iron type meters do respond to the rms value of AC or DC waveforms but are less accurate and have non-linear scales. Measurement using a dynamometer would also have been rms accurate, but this instrument is challenging to use for just voltage or current measurement.

Both Strand's London works and especially Wood's Manchester ad-hoc workshop would only have been equipped with basic electrical instruments, working as they were with simple sinusoidal AC power or rectified DC, powering nothing more complex than lights, motors and relays. In Figure 2 the prototype output voltage is being measured with an AVO multimeter[36], which is DC mean-sensing. The effect with the very chopped waveform is that at a low setting such as 35° conduction angle, the AVO on a DC range (the dimmer being claimed as DC output) would have read only 26 V despite the real output being 56 V rms. There may have been some puzzlement as to why the lamps were visibly glowing at such low voltage! However by March 1949 it became mandated to use a moving iron instrument to measure output voltages, so at least the full 240 V output was being correctly set (a mean-sensed DC voltage would have been only 210 V) (Bentham 1948-50).

Examples of confusion however continued to exist in the minutes. Jordan (Jordan 1950), the Works Manager, noted in 1950 that with a 2 kW load the anode current per valve was 2.9 A measured with an AC meter (inevitably moving iron) whereas it was 2.1 A on a moving coil meter. He noted that since the valves were rated at a maximum average of 2.5 A, it was important to know which was right! Strand invested in a clip-on ammeter by about 1950 (Bundy 1983) and used it to measure the neutral currents, probably not realising that some of those instruments did not record DC[37]. They could give a low misleading reading on a chopped DC waveform, much less than the true DC rms current. Despite this, Bundy recalls that the new ammeter measured 60 A in an overheating bank neutral at Blackpool. While this was reported in 1950, it was not until 1952 when the true magnitude of the neutral supply current overloads was appreciated.

6.5. Schematic diagrams

The referred schematic diagrams are given below. For the rack, there were three versions, the last and thus current is Figure 36

[36] On AC ranges it is still mean sensing, though rms calibrated assuming sinusoidal AC.

[37] Ammeters that used a clamp-on current transformer would only measure alternating current, thus would only partially detect chopped DC current, sensing it as an alternating (on/off) mean current. Moving iron vane ammeters (e.g. the Crompton Parkinson 'Tong-Test') would measure the true rms current, AC and DC.

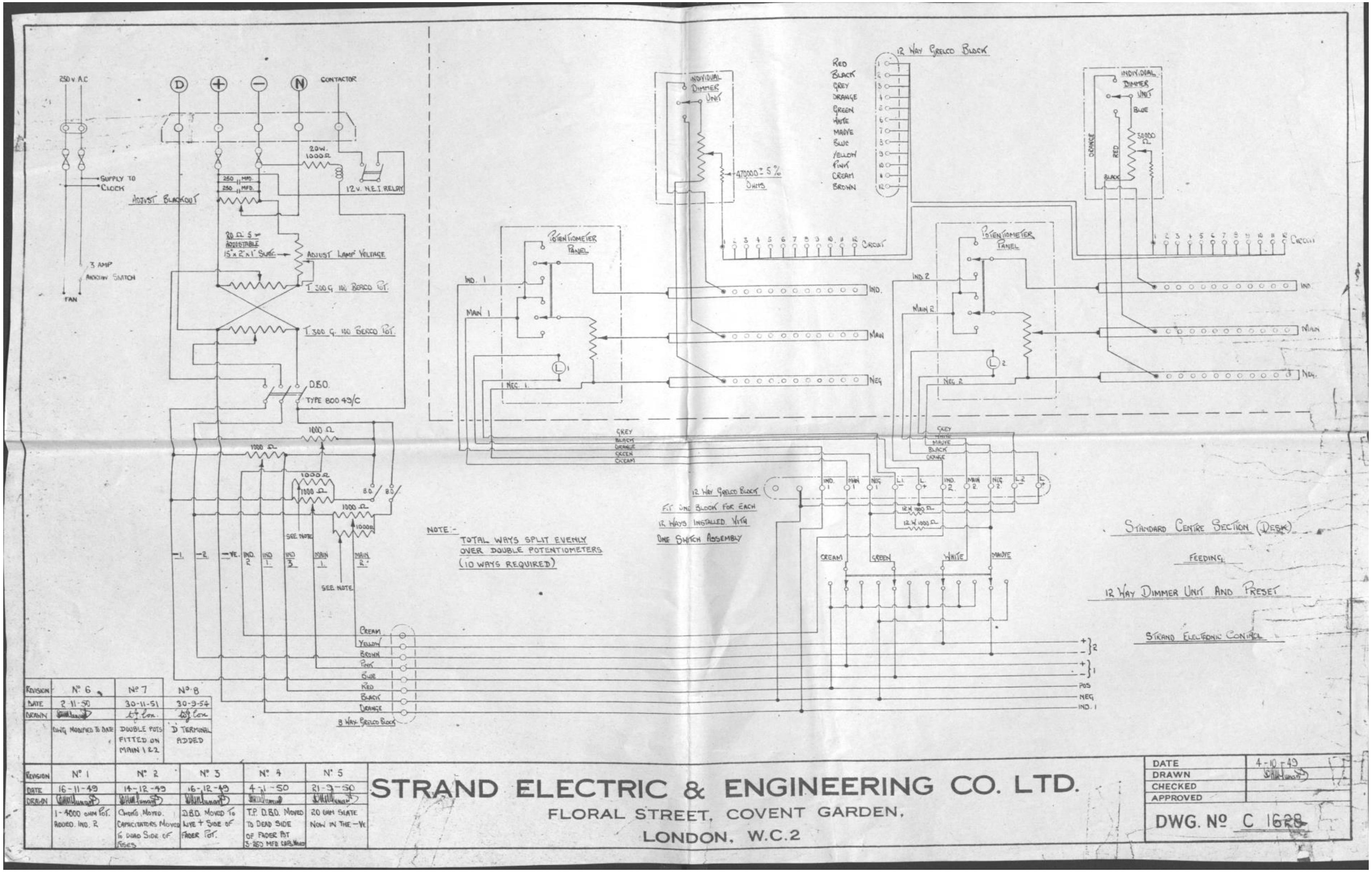

Figure 33. Control console circuit C1628 (1949b)

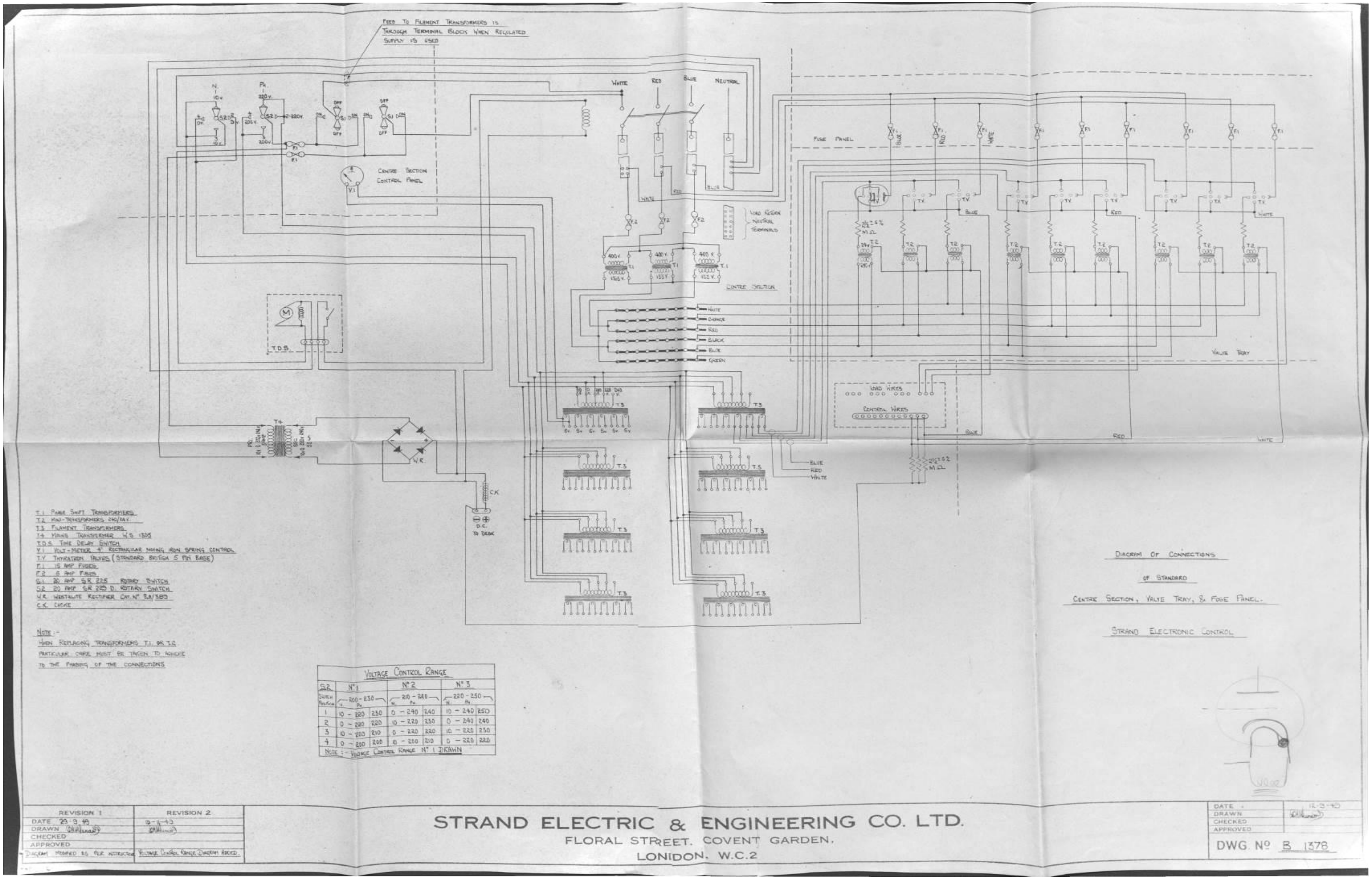

Figure 34. First valve rack circuit B1378 (1949) (1949a)

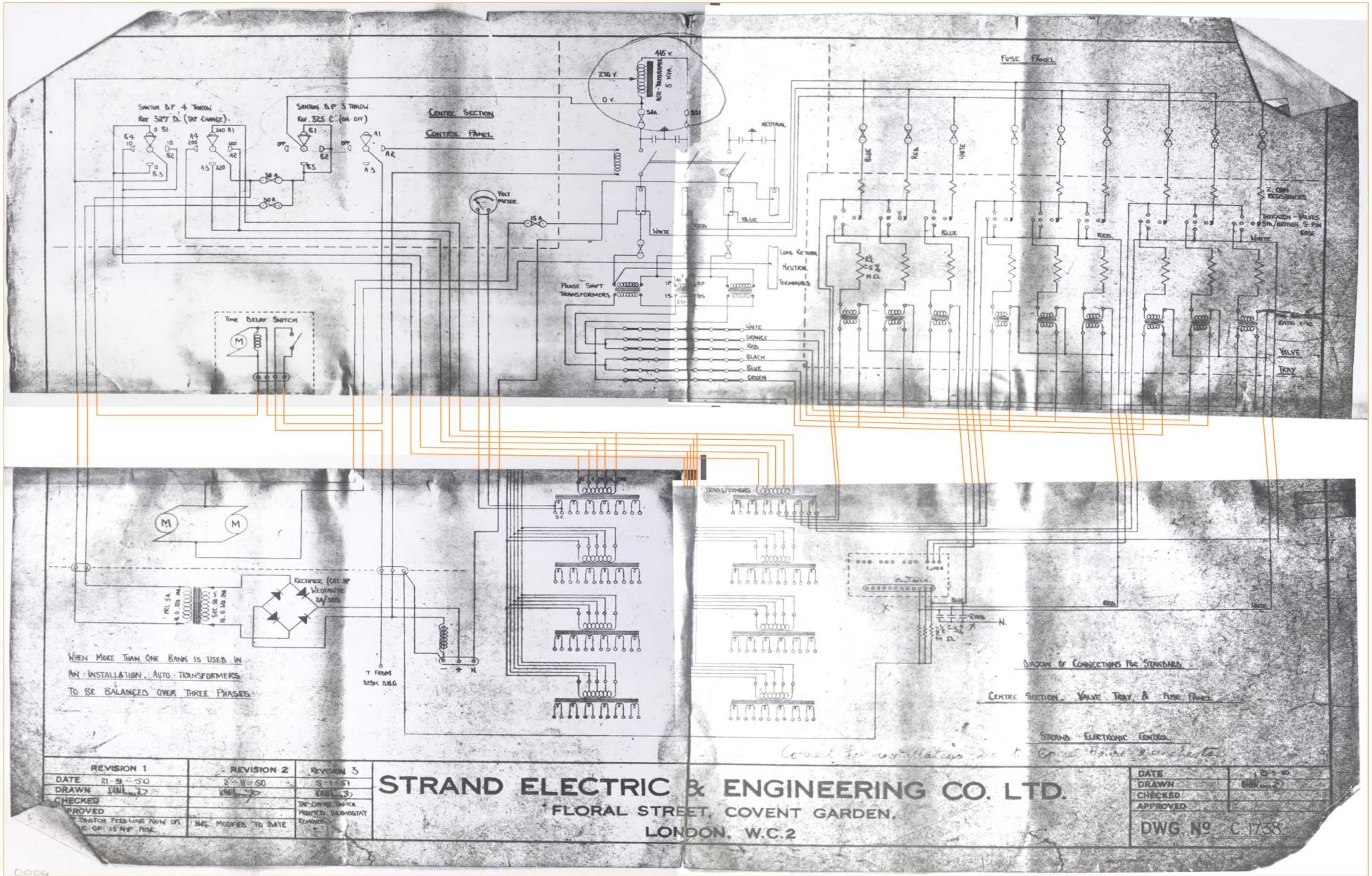

Figure 35. Second valve rack circuit C1738 (Manchester Opera, 1950 reconstructed) (1950b)

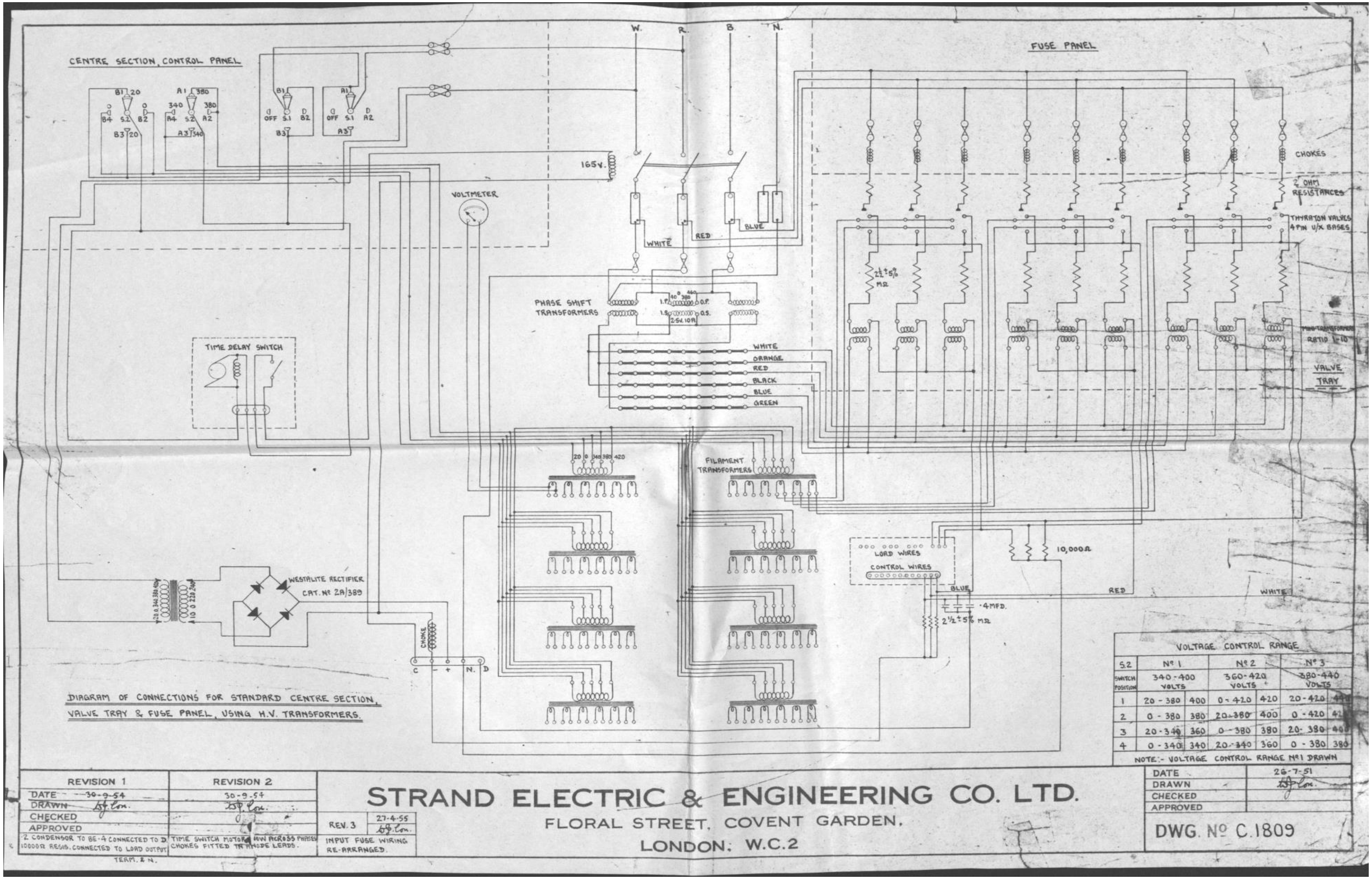

Figure 36. Final valve rack circuit C1809 (1951) (1951a)

7. Model and Analysis of Performance

7.1. Firing phase shift angle uncertainty

The published patents give a basic circuit for the control and firing, however this is not quite as finally designed and installed. The major difference is the phase angle delay for the thyratron firing ac voltage. In the patents and all Strand, BBC and Kliegl literature it is described as being 90° lagging for each phase (Bentham 1949-50). The patents show this achieved by a special (but unspecified) phase-shift input transformer, with the grid transformers connected in star to generate the net 90° delayed signal.

