The low down on gear for operating low down

A wireless-controlled antenna coupler for 136 kHz and 475 kHz

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Our lowest-frequency amateur bands offer unique challenges in antenna and technology development, signalling and propagation. However, keen experimenters face the hurdle of impedance matching to what are electrically very short antennas. In this article, VK6HP uses the case of his remote LF/MF station, VK6MJM, to illustrate the issue and outlines a convenient solution using a common RF matching approach and a wireless controller.

Introduction

A previous article of mine [1] gave an overview of VK6MJM, a low-frequency (LF) and medium-frequency (MF) station based on a modest, de-commissioned, aeronautical non-directional beacon (NDB).

Most VK6MJM development effort was devoted to RF aspects, with IT needs met by commercial solutions. A contemporary approach to station design was taken, including the use of an embedded vector antenna analyser for tuning as well as efficient push-pull Class D RF power amplifiers.

Monitoring and control of the remotely-operated station is via the AnyDesk remote desktop application connected via a 4G/LTE mobile data link.

VK6MJM has now been operating reliably for 18 months with recent 136 kHz highlights including spots by SWLEM3 (Texas) to better the previous VK6MJM – KM5SW Oceania – North America one-way digital record, spots by KL7L (Alaska) and reception of G3SDG's digital transmissions, all using the WSJT-X FST4W-300 (300-second) signalling mode.

The antenna coupler described in this article has enabled longer transmissions and, on the day of its commissioning, resulted in FST4W-900 spots by W1CK, K6VZK and KPH [the historic coast radio station in California, USA – Ed].

One of the surprises has been the effectiveness of the 22.5 m monopole as a receive antenna, due largely to the RFI-quiet location near Manjimup in southwest Western Australia. **Figure 1** shows a general view of the station, with the umbrella top-loaded mast and the 3 x 3 m steel shack. Additional images and descriptions are available on-line [2].

The coupler is a central element of an LF/MF antenna system and, as a starting point, it's useful to look at its function and the motivation for an upgrade at VK6MJM. By the way, the semantics of "coupler" and "tuner" are not too important, although "coupler" is more often used to describe an impedance matching network located at the antenna feed point.

For brevity, much of the description in this article relates to LF requirements, since MF needs are met by conceptually simple switching within the coupler.

The amateur LF and MF spectrum allocations at 136 kHz and 475 kHz correspond to wavelengths of 2200 m and 630 m, respectively. Even physically big antennas are electrically small at these frequencies; consider, for example, that the 22.5 m VK6MJM tower on 2200 m is about the same electrical length as a 0.8 m whip on 80 m.

The antenna radiation resistance is very small (< 1 Ohm on LF and MF) and the terminal impedance is highly capacitive, to the extent of about -j2000 Ω at 136 kHz – as expected from the measured 600 pF static capacitance of the top-loaded antenna.

Functionally, the coupler matches the antenna and transmitter impedances by resonating the highly capacitive antenna and transforming the resultant antenna resistance (perhaps 15 Ohms, and dominated by ground resistance) to 50 Ohms.

In contrast to more familiar HF matching networks, LF/MF couplers typically require fairly frequent adjustment in response to changes in weather, the first effect of which is usually a change in the antenna reactance. Ground resistance changes are also observed and are reflected in the antenna resistance value, although antennas with extensive radial fields and/or high-conductivity soil may require only seasonal compensation for resistance changes.

The exact VK6MJM radial configuration, and its health, are still to be determined but weather-dependent changes in antenna resistance over the 10 – 20 Ohm range are often observed at 136 kHz.

The maximum allowable effective isotropic radiated power (EIRP) in Australia and many other countries is 1 W at 136 kHz and 5 W at 475 kHz. **Figure 2** shows a typical maximum-power situation for VK6MJM at 136 kHz, where a loading inductor variable at the

Figure 1. View of the VK6MJM site at Manjimup, WA, showing the 22.5 m live mast antenna and the shack, separated by about 70 m. (Photo credit, Audrey Bell VK6FAUD).

approx. 10% level is used to account for changes in the antenna reactance.