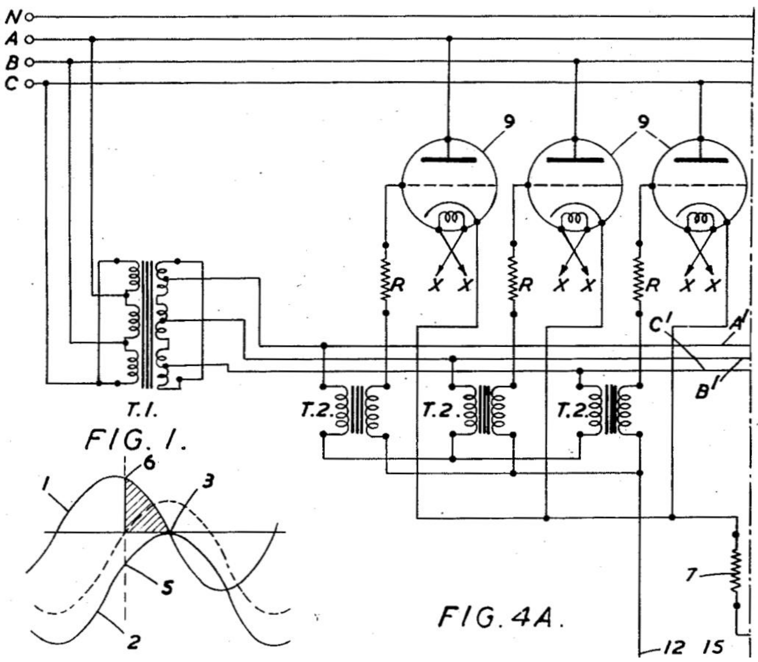

Figure 37. Valve and phase shift circuitry in US patent (Wood 1951a)

However in the Strand and Kliegl rack drawings the standard transformer connection is delta-star-delta giving a 60° delay. The two Strand rack drawings C1738 and C1809 have identical input transformer connections but differ in the grid transformer connections.

In both drawings they imply an unconventional White>Red>Blue phase rotation. In C1738 if this rotation is used, then the grid transformer connections shown give the correct 60° delay to the thyratrons. But the phase rotation convention at that time was Red>Yellow(sometimes White)>Blue, and if this is used on C1738 the grid signals have a 60° lead rather than lag. In consequence early installations must have had to follow Strand's rather idiosyncratic phase rotation.

However in C1809 the revised grid transformer connections as drawn generate 120° leading grid signals for a Red>White>Blue phase rotation, but this is compensated in the grid transformers. Tests on the grid transformer from the 1950 Manchester Opera House show that while the transformer input-output winding polarities match (+ > +), the actual winding connections are inverted to the drawing (e.g. the +ve polarity winding for the white phase thyratron is driven by the orange wire, not the white wire as drawn). The net result is 60° lagging, as expected.

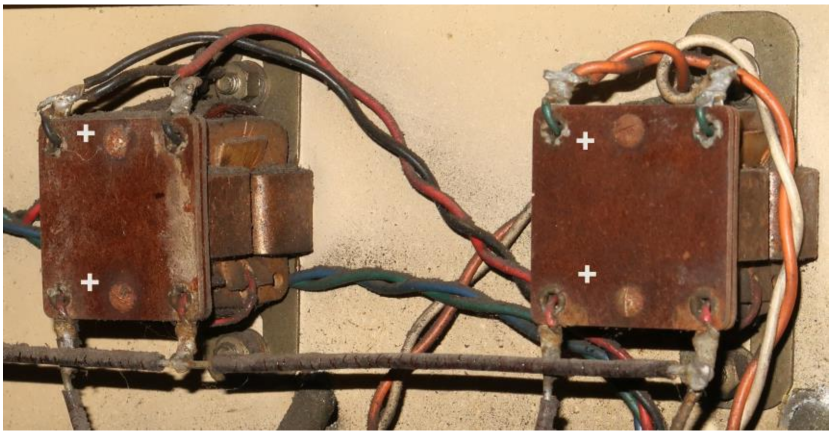

Figure 38. Grid transformers from Manchester Opera, red (left) and white (right) phases, showing winding polarities.

Further the grid transformers are specified at 1:10 on both C1738 and C1809 drawings. However measurements on the Manchester sample gave a 1:7 ratio, so the design must have changed at some stage or was a drafting error. The phase error and ratio were tested on a sample Manchester transformer and shown in Figure 39, and it can be seen that partly due to the high primary winding resistance (68 Ω), have ~4° phase angle error at 50 Hz, varying considerably with operating voltage. The nominal output voltage is ~47 V.

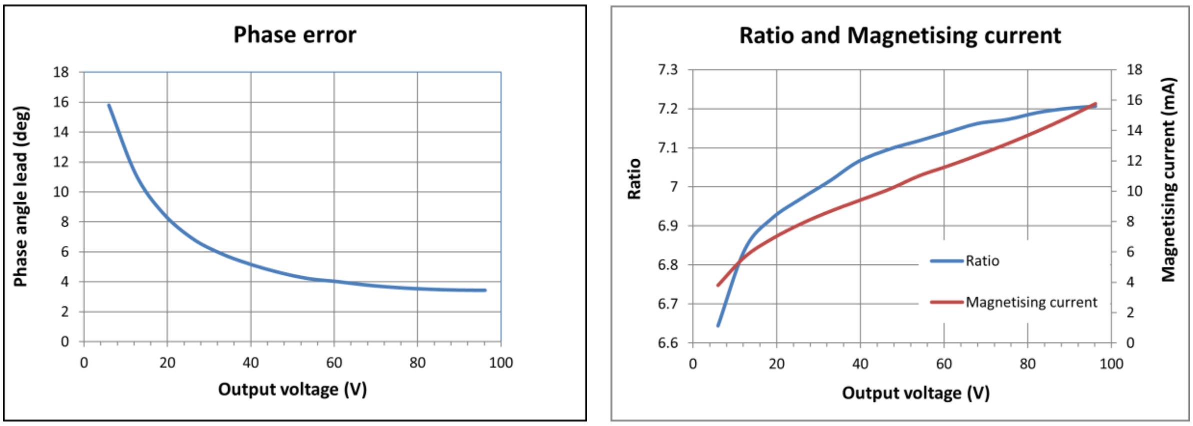

Figure 39. Grid transformer phase error and ratio

The phase errors of the transformers are important in that they affect the firing angles achievable. While the grid transformers have a large error of -4° the input transformers will also contribute slightly to this, with the total transformer phase error[38] estimated at 5° leading.

If the phase shift transformers operate as drawn, the impact of this is to cause conduction to start at a minimum 35° conduction angle, giving a step start to the fade law, with a minimum 56 V rms output when snapping on. This gives negligible light but still a distinct glow on a 240 V filament. Further, because of the broad top to a sine-wave, by a 5% setting on the fader the output is 90 V with significant light (~5%) being emitted resulting in a very rapid increase in light. However a lighting designer from that era, Pilbrow (Pilbrow 2018a) felt that 'fading in/out was very smooth' belying the 55° phase delay with its step-start?

[38] Transformer phase errors due to winding and core losses always introduce a small leading phase angle on the secondary voltage.

Given the total lack of any description of the control voltage lag as being other than 90°, it is most likely that the phase shift transformers were special in some way, or like the BBC, the input windings were actually star connected to the incoming mains. It is frustrating that a definitive answer to this question cannot be determined for the theatrical Electronic dimmers sold. It is likely that the only means will be to examine and test an actual dimmer rack; unfortunately the only one known in existence no longer has the central bay with the phase shift transformers.

7.2. Dimmer law

The dimmer response has been modelled assuming a nominal 90° control voltage lag, reduced by 5° transformer errors to 85°. The valve anode voltage drop is set at 10 V. The channel faders have an offset fader scale of ~16%. This appears to be to accommodate the fact that thyratron valve voltage firing thresholds varied, and the desk voltage rails were unstabilised. It is also assumed the system was adjusted so that all dimmers were off (not firing) with the fader set to 'OFF', and the 16% OFF band was needed to accommodate variances in valve sensitivities and unstabilised desk supplies. From this, the average dimmer would start firing in the middle of the OFF band, ie at -8%.

The control characteristic differs from basic thyristor dimmers, with the curve shown in Figure 40. For comparison a nominal square law curve $(Output\ Voltage)^2 \propto Control$ is shown[39]. The Electronic curve appears at first somewhat slow, however if one allows for the Electronic's offset scale the resulting curve does closely follow a square law. This indicates the dimmer would have been quite effective for fine TV lighting balancing as well as stage lighting if one didn't mind the initial step on. A step start was common in Strand, motorised auto-transformer dimmers in the 1950s reportedly had a 12% bottom offset (29 V) to improve their fade curve (Bentham 1958), while Simpson claims it was 14% (Simpson 2003).

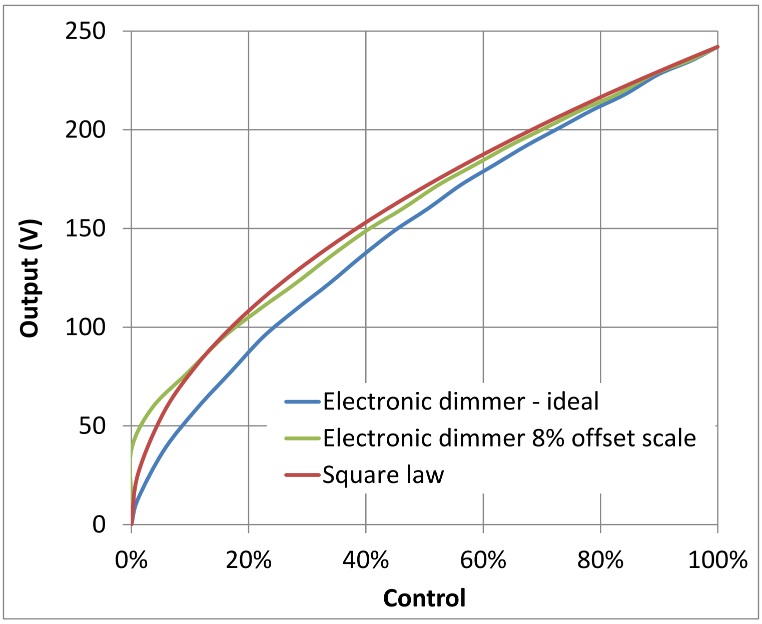

Figure 40. Dimmer law from control signal

[39] Strictly the ideal 'square law' curve for cameras (1 stop = 10% fader step) is $Lumen \propto Control^2$. However since for tungsten lamps lumen output is proportional to $Voltage^{3.4}$ the inverse formula gives a fair approximation (2000)

8. Harmonic Content of the Electronic Dimmer

It is important to study the harmonic content of the Electronic dimmer's current supply to better understand the electricity supply problems inherent in the design. All three phases are identical, so just one phase needs to be analysed. The worst case is when the dimmer is at 90° conduction which equates to 199 Vrms dimmer output, i.e. 69% power output, a likely mid setting for the dimmer.

The resultant chopping of the current waveform, shown in Figure 41 for phase A, causes harmonic currents to flow in the supply and neutral conductors. *Fourier* informs that any non-sinusoidal repetitive waveform can be synthesized by an endless series of harmonics of the repetition frequency summed together. This is not a mathematical nicety; they really do exist and are a substantial problem. It is also much easier to understand the impact on the supplying network and other users (since both are frequency dependent) by considering the harmonics rather than the wave-shape itself.

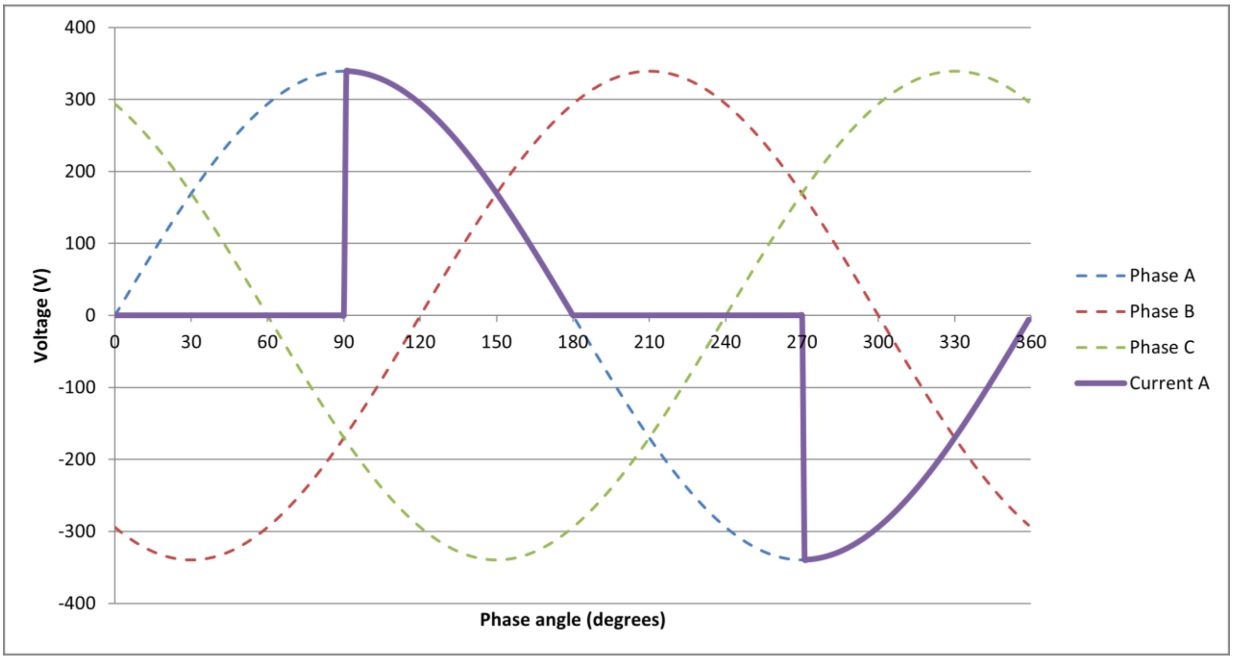

Figure 41. Phase A current waveform at 90° conduction.