In practice, the inductor is a shorted-ring variometer in which a motor-driven aluminium ring is rotated vertically within the horizontally-wound coil to vary the inductance. At resonance there is no net reactance in the series circuit and the antenna resistance (R_a) is transformed to 50 Ohms via a tapped ferrite-core transformer (not shown).

An important safety point concerns the RF voltage at the base of the antenna, particularly at LF – even with a modest 2.2 A antenna current (giving 1 W EIRP at 136 kHz), the voltage is about 6 kV peak. The smaller and more reactive antennas often used by amateurs can easily see that voltage quadrupled, making good insulation and safety practices essential.

One of the early jobs in commissioning VK6MJM was to repair, modify and re-build the NDB coupler to produce a "Mark 1" VK6MJM unit. This produced acceptable results and the coupler's Litz wire variometer proved quite effective, allowing the antenna to be resonated in the range 110 – 1300 kHz.

Despite having only three conductors in an underground control cable between the antenna and the shack, there was enough

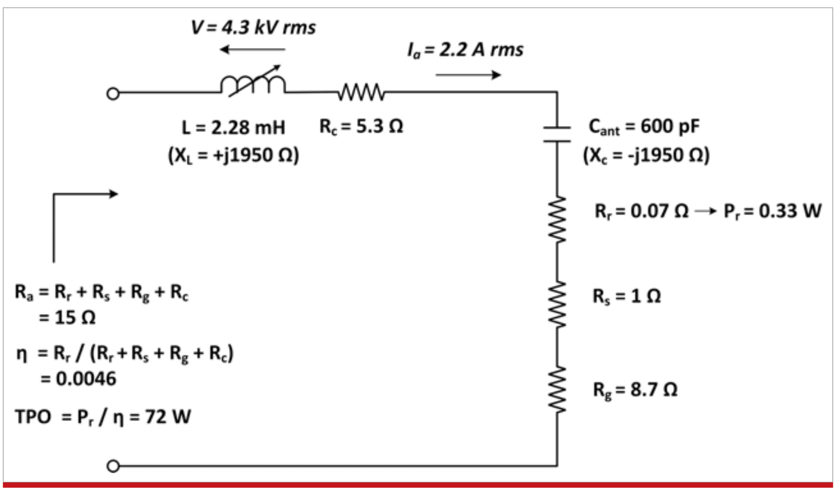

Figure 2. Equivalent circuit of the VK6MJM resonant antenna system radiating 1 W EIRP at 136 kHz; a short-monopole directivity of 3 is assumed. C_{ant} is the capacitance of the electrically-short, top-loaded monopole. R_c is the AC resistance of the loading coil, L, having a Q of about 370; R_r is the calculated radiation resistance accounting for P_r watts; R_s is an estimate of the tower radiator AC resistance; and R_g is a representative ground/counterpoise resistance. R_a is the antenna resistance to be matched to the coaxial feedline (via a tapped toroidal transformer). Note the tiny value of the radiation resistance and hence the low antenna efficiency (η) of 0.46%, requiring a transmitter power output (TPO) of about 72 W to achieve the P_r x 3 = 1 W EIRP legal limit. The antenna current is then about 2.2 A rms, resulting in a 4.3 kV rms (6.1 kV peak) voltage at the base of the antenna.