Harmonic order (n)	Harmonic frequency (Hz)	Electronic half-wave phase control harmonic amplitude (% fundamental)	Thyristor full-wave phase control harmonic amplitude (% fundamental)	Harmonic phase sequence (+/0/-)
0	0	107%	0%	0
Fundamental 1	50	100%	100%	+
2	100	81%	0%	–
3	150	56%	54%	0
4	200	32%	0%	+
5	250	18%	18%	–
6	300	18%	0%	0
7	350	18%	18%	+
8	400	15%	0%	–
9	450	11%	11%	0
10	500	11%	0%	+
11	550	11%	11%	–
12	600	10%	0%	0
13	650	8%	8%	+
14	700	8%	0%	–
15	750	8%	8%	0
16	800	7%	0%	+
17	850	6%	6%	–
18	900	6%	0%	0
19	950	6%	6%	+
20	1000	6%	0%	–

Table 3. Harmonic current content of 90° phase control, half-wave (Electronic) and full-wave (thyristor) dimmer

While normal thyristor dimmers with full-wave phase control cause odd order harmonics to appear (3rd, 5th, 7th etc.), the half-wave nature of the Electronic dimmer causes even harmonics as well. The harmonics are easily computed by a Fourier Transform analysis of the above waveform. The results are shown in Table 3, with the harmonics caused by full-wave phase control (i.e. normal thyristor dimmer) also shown in the fourth column for comparison.

The results show that half-wave phase control is a prodigious source of harmonics, much greater than full-wave phase control. The Electronic dimmer causes all the same odd harmonics as full-wave, while also adding in all the even harmonics at equal or greater amplitude. The 2nd harmonic is almost the same amplitude as the 50 Hz fundamental.

A further damaging aspect about harmonics is their phase rotation sequence[40]. The positive sequence rotation of the phase voltages is fundamental to the correct operation of three-phase AC electric motors and transformers. If the harmonics on each phase are caused by a phase-control process, as is the case for the Electronic dimmer, then most harmonic currents do not rotate in the same direction as the fundamental 50 Hz current. This is due to the constant time

[40] The supply phase voltages Red, White and Blue ‘rotate’ in that R peaks before W, W before B, then B before R again.

delay that occurs between each of the three phase sources of harmonics. It can be seen in Table 3 fifth column that the 2nd harmonic has a negative phase sequence, as does the 5th, 8th etc. It can also be seen that all harmonics that are a multiple of three of the fundamental frequency (triplen harmonics) have zero (0) phase sequence, i.e. they are in synchronism across the three phases. The impacts of these harmonics and their sequence are considered in section 9.2.

9. Analysis of Problems Afflicting the Electronic Dimmer

9.1. Valve reliability

Valve reliability had been understood to be a potential problem since inception. In June 1948 life tests were started, with three dimmer ways on constant full load until failure, and another dimmer on repeated short on/long off flashing cycles to simulate full load cold lamp surge effects (Bentham 1948-50). There is no record of the results, but by March 1950, the initial supplier (STC) was guaranteeing the valves for 12 months and expecting them to last at least three years (unstated if continuous or theatrical duty cycle) (Bentham 1948-50).

Despite the early encouraging tests, valve reliability was an almost endless plague on the product for virtually the whole of its life (1952-54). The initial installations used the 3V/390A (SV57) (1957a) thyratron from Standard Telephones and Cables (STC), followed by the MT57 (1952a) from Mullard. Both STC and Mullard were also learning how to make reliable thyratrons and Strand's rather idiosyncratic application didn't help. They both reviewed and approved the application. From STC, the 3V/420B (1946a) and slightly higher rated[41] 3V/390B (1957a) were used as well as the Mullard MT57.

In the first seven installations STC valves were used, and while they suffered from greater thermal sensitivity, leading to the special valve base vents and much better dimmer room ventilation requirements, operationally they performed. Following overtures and successful sample tests of the Mullard MT57, the next seven installations used the Mullard valve. However the production Mullard valves suffered much greater failures, such that Strand even advised Mullard that *'touring managements are noticing the installations are satisfactory in some theatres and not others, the sole difference being the thyratrons employed'* (1952-54). By 1952 Mullard's version was barred from use until they redesigned the valve to make it more reliable, achieved at the end of 1952 (1952-54). Eventually, judging from Blackpool, Mullard valves became preferred (Bentham 1950+).

In addition 28 STC 3V/490A thyratrons rated at 6 A were supplied to Stratford (1950a; 1952-54). These were to support a number of 4 kW circuits, and there was no report of untoward failures of these valves.

The scale of replacements was substantial. Foster from Blackpool (managing three theatres) reports in July 1953 that a total of 467 valves had been returned for exchange. In 1953, the Pavilion Theatre in Blackpool reported 74 valves had already failed during initial trials prior to first performances, being some 30% of the total.

Lamp flashing was also a regular but poorly understood effect, where a valve would fire for one or two half-cycles, noticeable on stage but very difficult to identify which circuit caused it!

In 1953 STC noted that the cold lamp surge of 2 kW loads was in excess of their valve's ratings unless Strand fitted/retained 2 Ω anode resistances. By 1954, Blackpool fitted both Mullard MT57 valves and increased the control delay capacitors to 0.4 μF and reported no further valve damage due to surges. STC valves also suffered overheated caps (with melted solder) partially due to heat from the anode resistors.

The importance of valve supply and reliability led to it becoming something dealt with directly by Sheridan, who conducted negotiations with both STC and Mullard on the failings of their

[41] 3 A average anode current vs 2.5 A for the 420B

valves. It seems quite a lot of valve replacements ended up being paid for by Strand as both Mullard and STC felt that the valves were being operated marginally or beyond their ratings.

In June 1953 Brown Boveri offered to supply their thyratrons for the Electronic. Despite the problems that had afflicted Mullard and STC, Brown Boveri was prepared to offer free replacement for all failures for the first two years, plus a capped replacement cost of no more than 2% of purchase for the following five years (1952-54). There is no record of this incredible offer being put to the test.

By 1954 Mullard valves had no problem with cold lamp surge, but remained at risk of sticking on a 2 kW load and susceptible to high temperatures, whereas STV valves were the opposite (1952-54). Shortly afterwards Mullard stated a 2.5 A average current was permissible, hence a 2 kW rating was reaffirmed (1952-54).

Valve reliability was also compounded by fracturing bases. At Blackpool in 1950, 85 valve bases were reported as cracked before the improved room ventilation had been completed (Bentham 1950+).

In a related vein, Strand eventually realised that the risk of phase-phase shorts required better fuse protection for the valves and changed to HRC cartridge fuses, recorded in 1954 for a possible retrofit (1952-54). Phase-phase shorts were being thought by Wood to be due to capacitive retention of output voltage on unloaded circuits, and consequently added the 10 kΩ output resistors in 1954. He also observed that it provided a reliable return circuit for the grid current when there was no load (1952-54). At the withdrawal of the product in 1954, there was a recommendation for 'home' systems to restrict circuit loading to 1 kW to 'improve valve life and performance' (Bentham 1954).

It does not seem to have been appreciated by Strand that the large number of valves means an almost constant rate of failure has to be expected. Once a system is past its infant mortality phase, and assuming STC's assurance of 3 years life was in theatrical service, then for a 120 dimmer system, with 360 valves, each having 3 years mean life, results in 2.3 failures per week. That is, at least 2 dimmers per week failing!

9.2. Harmonic impact on neutral conductors, other users and transformers

Harmonic currents cause problems in neutral conductors, other users, and supply transformers. In the neutral conductor, harmonics that have zero phase sequence become coincident in the neutral conductor, adding and potentially overloading an undersized conductor. The use of the half-wave Electronic dimmer generates considerably more zero-sequence harmonics than full-wave and also the massive 0^{th} harmonic, being the DC current. In essence the entire load current adds in the neutral, in rms terms reaching $\sqrt{3}$ x each phase conductor current at maximum (see Section 9.3 for details). Thus a feeder cable with equal sized phases and neutrals, as might be installed for lighting dimmers, will experience 300% more heating of the neutral conductor than the phase conductors[42].

They can also cause problems to other users since they interact with the supply impedance (which usually rises with frequency) to cause the appearance of interfering or damaging harmonic voltages on the other user's equipment. The DC current will also cause the appearance of small standing DC voltages on the supplies to other users. This can cause transformers and motors to overheat.

[42] Dissipation in a resistive conductor is proportional to the square of the rms current.

Negative sequence harmonic voltages are particularly problematic for three-phase motors since they generate a magnetic field rotating opposite to the motor's rotation. This reduces its power output and induces eddy currents in the iron rotor causing rotor overheating. The massive 2nd harmonic is thus a serious problem.

The triplen harmonics (3rd, 6th etc.) are all in phase and not rotating. This means that in a normal delta-star (or Y) supply transformer shown in Figure 42, the zero sequence harmonic currents, once translated to the delta primary, are all in phase. These currents thus circulate around the delta windings, increasing the heating of the windings for no benefit, and reducing its effective rating. However this does prevent the zero-sequence harmonics propagating further into the supply network.

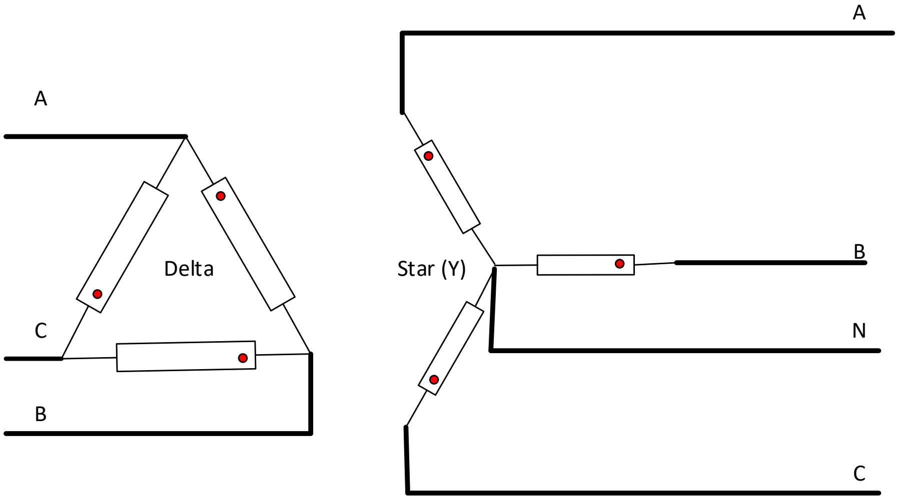

Figure 42. Delta-star supply transformer windings

It will also be noted that the zero harmonic is also very high, which is of course the DC component. Transformers cannot transfer DC current from secondary to primary, so this does not appear on the primary and hence the network. However the DC current pulses act on the 3 windings always in the same direction as shown in the three-phase transformer construction shown in Figure 43. This is problematic as it is liable to induce permanent magnetic remanence in the iron, leading to higher iron losses and overheating.

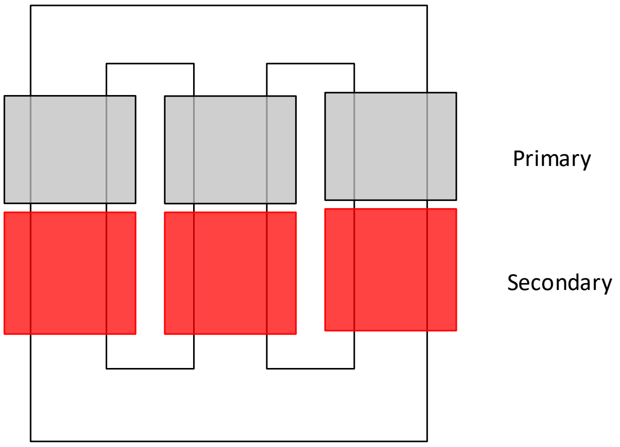

Figure 43. Delta-star transformer construction

The primary supply current balances the secondary current pulses and becomes DC free, however the power flow remains unbalanced between the half-cycles. The consequent poor power factor is discussed in section 9.3.

The problems of harmonics on supply systems is almost as old as AC electricity networks themselves (Owen 1998):

> *'We operating men, I think, all agree that we have harmonics. I think we all agree that, like the poor, the harmonics will always be with us. If we could get rid of them, we would be very glad to do so. – J. B. Fisken (Sept.8, 1916)'.*

Due to the unpleasant effects of half-wave rectification on the mains supply, it is now totally banned in all relevant standards, many of which have legal effect. In the UK BS5406:1976 and EN50006 in the EU initially banned half-wave rectification, followed by IEC 555-2:1982, now replaced by the current EN61000-3-2 and EN61000-3-4. In the USA, IEEE std 519 introduced in 1981 also outlaws half-wave rectification. Both standards set compatibility levels for maximum harmonic voltage content of supplies that users could tolerate, which harmonic generators should not exceed.

However these standards did not exist in the 1950s. The post-war ethos was to electrify the UK as fast as possible to achieve economic regeneration, and there was also little experience of non-linear loads such as this (Lamb 2017). Problems would have been managed by supply engineers on a case-by-case basis only when reported.

9.3. Efficiency and Power Factor of Electronic dimmer

Thyratrons are vacuum tube devices (though in fact have a low pressure gas filling) but one should not think of the ones used in dimmers as being like radio, TV and Hi-Fi valves with their homely little heaters glowing in the background. The currents they handle are of a very different magnitude. Bentham's literature (e.g. (Bentham 1958)) mentions several times that the aggregate thyratron dissipation can exceed that of a resistance dimmer in typical use, and a study of the valve specification shows why.

The standard Electronic MT57 thyratron 5 V heaters need 4.5 A each, so each 2 kW channel draws 13.5 A heater current, dissipating 68 W continuously at zero setting. Further, thanks to a worst case 16 V anode drop (though only 10 V was claimed by Strand), another 133 W is lost at full. To this must be added the 139 W losses from the three 2 Ω anode resistances, totalling 340 W, being 17% of the full 2 kW load.

While the valves look underrated, the substantial phase control even at full, means at full output the average (mean) current is only 50.3% of the rms value. Thus for a 240 V UK installation the three valves were just operating within their rating at 2.43 A mean for a 2 kW load. However on a 220 V (Continental) installation, at 2 kW the per-valve average current is 2.64 A, being a slight (6%) overload of the 2.5 A valve rating.

Losses get worse at 120 V. The thyratrons used at the 120 V BBC Riverside Studio 2 were XR1-6400 (1959; Bentham 1958; Hersee and T 1957) which have 2.5 V, 21 A heaters, thus each dimmer needed a 63 A heater transformer! This gave a constant 158 W loss on top of a doubled anode loss due to higher current, raising the total loss to 20% at full 2 kW load. The BBC (Hersee and T 1957) reported in practice a higher standing (constant) loss of 250 W per circuit, though this may have also included desk and ancillaries.

Even this loss was eclipsed by the design licenced to Kliegl. This used C16J thyratrons (1956b; Bentham 1958) with a 2.5 V, 31 A filament, thus running a constant loss of 232 W per dimmer (probably considerably higher with filament transformer losses), though this supported a 6 kW dimmer rating.

By September 1952, Bentham acknowledged that the initial efficiency claims vs resistance dimming were false, and recommended their discontinuation (Bentham 1951-52b). The claims were removed in the 1953 literature (1953d).

Another drawback of the Electronic dimmer was its very poor power factor, though this was only reported by the BBC. Power Factor (PF) is the proportion of the actual power taken by a system to that apparent delivered. It is simply *PF = Watts / Volts x Amps*. It is important since dimmer systems have finite supplies, with the power available limited by the supply or transformer current rating as well as system power. If for example a simple 240 V supply has a 100 A limit, then it would be expected to offer a maximum power of 24 kW. If the dimmer has a power factor of 0.75, it can only deliver 18 KW, requiring the supply's current limit to be uprated to 133 A to support the full 24 kW.

The rms measure of the current is also the important one, since it reflects the heating effect in the cables and transformer windings. The Electronic dimmer only takes power for part of each waveform, even at full output. Because the output current is taken in three non-overlapping pulses from the three phases, the rms current drawn from each phase is $1/\sqrt{3}$ (not 1/3) of the output current. The individual dimmers however all draw their currents from the same phases simultaneously, thus the rms current for the phases and the neutral sum linearly with multiple dimmers. In consequence the overall *PF* is only 0.58 at full output, meaning that, in the above example, a 173 A supply would be needed. However if the supply is being supported by a static balancing transformer, the overall *PF* rises a little to 0.66.

The inefficiency of the heaters and anode voltage drop of course adds to the poor power factor to further reduce the dimmer's capability on a limited supply. In consequence a 240 V Electronic dimmer would have needed a total supply current capacity nearly double that of a traditional resistance dimmer for the same full load power. It is curious why this is so little mentioned. One possibility is that users' ammeters (where fitted) were current transformer sensed which respond to the AC rms current component, not DC rms.

The BBC R2 (Hersee and T 1957) supply limit of 450 A (per phase) provided only 110 kW of dimmed load due to thyratron losses and poor power factor, but could drive 160 kW of switched load. This is not as bad as the same report that the net efficiency including power factor was ~60%, which indicates that possibly some overload was being tolerated. The BBC Monograph (Nickels and Grubb 1957) observes that the Riverside 2 had a 185 kVA transformer, so 160 kW of resistive load was not the absolute limit.

There is no evidence of the poor power factor being understood in any Strand or Bentham publication, the BBC is the sole commentator. It is probable that Strand did not appreciate this as a separate effect (even though it was larger than the inefficiency). Even by 1957 Bentham (Bentham 1957) only reports on the inefficiency of thyratron dimmers in BBC R2, despite the BBC Report (Hersee and T 1957) on the studio already being issued. In 1958, Bentham (Bentham 1958) further reported in 1958 that the new magnetic amplifiers coming from Europe had poor power factor when dimmed (falling from 0.9 at full to 0.75 at half-light) yet failed to appreciate that the Electronic's power factor had been much worse. However by this time the Electronic dimmer had already reached the end of its short commercial life.

9.4. DC in mains supplies and neutral overload

It has been noted that the system drew large amounts of DC, and returned all of it down the neutral supply which ran at 173% of any phase current and 300% of assumed phase current. This led to unexpected neutral heating in many sites, first noted by Bundy (Bundy 1983) at The Palace, Blackpool[43]. Bundy (Bundy 1983) reports that Strand reluctantly invested in a clip-on ammeter to measure the neutral current and found 60 A there. It is unknown if this clip-on ammeter was actually DC rms sensing, but the true DC rms neutral current for those dimmers (if all at full) would have been ~125 A.

For four years since the design proposal in 1948, Wood, Bentham and others in Strand (and surprisingly all their customers) remained apparently oblivious to the problem that DC drawn from the mains can cause a neutral overload problem and other issues, despite Bundy's reports. This was until Bentham (with Paul Weston) in the Saville Theatre in October 1952, wondered why the neutral feeder had '*undoubtedly got very, very hot*.' (Bentham 1992). He then recalls being told on another job '*the neutral gets bloody hot'*. Even with these obvious clues, he still needed to take current readings, then go home and mull it over a Sunday lunch, to realise that the DC load currents in the neutral always add!

Shortly afterwards in November 1952, Bentham correctly computed the rms phase and neutral currents by consideration of power, finding that the rms phase current is $\sqrt{3}$ x that expected for a resistive load, while the neutral carries 3x that current (1952b). He then further pronounced that the currents and voltages can only be reliably measured by dynamometers or moving-iron meters. A survey of the more important (UK) installations showed several theatres had insufficient mains feeders for the total actual lamp load typically in use, though artistic diversity would ameliorate this.

Bentham kept the neutral current problem mostly under wraps, and just tweaked the 1955 and 1957 editions of his original 1950 book 'Stage Lighting' (Bentham 1955 (revised 1957)) to state 'a double wound transformer is advisable close to each bank' (or static balancing transformer which he recommends in 1957 (Bentham 1957)). He admits this made the dimmer uneconomic. The 1953 edition of the Strand Catalogue (1953d) fails to make any mention of this requirement of the Electronic dimmer. However the 8/52 edition (assumed to be August 1952) of its product data sheet H.61 (1952c) finally explicitly stated:

> *'This supply must come from a transformer or transformer winding reserved for the sole use of this equipment. Between the transformer and the banks, mains must be of such as size as to carry the total intended lighting load on the neutral.'*

That the phase currents are $1/\sqrt{3}$ of the neutral load is also finally acknowledged.

9.5. Liability established and dimmer transformers finally required

In 1952 Strand eventually started to appreciate the scale of their potential liability caused by the Electronic's high DC currents imposed on the mains and returned down the neutral. The situation came to a head in 1952 when the Midlands Electricity Board refused permission to connect the Crescent Theatre, Birmingham. This was resolved by fitting a static balancer transformer.

[43] "Green stuff" oozing out of neutral Pyrotenax joints!

In November 1952 Strand asked Counsel (Mr Ronald Hopkins, AMIEE) to advise. In particular they asked if, having managed to get the theatre and Electricity Supply Board to connect and operate the Electronic, any subsequent problems or damage became the Theatre's or Board's liability?

The answer was a robust no, it was wholly Strand's continuing liability for any damage caused by DC current emanating from Strand Electric's apparatus to the Board's system or any other connected user (Ashurst Morris Crisp & Co 1952). Further it was not permitted under the Electricity Supply Regulations 1937 (1937a). Consequently a supplier would be fully warranted in summarily disconnecting an existing theatre installation if it discovered that the DC currents were posing a threat, as well as refuse any new connection. In addition any contract with a customer that attempted to limit this liability would be void as Strand had hidden the defect. Strand had no option but to provide (if not already existing) isolating transformers to all existing installations on request as well as new installations.

In the Dec 1952 R&D meetings, the cost and size of either fully isolating transformers or static balancer transformers was discussed (respectively £807 or £400 for 144 ways) (Bentham 1952-53). By Jan 1953, a static balancer solution was accepted (now £625 for 144 ways) and mandated to be fitted to all future jobs priced at £45/way fitted (Bentham 1952-53).

9.6. 'Stickers' and phase-phase shorts

'Stickers', being valves that turn on uncontrollably, were a perennial problem even with improved valve base cooling. It seemed the solution was to pull the anode fuses (Bundy 1983), a hazardous task with the hot exposed valves close by!

The BBC report (Hersee and T 1957) states that there must be very careful control of the dimmers to ensure that no two thyratrons fire simultaneously else a phase-phase short can occur. Whilst for full output the thyratrons don't (just) need to overlap their firing, in fact commutation (i.e. turning off the arc) is normally done in other apparatus such as inverters by another phase forcing the anode negative to its cathode, so the internal discharge extinguishes. Consequently this warning appears over-cautious in theory. However the BBC stated that nuisance anode fuse blowing occurred despite 1 mH chokes fitted in each valve anode to limit phase-phase surges.

Bundy reports that if a phase-phase short occurred on the earlier systems, the fuse holders would blow off the panel with a load bang (Bundy 1983)! This was ameliorated in 1950 by fitting 1 Ω anode resistors to limit surge currents (Bentham 1948-50), later increased to 2 Ω.

9.7. Valve heating and cooling

Mercury dosed thyratron thermal management is not conventional. While the heater in the cathode heats up quite quickly, the standard MT57 valve will only operate correctly when the whole valve has adequately heated and sufficient mercury inside has vaporised for full load conduction. Particularly, the envelope has to heat up enough such that the mercury vapour is not simply all condensing back again on the inside surface. This can take a lot longer than the simple heating of a filament; the MT57 requires a minimum of 5 mins for an ambient of 26 °C, rising to 15 mins at 12 °C (c1952b). It is unclear if the valve is permitted to operate at <12 °C.

In operation the envelope has to be maintained such that the condensation point for the mercury is held between 40-80 °C envelope temperature to manage the internal mercury vapour pressure (1960b; c1952b). In April 1950, STC advised that the glass at the base of the valve should be maintained between 25–50 °C and room temperature not exceed 40 °C (Bentham 1948-50). Excessive lower or higher temperatures could cause damage and certainly malfunction. Strand also discovered that 'temperature reversal' where the top of the valve was cooler than the base caused a short between grid and cathode and the valve to 'stick' on (Bundy 1983). Since it was not necessary to cool the whole envelope to manage vapour pressure, just a localised condensation spot[44], the solution was a small cooling vent directed at the valve base to regulate the mercury pressure, designed probably by trial and error. This solution was approved in June 1950, and Bundy (Bundy 1983) recalls drilling and retrofitting 288 pipes and associated plumbing at Blackpool Palace[45] (Bentham 1948-50).

Bundy also reports fitting a 10-15 minute time-delay (made from war surplus components) at the Palace Theatre, Blackpool, when it was realised that a mandatory delay was needed to reduce phase-phase shorts from cold valves. However the downside was the lengthy delay getting lights back on if any rack had to be turned off for maintenance during a show.

It is notable that no such pipes are visible on the publicity picture in the 1953 Strand Catalogue (1953d) shown in Figure 15 but had appeared as the small cooling pipes by the valve bases at the Old Vic (1950c) and Manchester Opera (Laws 2018) shown in Figure 21(b). These cooling issues are not present in inert gas filled thyratrons such as the XR1-4500, a 60 sec cathode heat-up time is all that is needed.

Despite the 1950 piped cooling modification, ventilation continued to be uncertain. In 1952 the April R&D meeting still did not know what best to propose, and several seemed ignorant of the heating effects on rack wiring and other components apart from the valves (Bentham 1951-52b). The dissipation of a 144 dimmer installation was estimated at 10 kW quiescent and 12.5 kW when fully loaded.

The Reykjavik installation, despite being the first, apparently did not significantly suffer stickers or fuse blowing, and Bundy (Bundy 1983) puts this down to the long narrow dimmer room which was well ventilated transversely and always very cool. Further the system had its own transformer for the dimmers.

9.8. Lamp sing

Lamp sing was noticed as early as February 1949 as a problem, even before launch while Works Manager Jordan (Jordan 1950) recommended asking the lamp manufacturers for guidance in 1950 (Bentham 1948-50). Bundy (Bundy 1983) also reported extensive lamp sing from Blackpool Palace Theatre's GLS lamps in 1950, while Lighting Designer Francis Reid noted lamp sing was normal (Reid 2005).

Bentham writes after a December 1953 visit to the New Theatre, London that complaints of lamp sing are justified, and suggests providing portable chokes to add to problematic circuits, and that future Electronics really must have the 2 mH anode chokes (rather late, the product was withdrawn in January 1954) (1952-54). He further notes in 1954 that the Pavilion Theatre, Blackpool will need 2 mH chokes added to suppress lamp sing there.

[44] The use of cold spots on mercury discharge tubes to regulate partial vapour pressure is a long established procedure from fluorescent tubes, where the ideal is 40–50°C, usually achieved by design of the tube and its heatsinking.

[45] The Blackpool Palace dimmer room over-temperature was exacerbated by the presence of a boiler steam pipe (Bentham 1948-50)!

The standard Electronic dimmer as supplied to the BBC in 1955 had 1 mH air-cored anode chokes (intended to limit phase-phase short-circuit current), however after much experiment the BBC added 0.6 mH inductors in the cathode outputs with 4 μF paper output capacitors, to achieve a rise-time of ~300 μs (modelled). These additions did not completely eliminate lamp sing but was the maximum they could add before output circuit resonance caused thyratron conduction to become unstable (Hersee and T 1957).

9.9. Interference

The rapid chopping of the mains supply naturally generated considerable audio and radio frequency interference, despite Wood's January 1949 reassurance to Strands' R&D committee that *'radio interference is negligible'* (Bentham 1948-50). Bundy (Bundy 1983) reported massive radio interference around the Kings theatre, Edinburgh in 1950 blanking out reception in the surrounding apartment blocks. The Post Office (GPO) got involved and investigated Kings Edinburgh, The New, Old Vic, and Grand Blackpool, adding ad-hoc 'choke and condenser' filter circuits to the mains at Edinburgh (Bentham 1951-52b).

The GPO were then consulted in 1951 regarding standard interference suppression fitments. While there were at the time no legal standards, draft British Standards did exist not dissimilar to those today. Conducted mains interference was measured at up to 50 db above the limits, particularly affecting the then very popular long wave 'Light Programme' (Bentham 1951-52b). The final solution was 0.5 μF capacitors between all phases and earth at the racks, and 1.0 μF capacitors at the mains intake. In addition, to minimise radiated interference, each rack had to be effectively RF earthed to ground.

Some sporadic reports also existed of audio interference on sound systems in theatres. However there is no evidence of changes made to improve this other than the fitting of some chokes to increase risetime and reduce lamp sing.

9.10. Interaction and stability

There was also interference between dimmers, occurring as one dimmer (or worse, many dimmers) pass the same level as another. It appeared due to the now floating neutral once Strand started fitting static balancer auto-transformers to isolate the load neutrals from supply neutral. Bentham ruminates on the subject in February 1954, but it seems the fitting of (2 mH?) anode chokes as done in Birmingham provides enough suppression to mask the problem. The Pavilion, Blackpool complained of a 10-15 V rise due to circuit interaction in 1953 (1952-54).

The BBC further reported (Hersee and T 1957) that regulation of the supply caused interaction between dimmers, in that bringing up large loads affected existing dimmer levels. This was assumed to be caused by the supply transformer unable to suddenly supply the current. They reported it was also exacerbated by the regulation of the fader control voltage master bus, being powered directly from the mains supply.

The BBC report also reveals that individual thyratrons did not match well as regards dimmer curves. Because the trigger circuit used the grid voltage trigger threshold as part of the offset against the fader voltage level, valve differences would cause dimmers to have different curves and to drift with age. The MT57 grid firing voltage range is a maximum ~4 V at 90° conduction, which results in a 7% change in output voltage.

9.11. Warranty

The warranty provided was not generous. The 1953 Strand Catalogue (1953d) states that the valves should have at least a 3 working year life (presumably this already allowed for the shorter theatre day), however the warranty reduces from 100% to 0% over just the first year. This implies that the cost of ownership of an Electronic may be quite significant over the years, a criticism made in the BBC report. The higher electricity bills and expensive routine maintenance may also have been a contributing factor for replacement at the New Theatre.

10. Should Strand have known better?

10.1. Commercial arrogance

There was both a serious lack of business foresight, coupled with naïve ignorance of the technology being developed. In business terms, Strand had already rightly noted that it needed to look overseas for market expansion, with Applebee touring America. By the 1940s, major American theatres using saturable reactor systems had become wedded to presetting, with five-scene presets commonplace. Izenour's 1947 Yale demonstration was of a ten-scene preset (Izenour 1988). In continental Europe, the Bordoni (Siemens) and Salani (AEG) tracker wire systems offered mechanical two-scene presetting (current plus next). Yet Applebee permitted Bentham to persist in his sole promotion of the Light Console without presets for systems over 144 ways despite all continental theatres of reasonable scale now using presetting. If the major theatres cannot buy your leading product, why should the middle ranking ones take the risk?

There was also ignorance of the impact of a DC output. The paranoia of phase separation of AC outputs was a peculiar British issue, all continental theatres were quite happy with three-phase power distributed across the stage, so this DC feature was of no value outside Britain.

Further Strand failed to recognise the already popular Continental (esp. German) use of low voltage, transformer fed luminaires, which can only operate on AC. A glance at the 1937 Siemens catalogue would show the popularity of 30 V, 900 W 'Kino' lamps in cyclorama luminaires[46] and 55 V lamps in effects projectors (1937b). Similarly fluorescent luminaires were already becoming used in large cycloramas, also needing AC control. It is thus unlikely, even if Strand had agreed to supply a 240 way Electronic dimmer installation for Hamburg (described in section 11.3) that a sale would have occurred. Perhaps not so obvious to Strand, was the post-war period also coincided with the rise in popularity of 24 V, parabolic luminaires derived from surplus naval searchlights, led by Karl Hessenbruch from 1946 (Bertenshaw 2020).

Between the wars, British theatre had been in a very insular and conservative state, dominated by powerful actor-managers and resistant to experimentation and investment (Esslin 1995). Smith reported views from the interwar years (Rupert James Buchanan Smith 1987):

> *"British theatre was still, in the thirties, very much the preserve of the 'theatregoing classes', and the wish to return to the popular theatre of the Shakespearean period, or to emulate the democratic appeal of the modern German theatre, was all but impossible in Britain at this time."*
>
> *"One of the greatest barriers…was the necessary admission that something interesting was coming out of defeated Germany at a time when there was nothing comparably original in the English-speaking theatre. This was particularly hard to accept in Britain, which had been used to seeing itself as the representative of the timeless standards of theatrical excellence."*

Strand had been part of this conservative stance, and post-war, having again defeated Germany, still could not see the need for radical change.