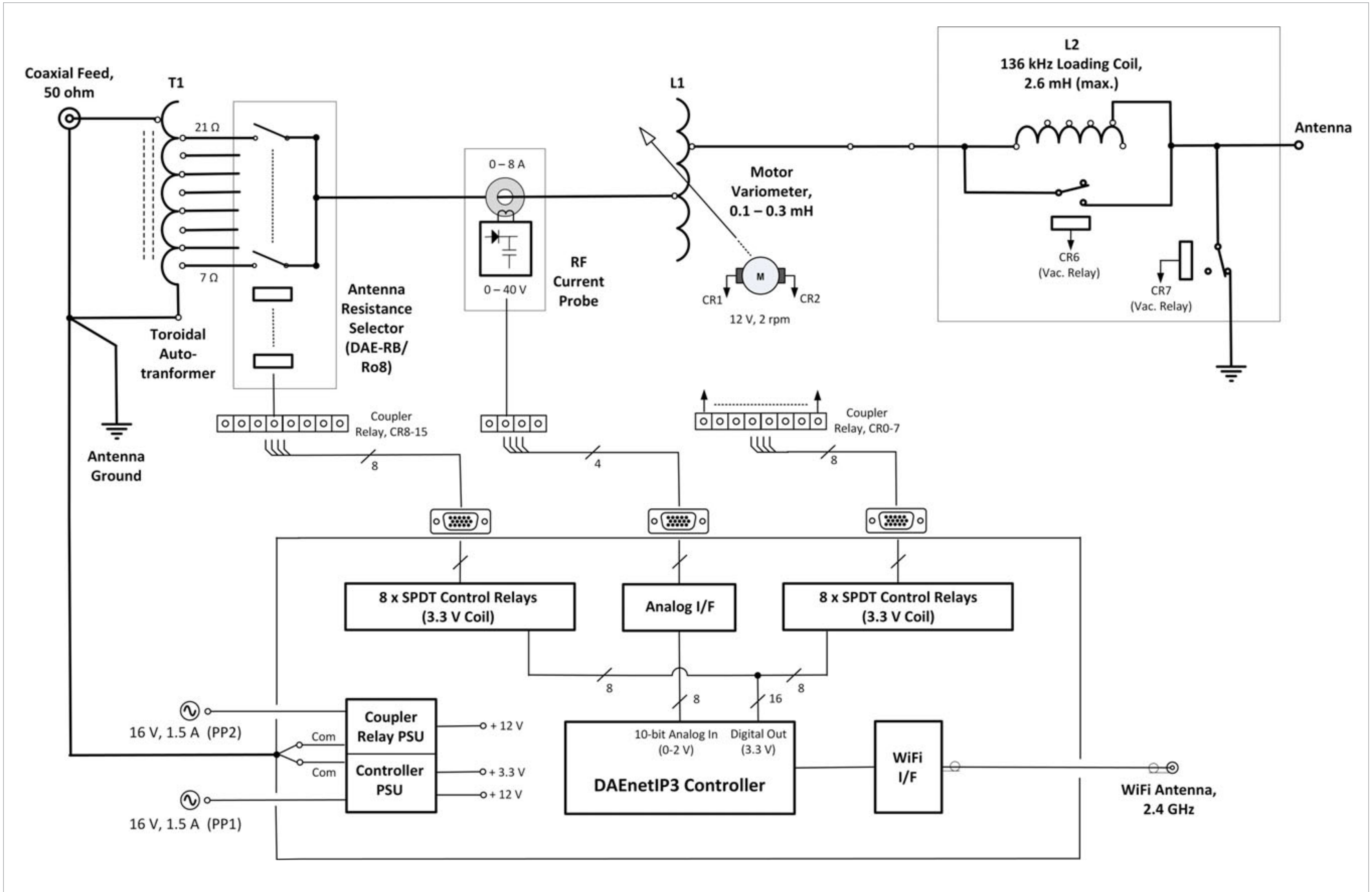

Figure 4. Block diagram of the Mark 2 coupler showing the RF elements of the CU8A and the interface to the DAEnetIP3 digital controller. Vacuum relays CR6 and CR7 (12 V coils) are rated at 15 kV, 50 A; CR6 enables operation on 475 kHz by shorting L2, while CR7 removes the precautionary short across the antenna terminal, allowing normal station operation.

capability to remotely control the variometer and tune the antenna using a PC data acquisition module and embedded vector antenna analyser [1]. Nevertheless, it became apparent that a new (Mark 2) coupler would confer significant advantages, the most important of which are:

- longer transmission times – NDB era damage to the Mark 1 Litz coil limited transmissions at maximum EIRP to 5 minutes;
- remote tuning invoking both variometer and impedance transformer tap adjustment, allowing station operation under variable weather conditions;
- a non-galvanic wireless control link from shack to coupler, eliminating surges from, for example, induced currents in buried conductors; and
- flexibility to support future all-mode HF operation, with by-passing of the LF/MF path and incorporation of a commercial auto-tuner.

Parameter	Requirement
Antenna tuning range (minimum)	135 kHz – 138 kHz (2200 m); 472 – 479 kHz (630 m)
Antenna impedance matching range	7 – 21 Ohms
Power handling	500 W continuous
RF current monitoring	0 – 8 A
Connectivity	2.4 GHz WiFi, 70 m all-weather link
Safety isolation	Galvanic isolation between coupler and wireless controller
RFI immunity	No controller disruption by full-power station transmissions
RFI generation	No detectable controller-generated receive noise at 136 kHz or 475 kHz
Power-up and re-start operation	Prescribed controller state at boot and while attempting communication link re-establishment
Software	Windows control/monitor application and driver(s) available
Operating temperature	-5 °C to +50 °C
Physical construction	Waterproof, ventilated and transportable

Table 1. VK6MJM Mark 2 Antenna Coupler requirements

Mark 2 Coupler – starting points

The design of a new coupler was driven by VK6MJM requirements but antenna matching is a significant hurdle for LF/MF operators and I wanted to contribute a few general, contemporary ideas.

As in previous station development, the aim was to use as much commercial IT hardware and software as possible, recognizing that an LF/MF coupler is a potentially hostile and demanding environment for digital systems.

The main Mark 2 requirements are summarized in Table 1, here.

Figure 3(a). Department of Civil Aviation CU8A "aerial coupler" (modified for VK6MJM use) with the front access panel removed and the digital controller attached externally for bench testing. The impedance relay switching module (cover removed) is mounted above the original potted autotransformer assembly, while the RF current sensor monitors the current flowing to the variometer. The original "line" and "aerial" RF current analogue meters are still functional. **(b)** External 136 kHz loading coil (2.6 mH maximum).

The specified power handling gives a safety margin at VK6MJM and ensures the coupler is useful with less efficient antennas, should the need arise. Similarly, the current monitoring requirement includes a safety factor to account for minor transients (including keying transients) in the antenna system.

I chose a surplus Department of Civil Aviation NDB “aerial coupler” type CU8A as a starting point, since its ventilated fibreglass enclosure was particularly useful in the VK6MJM outdoor application.

This coupler, modified for VK6MJM use and with the digital controller (to be described) attached for bench tests, is shown in **Figure 3(a)**. The CU8A loading coil inductance is 1 mH maximum, with a ring variometer providing up to ± 10 % variation around that figure. The coupler is specified as being able to handle 500 W carrier power, and its coil Q is a modest 200 – 250, depending on the variometer setting.

The unit is suitable for tuning the VK6MJM antenna at 475 kHz but additional series inductance is required for 136 kHz operation. In practice, only the central (approx. 200 mH) portion of the CU8A variometer is needed for MF tuning at Manjimup and this part of the coil is also used as a variable element in the 136 kHz path with the higher-Q series coil, pictured in **Figure 3(b)**, housed separately and providing the bulk of the 136 kHz loading inductance.

The CU8A is a convenient physical platform, but there is nothing special about its electrical design and LF/MF operators routinely build similar couplers.

Initially, I had hoped to find a ready-made digital controller assembly suitable for the coupler application but several prospective options failed one or more of the requirements in **Table 1**. Ultimately, I compromised and used mainly commercial modules, but with custom packaging and interfacing (**Figure 3**).

Two key modules, a DAEnetIP3 wireless internet-of-things (IoT) controller and a DAE-RE/Ro8 power relay board, are from Denkovi Assembly Electronics (DAE), [3]. These are supplemented by generic (eBay) control relay boards and homebrew sensor, analogue interface and power supply modules.