[46] Used to achieve a higher colour temperature thus higher optical output in the blue circuits.

10.2. Technical ignorance

The more serious problems stemmed from use of phase control and rectification with no appreciation of the consequences in harmonics and supply power flow. The IEE wiring regulations of 1950 (applicable to AC and DC services) (1950d) are silent on any rectification or harmonic issues, though still required that all service conductors are fully rated for their load[47].

The rectification of AC mains supplies for DC services was however commonplace in 1920–50s, chiefly using mercury arc rectifiers, with many texts written in that era dedicated to their application. In these the need for a much higher current rating compared to delivered power for the secondary of a supplying transformer is universally noted, e.g. 174% for the basic three-phase half-wave model, similar to the design used by Wood (Orchard 1936). This was also discovered by the BBC. It was further well known that these produce substantial harmonics, the three-phase, half-wave design was only recommended if used with delta/star or zig-zag transformers to suppress triplen harmonics on the supply (Rissik 1935+41). All designs used a dedicated transformer to isolate the rectified DC load current from the supply.

It has been noted that Strand only invested in a clip-on ammeter by 1950 to measure the supply and neutral currents, apparently not realising that these instruments may not measure the DC rms current, despite mandating the use of moving iron meters (being rms indicating) for voltage measurement in 1949. This confirms that there was very little understanding of AC instrumentation or the differences between rms and mean measurement of current and voltage, and especially of the impact of non-sinusoidal waveforms. This is despite being on the syllabus of basic first year electro-technology courses by 1947 (Teasdale and Walton 1947).

Bentham was managing R&D even though his electrical engineering education consisted of just school certificate then apprentice draughtsman at GEC. He had been persuaded to switch from Arts and Crafts evening classes to three nights a week of Electrical Engineering before joining Strand, though this was soon given up (Bentham 1992). Despite this paucity of professional education, he was eventually (after two years) able to work out the DC neutral problem from first principles; there must thus have been no better skilled electrical engineer at Strand, including Wood.

Strand had developed as a contracting company, both pre- and post-war, providing and installing custom theatre electrical distribution equipment that happened to include dimmers. In consequence there was little need for engineering rigour. Thus when Wood proposed his Electronic design it was taken on trust, everything hinged on Wood's competence. Sadly this was lacking in electrical engineering terms. Strand chose not to question Wood's competence and also failed to appreciate that they were now technically out of their depth and should have sought more expert help.

[47] Current regulations (2018) require harmonics to be fully considered in all conductor rating calculations.

11. Other Manufacturers of Thyratron Dimmers

11.1. The Izenour/Century dimmer

Philip Rose (Rose 1966) claimed that the first two-valve thyratron dimmer was designed in Holland[48], but that Strand's three-valve design dominated large European sales. The Izenour designed Century product is described in section 3 and followed the classic two-valve antiparallel design in Figure 11. The Yale prototype installation is shown in Figure 44.

Figure 44. Professor George C. Izenour with the 44 Yale thyratron dimmers (1947)

11.2. Brown Boveri 'Thyralux'

This product was designed in Switzerland by Brown Boveri and used their own valves. It was rated up to 14 A (Bentham 1951-52a). Strand signed up to manufacture under license in 1952 solely for UK sales, providing Strand used Brown Boveri valves and the 'Thyralux' name (British Brown Boveri 1952). By August 1953, Strand R&D had not yet provided manufacturing details to the works, and a contract for three dimmers for a Lyons Corner Tea House had to use imported Swiss dimmers. GEC also approached Strand at the same time offering the manufacturing opportunity of their own design of Thyratron fluorescent dimmer but it seems this was never taken up (1952-54).

The design used two thyratrons in normal antiparallel fashion as described in Figure 11. The purpose was to acquire a dimmer capable of dimming architectural fluorescent and gas discharge lighting, which absolutely needed an AC output. The product is shown in Figure 45. It never featured in any Strand catalogue, and in 1954, the product was withdrawn '*until the Strand (Lyons) Corner House and other experiments are completed satisfactorily'* (Bentham 1954). By 1958 saturable reactors were being offered for architectural dimming.

[48] No other records have been found.

Figure 45. Brown Boveri Thyralux dimmer (cover removed) (c1952a)

The schematic is shown in Figure 46 and uses transformers to isolate the two grids. The control is a simple motorised UP/DOWN/STOP scheme that, with an internal AC driven potentiometer, offsets the AC bias on the thyratrons thus affecting their firing angle. This makes the dimmer impossible to remotely control by electrical presetting schemes. This restriction led to the dimmer not being suitable for the 5 kW circuits at BBC Riverside 2. It is not clear what wattages were normally catered for, but probably up to 5 kW.

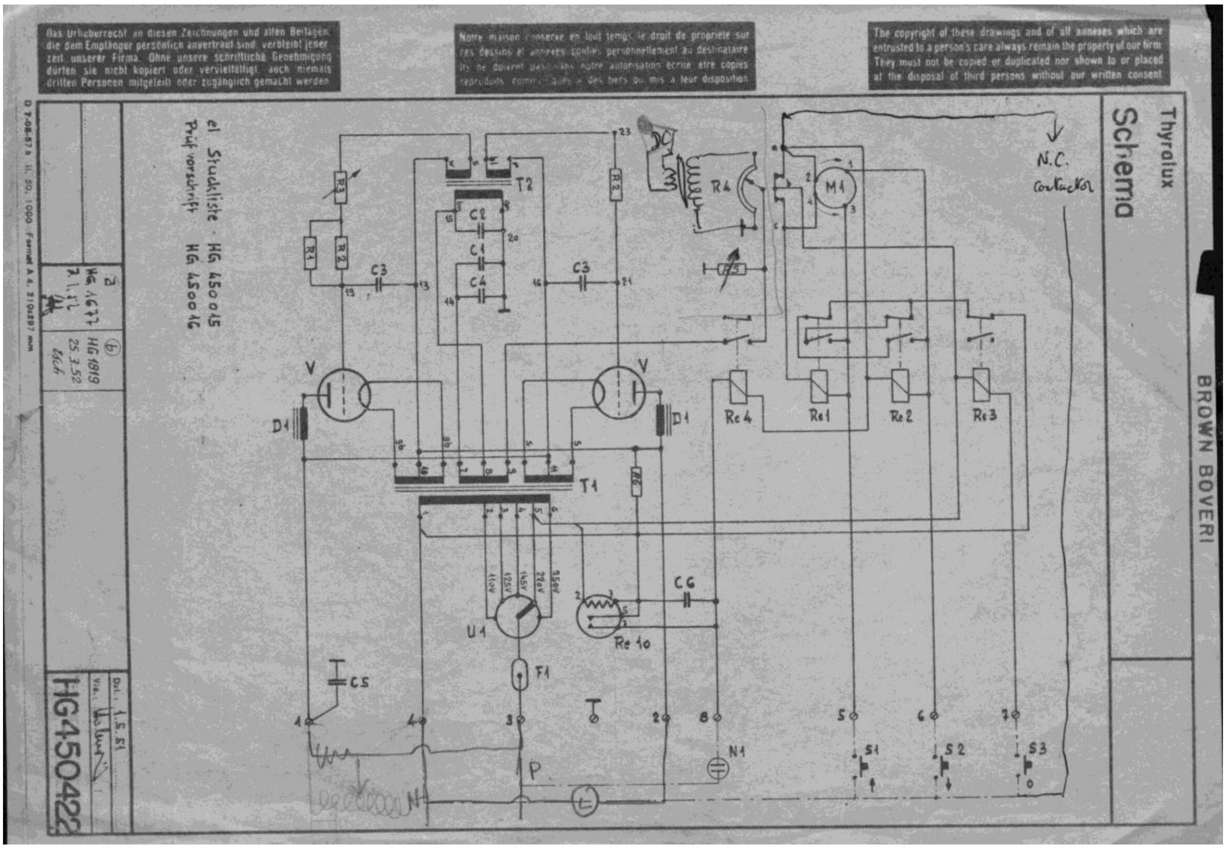

Figure 46. Brown Boveri Thyralux schematic (British Brown Boveri 1952)

11.3. AEG ‘Regolux’

Bentham reported that Hamburg Opera visited the Kings Theatre Edinburgh in August 1954 and being particularly impressed by their Electronic dimmers, asked Strand to quote for 240 ways (Bentham 1964). Strand declined since it exceeded the maximum number of ways (144) and by then the product had been withdrawn[49]. Bentham’s apocryphal story tells that as a result AEG developed a competing system for Hamburg. There is no truth in this, AEG both manufactured thyratrons and was already active in thyratron light dimming applications for both auditorium and stage use. Hamburg was probably just seeking a competitive quote against AEG. Wood visited the completed installation in 1955 (Wood 1955).

In Germany AEG first used thyratrons for auditorium dimming in 1937 at Dessau, but this failed in service and had to be removed (Schott 1954d). However by 1954, AEG had revived the use of thyratrons for auditorium and stage dimming with a new installation in the Hochshule für Musik in Berlin (Warsinski 1954). This used 32, 6 kW dimmers for the auditorium and platform lighting, using a boosted 240 V mains for the 220 V lamps, controlled by push-button presets.

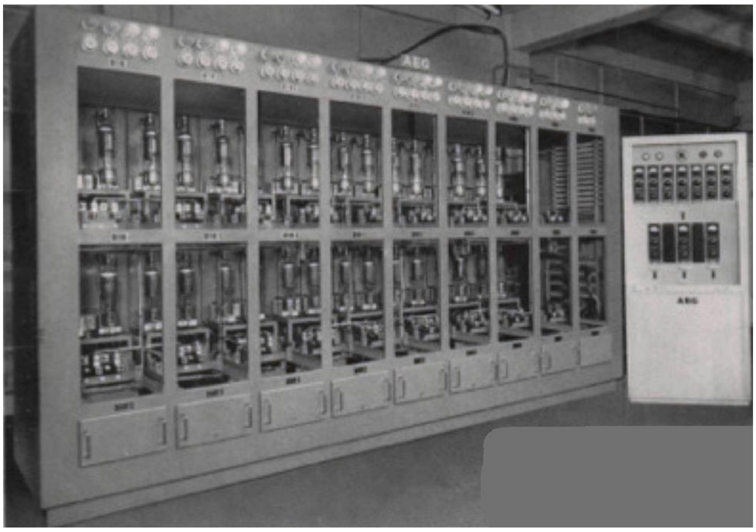

Figure 47. AEG 6 kW Thyratron dimmers at Hochschule für Musik, Berlin, 1954 (Warsinski 1954)

In addition to auditorium dimming, AEG replaced their autotransformer tracker-wire ‘Salani’ theatre dimmers with a thyratron dimmer, constructed in the usual array of valve banks and a dual preset desk called the ‘Regolux’ (1955a). The product was announced in a series of Bühnentechnische Rundschau (BTR) papers from April 1954 with the prototype presented at the October 1954 Bühnentechnische Tagung in Stuttgart (Schott 1954a; b; c). Installations started by 1955 with the 240 way, 2 x 2 preset, three group, Hamburg Opera installation and the Münster installation in Figure 50, though their 1956 Stage Lighting catalogue did not yet list them (1956a; Pinck 1956).

The theatre design shown in Figure 48 used the conventional antiparallel pair of valves but with an integrated 235 V autotransformer for each dimmer to provide 220 V output with 220 V

[49] The method of resistive mastering would also have required significant redesign to extend a further 96 ways. In addition Bentham had managed to enforce the policy of selling only Light Consoles over 144 ways.

input. This obviated any need for a boosted supply transformer. Ratings of 3 x 3 kW or 2 x 5 kW per panel were provided using AEG thyratrons containing both mercury and argon, with a claimed life of 15,000–20,000 hrs (Wood 1955).

Figure 48. AEG 'Regolux' thyratron dimmer racks (three dimmers per panel), Germany, 1954 (Frank 2015)

The schematic was described by Schott in Figure 49 (Schott 1954b). Phase angle control is achieved by use of a small, double-wound, saturable reactor (naturally a phase control device). Through a set of transformers, the reactor generates a standing negative voltage on the thyratron grids, on which is superimposed a positive firing pulse when the reactor saturates. The two desk wings each provide an AC control signal of 0–25 mA, rectified in the dimmer before the saturable reactor in a current summing fashion to achieve a dipless crossfade (Schott 1954a)

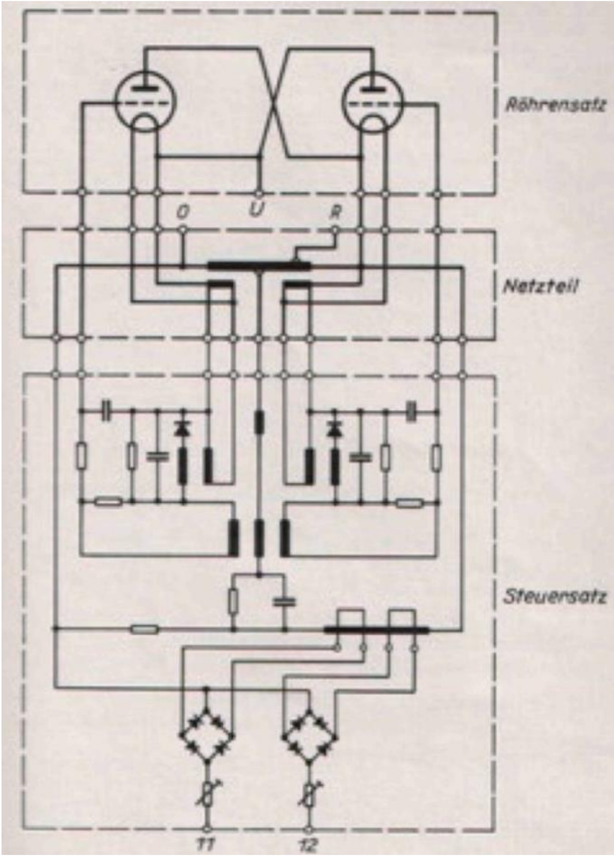

Figure 49. AEG Regolux thyratron dimmer circuit
(R = phase, U = Load, $\bar{U}$ = neutral, 11 & 12 = preset inputs) (Schott 1954b)

The control desk shown in Figure 50 emulated the Electronic with a pair of preset wings, either of which can be active. There was a motorised crossfader which faded between a left and right preset bank using a variable transformer (since the control signal was AC) rather than the lossy potentiometers used by Wood (Pinck 1956). The crossfader was motorised with a speed range of 1 sec to 10 min. Dimmers could be switched to one of three 'Lines' which were independent of the crossfader for separate control, plus nine stage area masters (probably fixed) to control areas such as FOH and Cyclorama.

All the desk master and dimmer levers had bi-directional roller clutches to common shafts, emulating the traditional manual tracker wire controls, but with the pitch reduced from 45 to 22 mm. The masters could thus be linked together for a synchronised operation of several masters.

The preset fader banks also each contained a system of top and bottom limit cams to provide the preset memories. Schott in 1954 states that there were two per fader (i.e. the top and bottom cam), but by 1956, Pinck reports that four presets were offered per fader wing at Hamburg, supported by Wood who also noted that full and off could be selected (Pinck 1956; Schott 1954a; Wood 1960). To use the cam presets, the levers had to be selected to move on the common shaft then run up or down using the side wheel to the cam stops.