The DAE controller comes with an inbuilt web server allowing browser control and monitoring, and is compatible with a range of automation software, including DAE’s own DRMv3 package. Drivers and other software utilities are available to allow integration with various custom control environments.

A comprehensive DAEnetIP3 manual details setup, communication options, a variety of use-cases, and analogue and digital interfacing. For a relatively low-cost controller the range of communication and control options is impressive.

The Mark 2 Coupler in more detail

Figure 4 is a block diagram of the new antenna coupler. T1 and L1 are the original CU8A toroidal auto-transformer and variometer; the 240 VAC variometer motor was replaced with a 12 VDC, 2.5 rpm unit run at 8 V for ~ 1.5 rpm operation.

Rather than rebuild the CU8A RF analogue current metering, an additional homebrew antenna current probe was fitted. The fixed antenna resistance selection (via taps on the potted transformer) was replaced with a controller-driven arrangement using the DAE power relay board; transformer taps down to 2 Ohm are available for use with really good ground systems, but the 7 – 21 Ohms range works well at

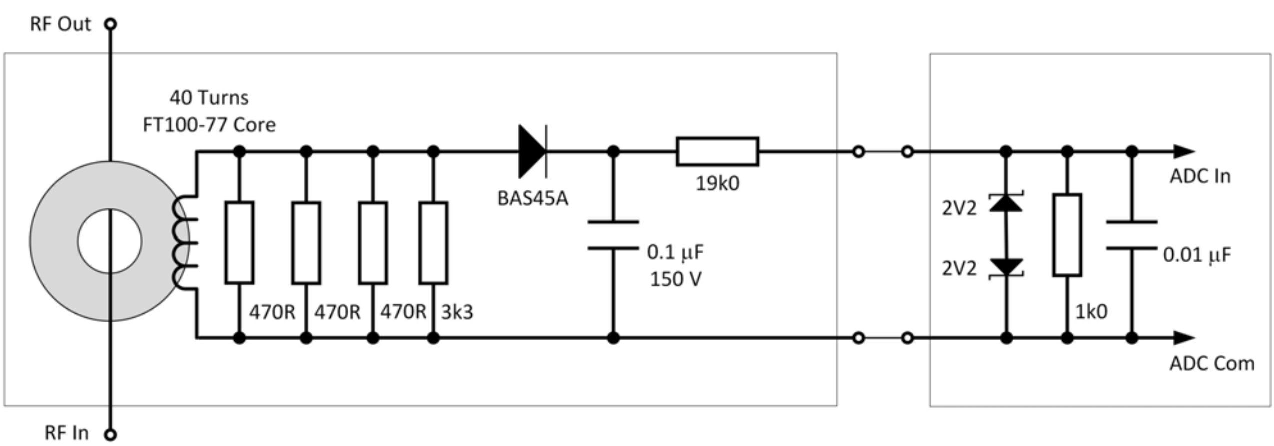

Figure 5(a). Schematic of the homebrew LF/MF current probe and **(b)** internal view of the probe. The toroidal current transformer secondary winding consists of 40 turns of 20 AWG or similar enamelled wire; see the text for a description of the one-turn primary. The total burden on the current transformer is 150 Ohms, with the 470 Ohm resistors rated at 2 W and the 3k3 at 0.5 W. Any signal diode with a PIV rating of more than 125 V may be used. A simplified ADC input arrangement is shown. The probe response is quite linear from under 0.5 A to about 7 A, when the limiting action of the Zener diodes start. For the prototype unit, calibration produced a linear-range working relationship of I = (8.2e-3)*C, where I is the rms RF current and C is the 10-bit ADC count in the range 0-1023.

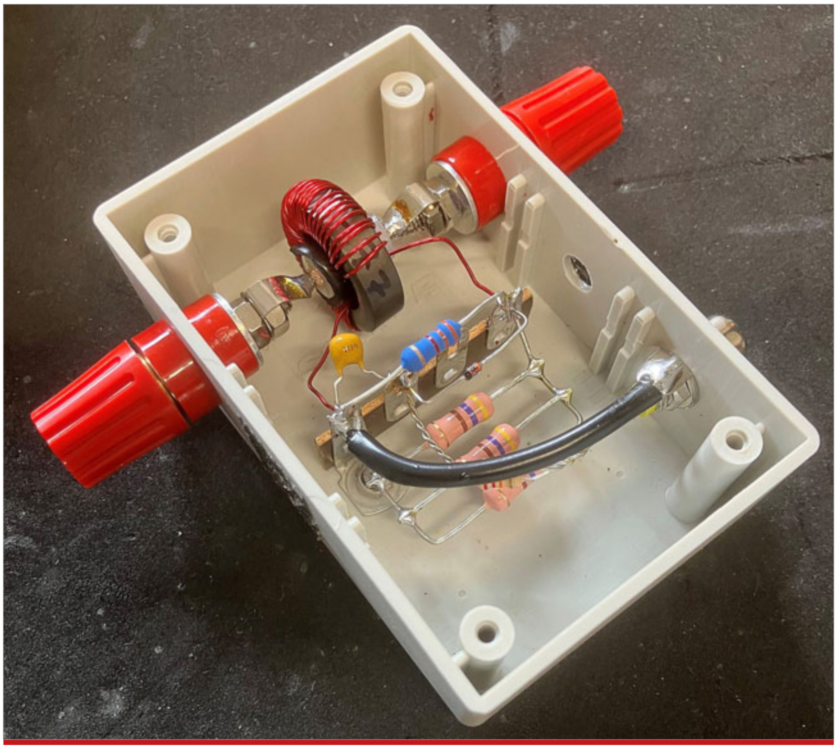

Figure 5(b).

VK6MJM on both LF and MF.

The relays are rated at 250 VAC, 10 A (50 Hz). The PCB has clearance cutouts and good track separation around switching contacts. Insertion mismatch at LF/MF is negligible and initial operation has been reliable, although RF hot-switching is deprecated; station power-fail sequencing minimizes this possibility in one obvious situation of concern.

L1 and L2 are both used on 136 kHz, while for 475 kHz operation vacuum relay CR6 shorts the large inductor. CR7 grounds the antenna when not in use. Spark gaps are installed at the base of the tower and at the external input to L2; gap widths are set to about 15 mm.

L2, shown in **Figure 3(b)**, is a homebrew loading inductor housed in a low-density polyethylene (LDPE) waste bin. It has several taps, with 2.1 mH of the maximum 2.6 mH selected for VK6MJM use. The coil consists of 90 turns of PVC-insulated, 2.5 mm2, 7-strand building wire, wound on a 412 mm diameter, heavily shellacked, 4 mm wall, display-grade cardboard former (obtained from The Tubeworks in Melbourne).

The measured Q of L2 is 370 at 136 kHz, giving an RF resistance of about 5 Ohms and a typical power dissipation of 25 W. The LDPE bin is ventilated via mesh-covered intake holes drilled in the raised base and a plastic-screened "mushroom-style" adjustable ventilator fitted to the lid.

The RF current probe details are shown in **Figure 5.** The probe is a conventional current transformer type based on an FT100-77 toroidal core. The single-turn primary uses a short length of RG213 cable with the shield removed and the (slit) outer jacked refitted; this gives a neat fit within the wound core and substantial insulation between the antenna line and the low-voltage secondary circuits.

Circuit constants are such that an 8 A rms current gives a rectified 42 V peak output, which is progressively divided to suit the 0-2 VDC analogue input of the DAEnetIP3 controller. Back-to-back 2.2 V Zener diodes are used as a final stage transient limiter on the analogue interface PCB, resulting in a calibratable non-linearity above 7 A.

The current probe and antenna resistance selector are both housed in plastic boxes within the CU8A fibreglass enclosure, making mounting and insulation convenient.

Turning to the digital controller, the majority of components are mounted in a perforated aluminium enclosure, which sits on an internal plastic shelf fitted to the CU8A. RF noise, unwanted ADC offsets, and susceptibility to antenna RF fields are minimized by building the controller as an isolated unit, with a single-point ground to the antenna earth (**Figure 4**).