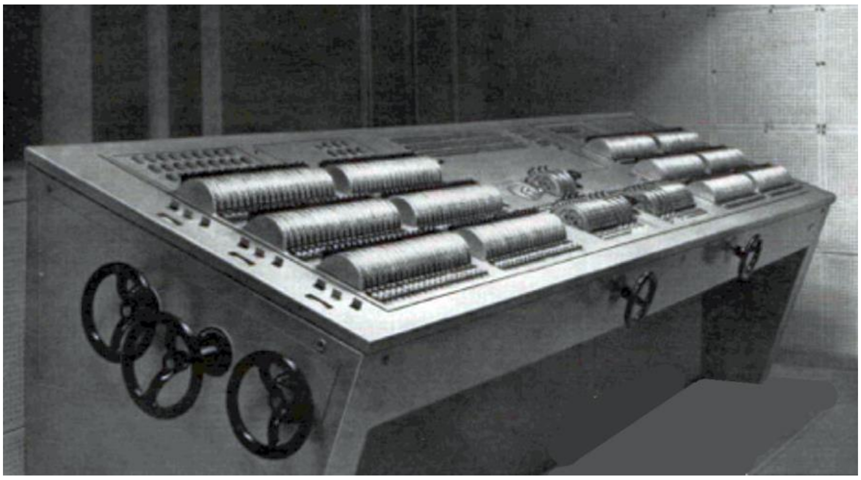

Figure 50. AEG 'Regolux' dual preset desk in Münster Stadttheater, Germany, 1956 (Pinck 1956)

AEG made marketing claims of ability to dim low voltage and fluorescent lamps, plus extra mechanical presets to counter the Strand Electronic. They also stressed the continuity of the inertial and immediate live nature of the fader levers (albeit swapping from one bank to the other) to reassure users migrating from traditional regulator controls. The Regolux name was retained when AEG introduced thyristors by 1964, retaining the same dual bank console arrangement (Huneke 1964).

11.4. Siemens ignore thyratrons and use phase control magnetic amplifiers

Siemens, then the dominant post-war German theatre lighting supplier, similarly saw the need to move away from over 50 years of tracker-wire controlled resistance and autotransformer dimmers to all-electric control. In their case they instead decided to perfect the magnetic amplifier dimmer (Kolbe 1959). Siemens claimed back in 1934 to have considered using thyratrons in anti-parallel connection for controlling low voltage loads, but instead felt for economic and reliability reasons magnetic amplifiers (not simple saturable reactors) were preferable.

While they had to wait for the development of suitable high current metallic rectifiers, they were not the first to market. Graham Bothers in Sweden introduced a magnetic amplifier system in 1950, equipping two Oslo theatres in 1950-2 before marketing in Germany (Gierdrum 1954; Wood 1960).

The operation is very similar to thyratrons. Two inductors, each in series with rectifiers (shown in Figure 51) and connected antiparallel, each conduct for opposing half-cycles. If the inductors are not biased by a control winding, they present a high impedance and very little current flows. Once the inductor's core is biased by a small control signal in addition to the load current it can saturate (about 2 W of control power is needed), then the resultant high load current flow to the load ensures it remains saturated for the remainder of that half-cycle. It thus operates as a phase control device very similarly to the thyratron dimmer, though the saturation step is more gradual and has less tendency to generate lamp sing. It remains still a complex electro-magnetic design to ensure load independence, requires a boosted supply voltage and losses in the inductors and rectifiers result in half-load efficiencies of 88-92% (Kolbe 1959).

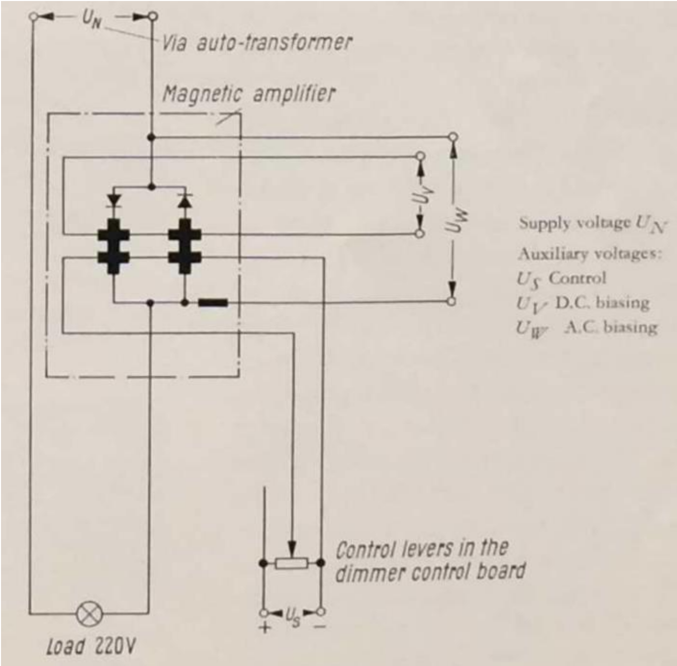

Figure 51. Siemens magnetic amplifier dimmer basic diagram (Kolbe 1959)

While expensive and quite space-consuming they were reliable. When installing new microprocessor Strand Galaxy lighting consoles in 1984, Sydney Opera House chose to keep their old Siemens magnetic amplifier dimmers and interface to them rather than install new thyristor dimmers (Marshall 1985).

Unlike AEG and Strand, Siemens chose to implement their ‘Living Lever’ system of motorised faders within a single desk, that can be driven to one of four presets. This more closely emulated the previous regulator controls on Bordoni dimmers, but retained their ‘shaft mastering’ rather than the artistically preferable proportional crossfade now offered by AEG and Strand.

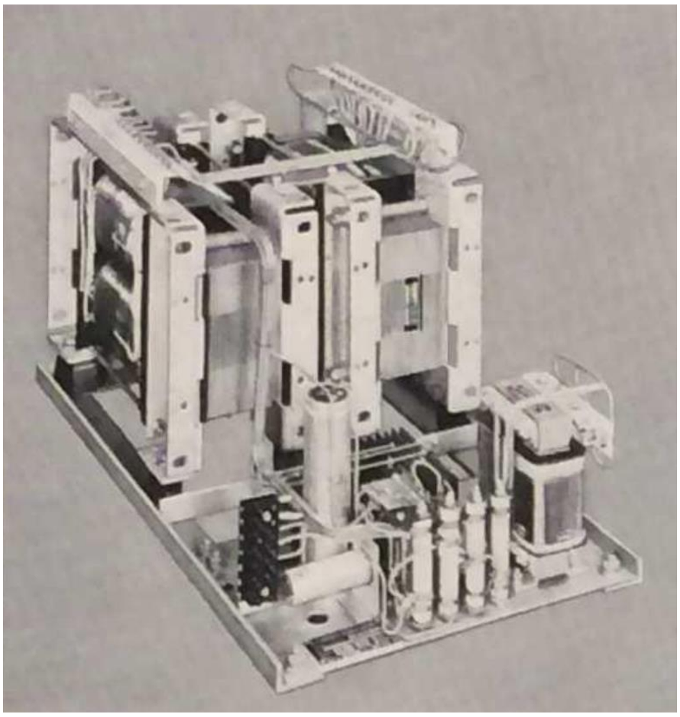

Figure 52. Siemens 5 kW magnetic amplifier dimmer (Kolbe 1959)

11.5. I.E.C.E.T.

An impressive ~300 channel system design was installed in Italy from I.E.C.E.T. or Galanti, at an anonymous venue photographed by Fred Brown (Brown 1953-56). This was probably La Scala, Milan, which Wood recalls was installed by 'Galantea'(?) in the 1950s, and which both Wood and Machin report was operated by 'Germanic' tracker-wire reversing regulator levers operating little radio potentiometers to control the dimmers (Machin 1976; Wood 1974).

Figure 53. Italian 'Galanti' thyratron dimmer racks, probably at La Scala, Milan (Brown 1953-56).

11.6. Francisco Benito-Delgado 'Fechatron'

An intriguing Spanish system was introduced to Spain in 1954 by the large electrical engineering company F. Benito-Delgado of Madrid, termed the 'Fechatron' system (1955b; 1955?; Fidel 2020). The console and dimmer bank are illustrated in Figure 54. It was installed at Teatro del Liceo in Barcelona in 1954, Zarzuela in 1956 and the Royal Theater of Madrid in 1957 (Fidel 2020).

The Barcelona console bears a strong similarity to the Electronic system, with 16 (plus one spare) faders per row, and a less massive cross-fader (Unruh 1955). The dimmer valve bank also looks similar but has two bays of 10 x 4 rows of valves to provide 40 dimmers/rack. The system used conventional antiparallel phase control. The company was noted for its policy of licensing overseas patents to manufacture for the Spanish market, however while the system looks very similar, there is no evidence that Benito-Delgado licensed a design from Strand (Fidel 2020).

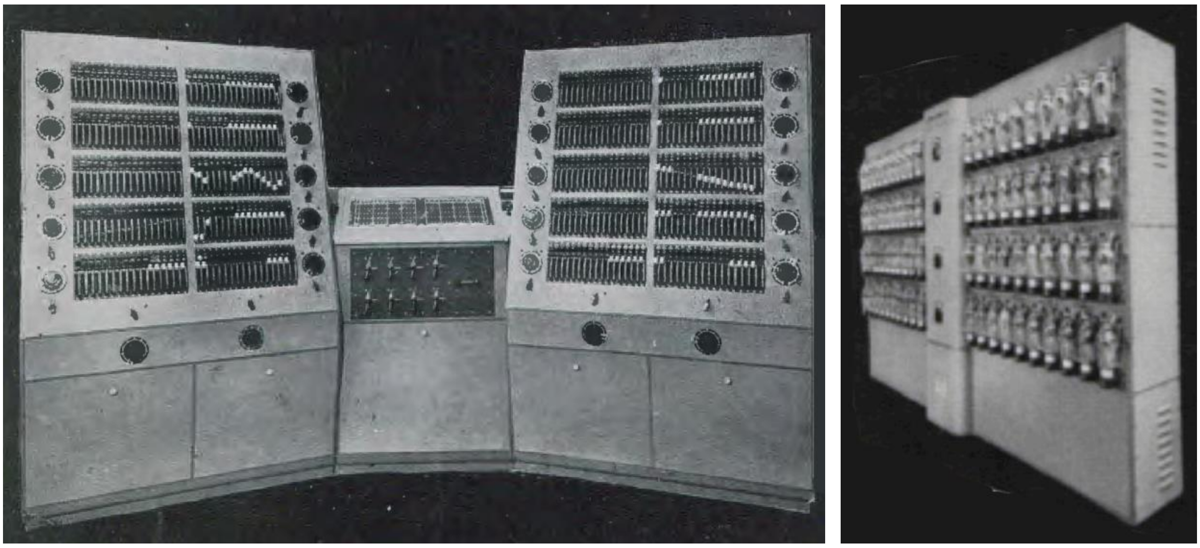

Figure 54. F. Benito-Delgado console and dimmers at Teatro del Liceo, Barcelona, c1955 (1955b; 1955?)

11.7. Others

Theatre and TV was not the only lighting application of thyratrons, commercial lighting companies saw their benefit for auditorium and hall lighting. For example, Atlas lighting in the UK used thyratrons (XR1-6400A) to dim fluorescent lights at St Albans Civic Centre. These commercial applications also proved troublesome (1960s). Thorn Lighting introduced a system in 1954 which was installed at the Regal Glasgow, but reliability issues led to this product's early withdrawal (Hatcher 2010).

12. Use of Transformers to Mitigate the Electronic's Harmonic Impact

The use of a normal delta-star supply transformer as discussed earlier would substantially mitigate the deleterious effects of the Electronic dimmer, however it needed to be oversized and correctly specified to allow for the extra burden of the circulating harmonic currents in the primary and the high DC current in the neutral.

A better solution, that was often adopted in the USA for the Kliegtronic, is the zig-zag transformer. It is used in situations where there is a need to generate a three-phase 4 wire (star supply) supply from a three-phase, 3 wire system (delta) or three-phase 4 wire supply (star), and there is the presence of high harmonics and/or DC in the load. It is the heart of a family of specialist transformers known as Harmonic Mitigating Transformers. It differs from the normal delta-star configuration in that the secondary has two windings per phase, combining the voltages from two incoming phases to create each outgoing phase. Figure 55 shows the primary and secondary windings in conventional phasor arrangement.

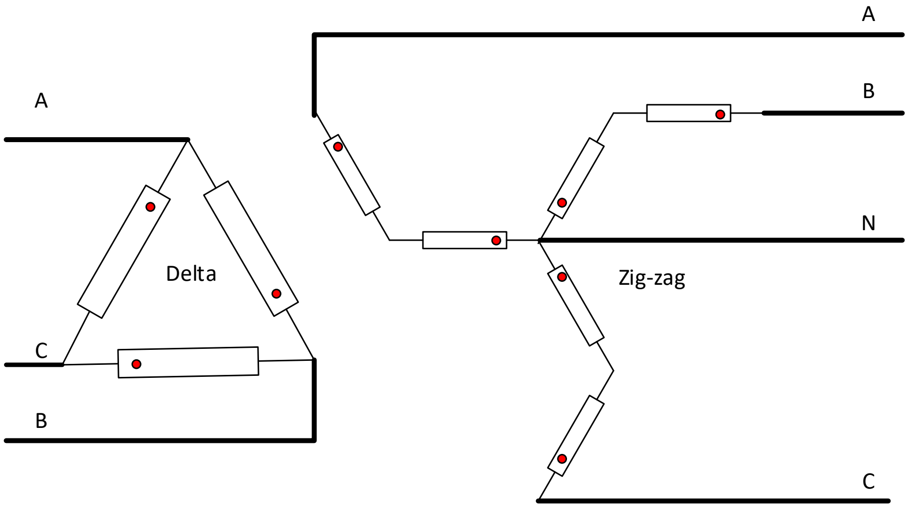

Figure 55. Zig-zag transformer winding

It is of course more complex to manufacture, and less efficient in materials since the secondary winding pairs are not completely in phase, thus require more turns to achieve the desired voltage. However this is offset by its beneficial performance.

In the three-phase zig-zag transformer, the iron core has three limbs show in Figure 56 on which the 9 windings are placed, with each phase wound on one limb. The precise way the secondary winding pairs are connected is also shown in Figure 56, aligned as they would be on the limbs of the above transformer core.

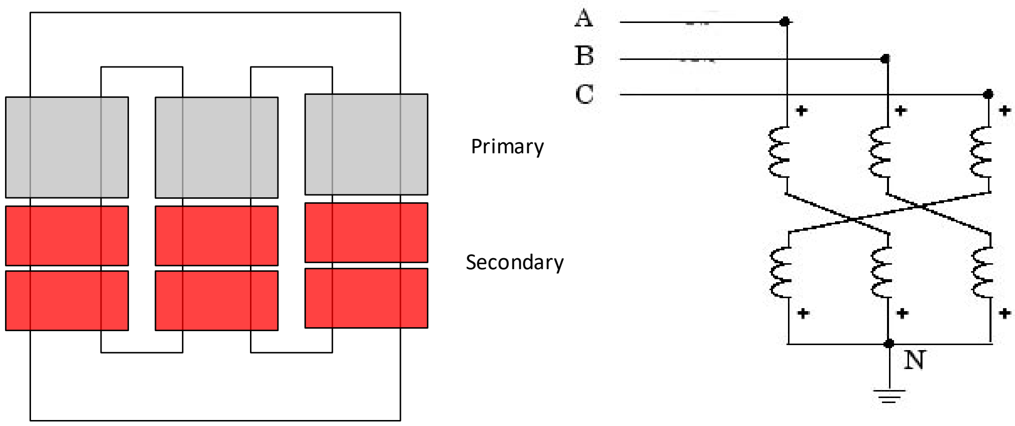

Figure 56. Zig-zag transformer construction and secondary interconnection

The DC output current from the Electronic dimmer causes pulsed DC currents in the 3 phases. While the zig-zag connection means the DC currents in each phase cause pulses of flux to circulate around each limb pair, since each phase windings are in opposition, successive phase current pulses reverse the flux, minimising the risk of remanence developing in the core iron.

This arrangement also assists with trapping some harmonics from the dimmers. The ones trapped are the zero sequence ones, 3rd, 6th, 9th etc. which thus do not propagate to the primary where their circulation would cause excess heating.

In the USA, the use of 120 V secondary voltages requires the frequent use of local supply transformers, and thus choice of a dedicated zig-zag transformer is normally only a modest extra cost. In European situations with 230–240 V systems there is greater tendency to distribute district power at this voltage level. In this case an alternate technique to absorb the high DC neutral currents is a Static Balancing Transformer shown in Figure 57 and later recommended by Bentham (Bentham 1955 (revised 1957)). This is often used to generate a neutral supply on a delta system or to reinforce the neutral on long rural distributions with considerable phase imbalances.

A static balancing transformer was reported by Anderson (Anderson 2017a) as used in 1956 to supply the neutral on the BBC Riverside Studio 2 Electronic dimmer system. However neither the BBC Report (Hersee and T 1957) on the system nor the BBC Monograph on the whole complex (Nickels and Grubb 1957) record such a transformer. There was however a single 415/208 V stepdown and voltage regulating transformer located in Riverside 2 dimmer room, and it is possible this secondary was zig-zag wound and operated in the same manner.

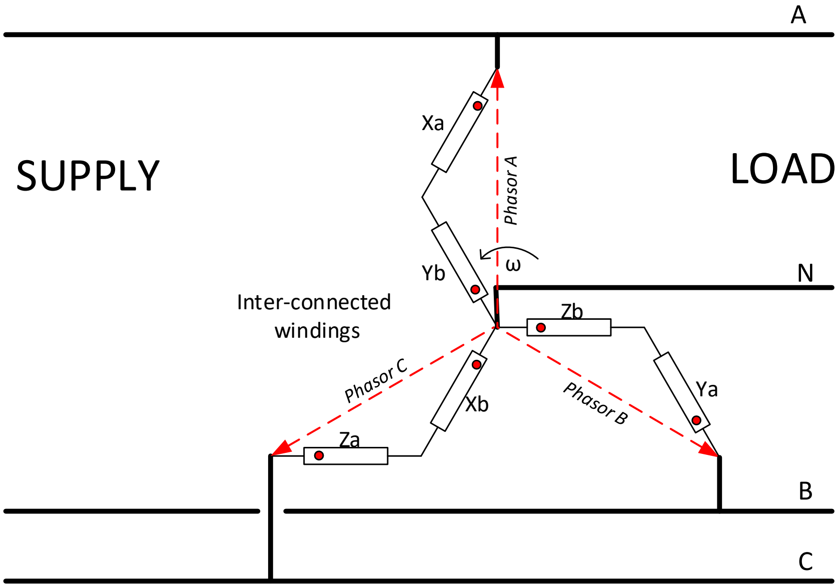

Figure 57. Static balancing transformer winding and phasor layout

The static balancing transformer windings are connected in the same manner as the zig-zag transformer and are wound on the core the same as the secondary windings of Figure 56. In normal phase imbalance use, this transformer couples the neutral current back onto the three phases equally. Effectively 33.3% of the neutral current is transformed inverse onto each of the three phases. Thus for example a single-phase load is mitigated by reducing the loaded phase current to 67% of original, with 33% now being drawn from the other two phases.

With the Electronic dimmer, the effect of this transformer is to trap the DC current pulses from the neutral and re-distribute them inverted back to the supply phases. This means each phase pulse reduces to 67% with two opposing 33% pulses added from the other two phases. However unlike the zig-zag transformer, zero-sequence harmonics are not trapped and still propagate to the supply transformer. The graph in Figure 58 for Phase A shows how the imbalanced DC current pulses are reflected from the other phases, resulting in a zero mean DC current in each phase. The Phase rms current also reduces by 18%.

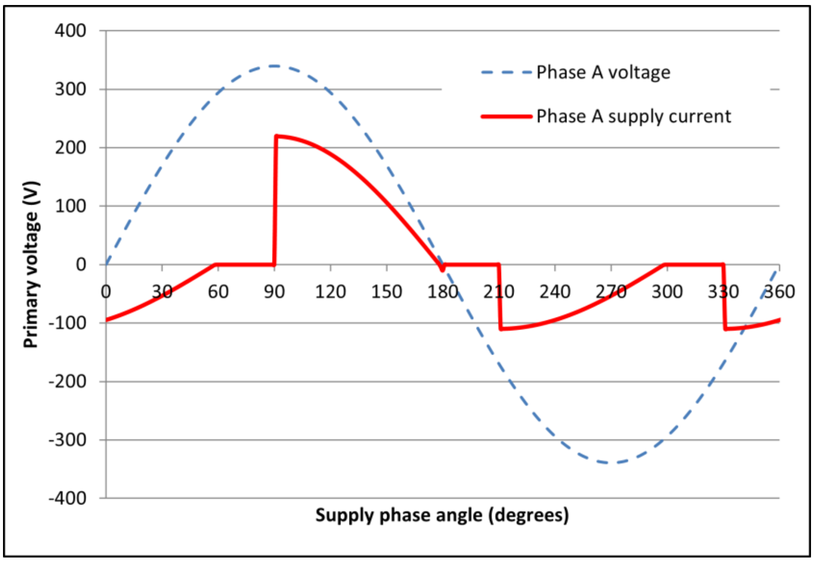

Figure 58. Phase current with a Static Balancing Transformer supporting the neutral

13. Conclusions

The Strand Electronic dimmer was unique in its use of three valves performing half-wave, phase-control rectification as a means of dimming. Preceding and succeeding designs all used two valves providing full-wave, AC phase control, leaving the Electronic as the international peculiarity. It was important in that it offered accurate presetting and proportional dipless crossfade between presets for the first time in the UK, as well as variable dimmer load with instant response. This ended reliance on operator hand and foot dexterity for lighting quality.

However Strand remained trapped in the between-wars British cultural insularity and failed to understand the importance of presetting and AC output for European theatre. Expecting major Continental stages to move back to DC loads having mostly converted to AC with such as Bordoni dimmers, abandon their transformer-fed, high performance low voltage luminaires, and accept an artificial limit of 144 ways was simply an exercise in self-defeating arrogance.

Further if all its technical drawbacks had been understood at the time it is unlikely this design would have been marketed. The severely overloaded neutral conductors must have afflicted all installations up to the end of 1952, after which Strand was more careful, while the inability to deliver the advertised full power (without a greatly over-specified supply current) would have impacted all 30+ installations. Premier British theatres like Stratford and Old Vic might have been expected to voice these issues, yet it seems only the New Theatre demanded and got an early replacement. It is surprising that there were no electrical catastrophes recorded from this era.

In Europe Strand was a pioneer of electronic theatrical dimming, in which case one could understand the need to iterate via initially less successful prototypes. However by 1954 Strand decided to abandon the concept rather than redevelop, just as others entered the market. Others also followed in the footsteps of the well-publicised Izenour thyratron dimmer design which had less drawbacks. As consolation, Bentham compared the Electronic dimmer with the ill-fated Comet aircraft, as both being brilliant pioneering efforts ahead of their time, but with unseen defects that needed time to discover (Bentham 1955 (revised 1957)). Unfortunately the human failings in both are less comforting[50], the Electronic's defects were clear from the design approach.

Strand was fortunate in that Bentham's dislike of the Electronic had encouraged continued development of his electro-mechanical dimmer systems. The post-war appearance of an affordable and sensitive polarised relay finally enabled preset servo control of Mansell clutch-driven electro-mechanical dimmers (systems PR/C/CD) to replace the Electronic (Bentham 1983). This was encouraged by the advent of commercial TV whose buyers were electrical engineers wanting reliable studio lighting systems, and for which the group memory functions were particularly attractive. Motorised resistance and transformer dimmers with presets and group memory were thus relaunched by Strand in 1955 for their last Indian Summer, until the thyristor changed the world of theatre again in 1960.

[50] The Comet's demise came from the designers underestimating the well-known concentration of stresses that occur at sharp corners of apertures, in this case the new 'stylish' square rather than round windows in the fuselage.

14. Acknowledgments

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16. Biographical Details

Dr. David R. Bertenshaw was an electronic design engineer rising to R&D Director at Rank Strand Electric / Strand Lighting Ltd from 1971-1997, developing stage and studio lighting and control equipment. In 1998 he joined Adwel International Ltd to manage their European division for large electrical machine condition monitoring. After retiring in 2008 he established ENELEC Ltd as a condition monitoring consultancy also researching stage lighting history. He has published 52 papers and articles and 6 patents.

https://orcid.org/0000-0001-6464-4516

Appendix James Templeton Wood

Figure 59. James Templeton Wood (Bentham 1986)

The Woods of Littleton

There is limited information regarding the 20th century life of James Templeton Wood (JTW aka 'Woody'). However he comes from a family with long established and well-connected pedigree, documented back to Henry VII (*r* 1485–1509). They have their own coat of arms in Figure 60 and motto, roughly meaning 'The Bull rejoices in the Wood', while JTW's father displayed his own hatchment, shown in Figure 61. The family has been closely connected to the village of Littleton, near Shepperton, Middlesex since 1660.

Figure 60. Arms of Woods of Littleton,

Figure 61. Hatchment of JTW's father.

Littleton is a small village and parish in the Spelthorne Hundred within the ancient county of Middlesex. It was separated off from Laleham in the 11th century (1911a). A further smaller parish and common of Astlam was later established between Laleham and Littleton.

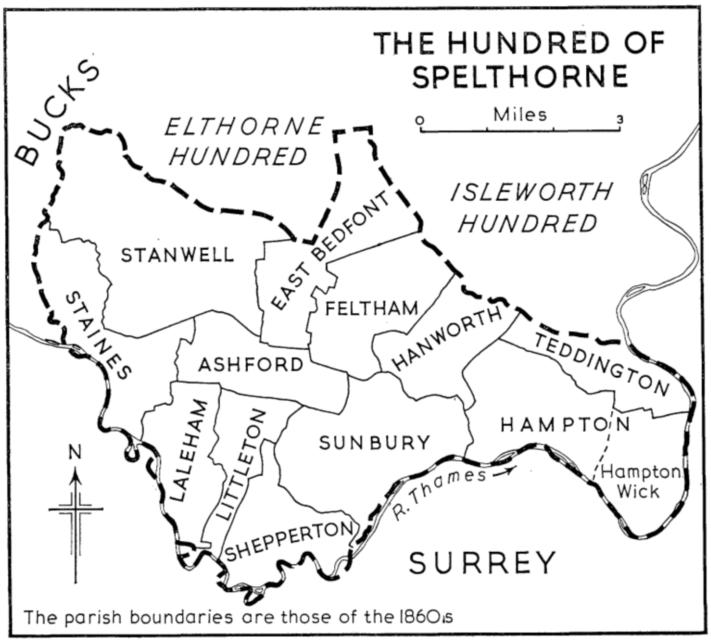

Figure 62. Spelthorne Hundred with Littleton (1962)

The connection between the Wood family and Littleton began in the middle of the 17th century when Edward Wood, heir apparent of Edward Wood, Alderman of London, acquired the manor of Astlam in 1660. The Wood family also bought the larger adjoining Littleton manor between 1749 and 1783 (1911b) but controlled it much earlier, probably also since 1660 (Woodbridge and Johnston 2012).

Thomas Wood built Littleton Park House in 1689. This remained the principal seat of the family until the house was destroyed by fire in December 1874[51], when the owner Captain Thomas Wood removed permanently to the family estate at Gwernyfed, Brecknockshire, Wales. The House remains were bought in 1876 and restored by Sir Richard Burbridge, Managing Director of Harrods. In 1931 Norman Loudon, owner of Flicker Productions[52], bought Littleton Park House with 60 acres of grounds for film production, which then became Sound City and is now Shepperton Film Studios. The rebuilt manor house illustrated in Figure 63 remains in the grounds though is now surrounded by film studios and used commercially[53]. Astlam and Littleton commons (with farmland and houses) were submerged by the construction of the Queen Mary Reservoir in 1925, covering 800 acres as shown in Figure 65.

[51] The fire also consumed a fine collection of paintings. The most famous of these was Hogarth's ‘Strolling Actors’, which had been purchased in 1745 by Thomas Wood. (2018b).

[52] Initially produced popular 'flick' books of photographs.

[53] Popular for events and weddings

Figure 63. Littleton Park House (2018d)

Figure 64. Littleton Parish Church

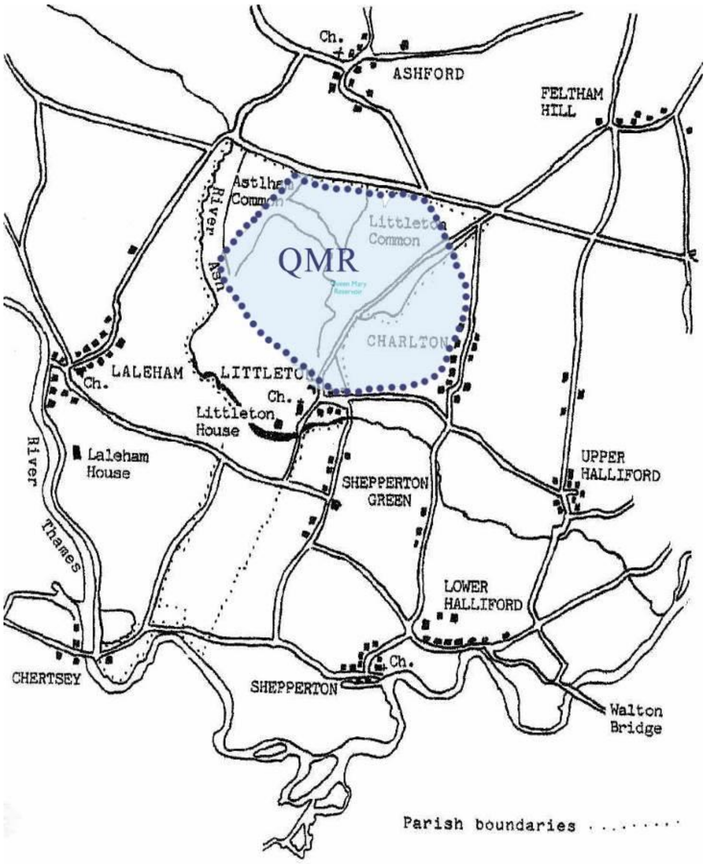

Figure 65. Astlam and Littleton parishes and Littleton House, with Queen Mary Reservoir (QMR) overlaid (Woodbridge and Johnston 2012)

The Littleton parish church of St. Mary Magdalene dates from 1135 with even earlier Saxon foundations and is believed to have been founded by monks from the Benedictine Abbey at Chertsey (Giles 2013). It has a 12th century nave and font with 15th century pews while the tower is Tudor with three bells dated 1666. The 15th century screen came from Westminster Abbey. The advowson (patronage) of the church and parish was acquired in 1673 by Thomas Wood (1911b) whose family held it up to 1933. Three memorial windows are dedicated to Wood family members, including one to JTW's grandparents shown in Figure 66, together with plentiful Wood family memorial wall plaques.

Figure 66. Littleton Church memorial window to JTW's grandparents

A burial mausoleum and chapel for the Wood family was added to the north side in 1705. This is now used as a vestry and storeroom though the vaults remain (Giles 2013). The addition is clearly seen as the lower brick addition to the right of main Church building in Figure 64. The church continued to hold an important position in JTW's family; his memorial service was held there in 1985 (Bentham 1986), while on his wife's death in 2011 donations were requested in her memory to the Restoration Fund of Littleton Church (2011). She is buried in the family grave there.

The Woods were substantial landowners with property in a number of other counties. The Middleham estate in Yorkshire was purchased in the seventeenth century and the estate at Gwernyfed was acquired in 1776 upon the marriage of Thomas Wood to Mary, daughter and heiress of Sir Edward Williams of Langoid Castle. The Littleton estate, comprising over 1,250 acres in Littleton, Shepperton, Ashford and Laleham, was broken up and sold from 1892, although Captain Thomas Wood still owned much of the land in Littleton parish in the early twentieth century.

For the most part, members of the family followed careers in law, government (particularly in India), and the armed forces (2018b). The first Thomas Wood to live at Littleton (1664-1723) built the manor house, continued his father's merchant business, and held the appointment of Ranger of Hampton Court[54]. His son Robert was a scholar and Doctor of Laws and, in the next generation, Thomas (1708-99) was Treasurer of the Inner Temple. His descendants entered the government, at home and overseas, often preceding this by military careers. Colonel Thomas Wood (1777-1860), Member of Parliament for Brecon for forty years, commanded the Royal East Middlesex Regiment of Militia for fifty six years and encamped with them at Aldershot in his eightieth year. His son Thomas (1804-72) commanded the 3rd Battalion Grenadier Guards in the early stages of the Crimean War. Prior to this he represented the County of Middlesex in Parliament. Thomas's son, again Thomas (b.1853), followed his father into the Grenadiers and saw action in the Sudan. Upon leaving the regular army he became a colonel in the Brecknockshire Rifle Volunteers and entered local government. Famous soldiers in the family include Charles Wood (1790-1877) who fought both in the Iberian Peninsula and at Waterloo against Napoleon, and his nephew General Sir David Wood (1812-94) an officer in the Crimean campaign and during the Indian Mutiny.

Throughout the nineteenth century the family consolidated its position among the landed gentry by contracting alliances with the aristocracy. In successive generations three Thomas Woods married, respectively, the daughter of 1st Marquess of Londonderry, the grand-daughter of 4th Duke of Grafton, and the daughter of 1st Lord Tollemache. Colonel Thomas Wood and his wife enjoyed the friendship of King William IV and Queen Adelaide, the King even nominated Wood to be one of his executors. Colonel Wood was host to George IV at Gwernyfed, and members of the royal family visited Littleton Park.

The Pedigree of the Woods of Littleton family is listed below (Burke 1894; Crisp and Howard 1905; Howard and Crisp 1896):

1) Thomas Wood, of Fulbourne, co. Cambridge, Sergeant-at-Law, *temp*. Henry VII (r1485-1509), left a son.
2) John Wood, of Fulbourne, *m*. Anne, dau. and heir of Hilton, of Yorkshire, left son and heir.
3) Nicholas Wood, of Fulbourne, *m*. Elizabeth, dau. and heir of Edward Clopton, of Dansunhall, and had a son.

[54] That the house bears a resemblance to Wren's contemporary Hampton Court has encouraged speculation that labour was 'borrowed' from the palace.

4) Edward Wood, of Fulbourne, co. Cambridge, bur. there 11 June, 1599; *m.* Elizabeth, dau. of Thomas Chicheley, of Wimpole, co. Cambridge (4th removed nephew of Henry Chicheley, Archbishop of Canterbury, Founder of All Souls', Oxford), and had issue, Nicholas 3rd son inheriting.

5) Nicholas Wood, of Sneterly *also* Blakeney, co. Norfolk, bapt. 20 Jan. 1565, Fellow of All Souls', Oxford, as Founder's kin 1581; *m.* 3 Oct. 1601, Anne, dau. of John Ferrour, of Gressenhall, co. Norfolk, and was bur. 31 March, 1646, having by her (who was bur. 18 Oct. 1648) issue, Edward first son inheriting.

6) Edward Wood, Alderman of London, b. 1604; *m.*. Susanna Harvey, and was bur. 10 March, 1666, leaving an only son.

7) Thomas Wood, Esq. of Littleton, co Mddx, b. 1641, Ranger of Hampton Court 1664-1723; bur. at Littleton, 14 June, 1723. *m.* Dorothy, 2nd dau. of Sir Robert Dicer, Bart, of Hackney, and by her (who was bur. 17 Nov. 1704) had issue, Edward first son inheriting.

8) Edward Wood, of Littleton, co Mddx, and of Hampton upon Thames, b. 3 Jan. 1670; *m.* Elizabeth, dau. and sole heir of Henry Briilgor, of Guildford, co. Surrey, and by her (who was bur. 22 May, 1755) had issue, Thomas 3rd son inheriting.

9) Thomas Wood, Esq. of Littleton, Treasurer of the Inner Temple, b. 25 Sept. 1708, MP for Mddx. 1799-1780. *m.* Anne, dau. of Jones, 2 Oct. 1743, and d. 25 June, 1799. Had issue, Thomas eldest son inherited. Henry 4th son.

10) *Great-grandfather and 'mother*

Henry Wood of Woodhill, in Send, co. Surrey born 11 August 1782, bapt. at Missenden Abbey, co. Buckingham, 14 September 1782; of the Bengal Civil Service, Accountant-General, Calcutta, R.E.; died at Torquay, co. Devon, 13 January 1871, bur. at Southborough, Kent. m. Margaret Elizabeth, dau. of Thomas Templeton, Attorney of the Supreme Court, Calcutta; born 27 November 1789; marr. at Calcutta 7 October 1809; died at Woodhill, 18 September 1879, bur. at Southborough. Had issue 7 children, 2nd son James.

11) *Grandfather and Grandmother*

James Templeton Wood of 10 Pembridge Gardens, Bayswater, London; born 7 November 1819, and bapt. at Moradabad, North-West Provinces, India; educated at Eton and at Trinity College, Cambridge, B.A. 1841, M.A. 1844; a Student of the Inner Temple 22 January 1838 (then aged 18), called to the Bar 31 January 1845; died at Stradmore, Llandyssil, co. Cardigan, on 19 October 1887.

m. Mary Elizabeth, 4th dau. of Richard Moon of Shaw Street, Liverpool, by Elizabeth his wife, dau. of William Bradley Frodsham of Liverpool, born in Liverpool 24 October 1823; marr. at Aigburth, co. Lancaster, 10 March 1858. Died 5 February 1913. One son Henry James Theodore.

12) *Father and Mother*

Henry James Theodore Wood of Fingest Cottage, Fingest, near High Wycombe, co. Buckingham; born at 42 Inverness Road, Bayswater, London, on Monday, 23 March 1863; Scholar of Eton and of Pembroke College, Cambridge, matriculated 1882, B.A.

1885, M.A. 1889; Barrister-at-Law of Inner Temple, admitted 8 March 1887, called 17 November 1890 and of Lincoln's Inn; J. P. for co Buckingham 1899; Member of the Alpine Club; a Director of the French Hospital (La Providence); on the Committee of the Most Honourable and Loyal Society of Ancient Britons. By 1911 census was Barrister – retired. Died 19th January 1918 at Camberwell House, Peckham Rd. Surrey, Probate £10,000. Family shield in Figure 61 (b).

m. Ellen Beatrice, 3rd dau. of Sydney Henry Jones-Parry of Ty-llwydd, co. Cardigan, sometime Captain in the Royal Madras Fusiliers, J. P. and D.L. for co. Cardigan, High Sheriff for co. Cardigan 1871, by Dorothea Anne his wife, only child of Charles Arthur Prichard of Ty-llwydd, J. P. and D.L. for the counties of Brecon and Cardigan. Born at St. Leonard's-on-Sea, co. Sussex, on Wednesday, 7 February 1866, marr. at St. James', Paddington, London on Saturday, 27 July 1889. Died 19th January 1961 at Barford St Michael, Oxfordshire.

Three children, Katherine Margaret Love (1898–1989), Nicholas Crispin (1900–1976) and James Templeton (1906–1985).

Life of James Templeton Wood

JTW was born at Fingest Cottage, Fingest, near High Wycombe, co. Buckingham, on 24 September 1906, and baptised privately the same day. The speedy baptism implies that he was born sickly. He was the third of three children and unlike the eldest brother, took family names.

At the 1911 Census the family was living in substantial accommodation in a six story town house, 32 Clanricarde Gardens, Bayswater, London, the five family members having four resident servants. The family lived there until at least 1929, though by then just his mother Ellen and brother Nicholas remained, and the house had been converted to three flats. The house remains today.

His brother Nicholas Crispin Wood[55] followed his father to Eton, however JTW apparently did not[56]. His father died when he was aged 11, thus the funds for schools such as Eton may have dried up. His school education is unknown, but in 1931 aged 24, he achieved a certificate 1st Class in 'Engineering Science S.1' at Dover Technical Institute[57] (1931).

JTW married Norah Gartside Tipping on 5th June 1937 in the Parish Church in Sutton by Dover, Kent (1937c). At the time, JTW's profession was recorded as 'Engineer' and he was living at Sutton House, Church Hill, Sutton by Dover CT15 5DF. Norah's profession was recorded as 'Private Secretary'.

Norah was born 1st March 1911 in Tyedesley, Old Park Villas, Palmers Green, London[58] of father Harold Tipping (? –1920) a Doctor, and Florence Nellie Cooper (1879–1923) who died in Allahabad, Uttar Pradesh, India. Norah had a twin sister Rhona Gartside Tipping (1911–1996) and older brother Brian Gartside Tipping (1906–1958)[59]. In 1936, Norah and Rhona

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55 However he did not follow his father into the law, at the time of his father's probate, he was a 'Schoolmaster'.
56 No record in 1920-1924 Eton registers.
57 At the time, 'Electrical Engineering S.1' City and Guild courses were also being run, thus JTW's more general course would have had only a modest amount of electrical engineering theory.
58 A substantial house with 8 rooms and 3 servants in 1911 Census.
59 It is not known why all siblings inherited the middle name Gartside.

were sharing a two-floor flat at 24 Norland Sq. Kensington, London W11 (a property very similar to 32 Clanricarde Gardens). Norah was still recorded there at her marriage the following year.

JTW and Norah had three daughters and at Norah's death, grand and great-grandchildren (1941-1945; 2011). However only two English births can be traced, 1942 in Northampton, and 1947 in Bucklow (Cheshire/Lancashire borders), the third birth was probably in Scotland[60].

Before the war JTW had initially worked in banking then as a schoolmaster (Wood 1974). Wanting to get into sound, he joined Western Electric (WE) during their second wave of recruiting[61] for Cinema sound installation staff around 1931. His training at Dover must have just preceded or been sponsored by WE. Being single, he was posted to Glasgow in 1931–2 where he shared accommodation with the chairman of the Glasgow Pantheon Club. This was one of many amateur Glasgow drama societies at the time (reputedly nearing professional quality), resulting in JTW being roped in to help Johnny Martin, who produced musicals in his spare time. Martin produced for both the Pantheon and 'Glasgow and Provincial' societies and JTW helped with the lighting, including the first Gang Show outside London.

JTW was involved in about four shows per year, produced in major Glasgow theatres like the Alhambra and Wyndhams, while still working for WE. During this period, he was hiring Strand Electric lighting equipment from Watts and Corry in Manchester, and Director Percy Corry came to stay in 1938-9. Corry discussed JTW starting a Scottish lighting hire depot for Strand, and plans were made to start by Christmas 1939 (Wood 1974). By the 1939 Scottish census JTW and Norah were recorded living at 18 Windsor Ave, Newton Mearns, Glasgow G77 5NX, with his occupation as 'Electrician and Cinematograph Sound Engineer' (2018a).

However WW2 intervened and all eligible Western Electric staff were enrolled in the Naval radar services (Wood 1974). On enlistment to the Royal Navy Volunteer Reserve (RNVR) in 1941 his trade was recorded as 'Electrical Engineer'. Initially appointed Prob. T/S Lt. (Special Branch) 8th December 1941, he was then promoted to T/Lt. (Sp. Br.) 8th March 1942, then Temporary Acting Lieutenant Commander (Sp. Br.) by January 1945. He was released from service in April 1946 (1941-1945).

His role as Special Branch officer was on scientific duties, being mainly radar duties in Dover and on the continent. The first 2 months of service were probably basic training, then a year from February 1942 to March 1943 at HMS Mercury II (Admiralty Signal Establishment, Haslemere, Surrey), where training and manufacturing of radar equipment occurred, after which he moved to HMS Lynx (RN base, Dover) until June 1944. His final postings are not recorded but saw '*exciting service'* in France, Belgium and Germany[62] (1946b). In naval radar, mercury thyratrons were sometimes used as pulse modulators[63] and power supply regulators, though their long warm-up time was a disadvantage in warfare[64], as was their rather short and indeterminate life (Kingsley 1995).

[60] These people may be living, thus their identity remains private.

[61] First round had been in 1928-9, but then there were big cut-backs in the 1930 recession.

[62] Radar development for naval and air defence were independent (though shared much technology). Thus JTW's work in the RN, since he was not seaborne, must have been in a coastal radar station since Dover was much too exposed for significant naval supply and repair operations. While most coastal radar was air defence, sea defence radar using modified naval equipment was also used at coastal stations, and also to direct the Dover coastal guns (Kingsley 1995). It is unknown what his later RN duties were in France, Belgium and Germany.

[63] Large triodes and spark gaps were also used.

[64] Faster warm-up hydrogen thyratrons were only developed after the war.

Figure 67. RNVR service photo of JTW (1941-1945)

Prior to demobilisation after the war, JTW went back to Glasgow at Christmas 1945, to find that Johnny Martin had joined Chalmers Wood and already started a Strand agency in Glasgow, thwarting his ambition (Wood 1974). Consequently JTW joined Strand as Assistant Manager, Northern Branch with Percy Corry at the Strand Manchester works on 1st March 1946 (Bentham 1964; 1986). By then his nickname of 'Woody' was also already commonplace (1946b). He was clearly rated highly, solely accompanying Applebee to the June/July 1948 session[65] of the International Commission on Illumination (more commonly known as CIE) (1948a).

His development of the thyratron dimmer by March 1948 led to a transfer to London by 1949. However since the Strand concept of R&D was rather diffuse, and Bentham disapproved of this competitor to the Light Console, he was placed with Sales Other[66] under Cotterill, from which he managed the first installation at Reykjavik in 1949. This led to him focussing on export sales (Bentham 1964), eventually culminating in the official title of Manager of the Export Dept. in 1959 (Bentham 1986). He was indisputably successful and credited with setting up Strand's extensive overseas agent network (Bentham 1992).

The Strand Electric and Engineering Company was taken over by the Rank Organisation in 1968 becoming Rank Strand Electric Ltd, and all engineering and commercial departments transferred from London to the Rank Audio Visual offices in Brentford over the following 1-2 years. JTW however did not transfer, and from 1972 Export Sales at Brentford was managed by Mike Lowe (Fitzwater 2018). His natural retirement date (age 65) would have been 1971, so his departure date was between 1969-71[67]. His retirement activity is unrecorded.

Joel Rubin (Rubin 2018b) recalls JTW as tall and dignified, never in a rush, happy to help and always the gentleman with what he called 'British Reserve'. Pilbrow (2018b) felt that he always seemed to listen, 'a great, if rare, attribute in a consultant or salesman'.

From at least 1950 to 1965 JTW and Norah were living at 20 Harold Road, Upper Norwood, London SE19 3PL[68], a substantial Victorian, 4 story, 8 bedroom villa built in 1889, shown in Figure 68. Prior to 1953 they must have rented or owned the property on leasehold; however in 1953 Norah (alone) purchased the freehold for £750 from the Church Commissioners

[65] Applebee was Chairman of the Stage Lighting Committee. This was the Session that adopted the Candela.

[66] Anything not UK Theatre sales, this being the domain of Applebee.

[67] Martin Moore who joined Strand in September 1968 recalls several customer visits with JTW (Moore 2018), thus he could not have left before 1969.

[68] BT archive directories and 1963 Croydon registers of voters.

(1953a)[69]. In 1963 they were recorded living in the downstairs flat, shared with Norah's twin sister Rhona. Since there is no record of the property being legally divided, they must have been privately letting the upper parts of the house. In 1965 Norah sold the whole freehold for £6,700 (1965), though they must have remained living in the London area for another 5–6 years. After his retirement, by 1983 JTW and Norah were living at 'Ty Coed', 21 Osborne Road, Eastbourne BN20 8JJ, a semi-detached three bedroom house on the outskirts of the town.

Figure 68. 20 Harold Road, London SE19 3PL

JTW died on 4th May 1985 at Eastbourne District Hospital of cardiac arrest aged 78 (1985). His death certificate records his occupation as 'Lighting Engineer (retired)'. He is buried with his ancestors at Littleton Church where a memorial service was held for him in October 1985 (Bentham 1986).

One surprising feature of his life is that at no time does he appear to have disclosed or referred to his extensive family lineage. Even his memorial service held in Littleton Church surrounded by Wood family memorabilia did not seem to elicit recorded comment.

Norah died on 9th September 2011 at Horsham, Sussex and is also buried at Littleton Church. The extended family (grandparents, parents, JTW, wife Norah, sister Katherine and brother Nicholas) share a family grave in Littleton churchyard near the entrance, shown in Figure 69. On it, James Templeton Wood has the curious epitaph 'LAST MALE OF HIS LINE'.

[69] The Manor of Lambeth stretched as far south as Norwood (still called Great North Wood in 1795) and had been owned by the Archbishop of Canterbury since 1196. The land was Enclosed in 1806 enabling commercial development and transferred to the Ecclesiastical Commissioners in 1862. The building of Crystal Palace at nearby Sydenham in 1854 stimulated good rail links to London, encouraging the Commissioners to develop Harold Road with 'City Gentlemen' residences in the1890s, which they let on leasehold. The ~85 m altitude added to the attraction since it lay above the notorious London smog, had good views, and was still semi-rural even in 1950. In 1952 the Commissioners commenced selling all the freeholds. The property now lies in the Harold Road conservation area (2014; Kelf-Cohen 1975; Malden 1912; Sheppard 1956).

Figure 69. The Wood family grave (above) and JTW's inscription

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