Coupler relays are activated by SPDT control relays, giving two stages of galvanic isolation between the RF path and controller. In fact, the original intention was to have a third stage via opto-isolators driving the 3.3 V control relays but, oddly, the relay PCB designer elected to use a common ground for the coil and opto-isolator returns. Avoid this trap if buying a similar eBay board.

The DAEnetIP3 controller has eight, 10-bit, analogue inputs available but only two are presently used in the Mark 2 coupler: enclosure temperature is monitored using an MCP9700A sensor and RF current is measured via the probe described previously.

A homebrew analogue interface provides a 1000 Ohm termination for all eight input lines, as well as resistive scaling to 2 V full-scale and over-voltage protection for the used lines. DAEnetIP3 analogue readings are limited to about 0.8 s per channel time-resolution by controller software filtering. In the coupler application, this is not a serious disadvantage but it needs to be borne in mind when adjusting the RF current.

Both WiFi and ethernet connectivity to the controller is available, with 2.4 GHz 801.11 b/g wireless capability enabled by a module plugged into the main DAEnetIP3 assembly. WiFi sensitivity

Figure 6. The Mark 2 coupler being tested in position near the base of the VK6MJM mast. The external 136 kHz loading inductor sits atop a low-density polyethylene (LDPE) box in a ventilated LDPE waste bin (206 l, Thor brand). The loss tangent of LDPE is low (< 0.001) at LF and MF, but the coil should be as far as possible from the ground and ferrous structures.

is good and connectivity is solid between a Teltonika RUT-240 modem/router in the VK6MJM shack and the coupler located about 70 m away. Simple external whip antennas are used at both ends of the link.

Power for the controller and the coupler relays is provided by two 16 VAC, 1.5 A plug-packs, the outputs of which are full-wave rectified and regulated to give 12 VDC and 3.3 VDC rails. One plug-pack alone powers coupler relays and the variometer motor and is adequate for present and projected devices, including 12 V vacuum relays.

The regulators are conventional three-terminal linear types assembled on eBay PCBs. Bear in mind the low RF operating frequencies and ensure there is effective de-coupling on power rails; low loss-tangent capacitors such as polypropylene and multi-layer ceramic types are useful in the 0.1 uF to several uF range.

A 10-turn (or more) common-mode choke on a Type 75 (or similar low-frequency) ferrite core gives useful first-line RFI suppression in the DAEnetIP3 12 V supply; wind a light-duty figure-8 cable carrying the power and common conductors through the core.

Operating and expanding the coupler

Figure 6 shows the new coupler at the VK6MJM antenna, while **Figure** 7 is a family of 136 kHz tuning curves with various antenna resistances selected sequentially; the optimum setting is 11 Ohms in this case.

Note the 500 Hz SWR = 2 bandwidth. Importantly, the coupler tuning is very stable over long transmission times, with the large coil in the ventilated bin dissipating heat with only minimal temperature rise. The ability to adjust both R and X allows operation in a variety of weather conditions and in the face of seasonal ground resistance changes.

In previous homebrew couplers, I have favoured double-wound (bifilar) toroidal impedance transformers, principally to give flexibility in breaking common-mode circuits between the shack and antenna.

However, the CU8A's autotransformer works well in the VK6MJM application, with the shack's 1:1 RF isolation transformer and an additional common-mode choke giving high common-mode impedance when using the autotransformer and legacy station ground arrangements.

Receive noise is low and Class-D PA carrier-to-noise ratio is high (80 dBc near-in products); C/N ratio is often overlooked in switching PAs and can be degraded by poor EMC practices causing unwanted modulation at the FET drains.

Figure 8 illustrates the Denkovi DRMv3 relay control software in use; data presentation type, scaling and labelling are settable by the user. The link between DRMv3 and the DAEnetIP3 controller is noticeably robust, with link re-establishment due to station restarts, etc, occurring quickly and without operator intervention. DRMv3 offers

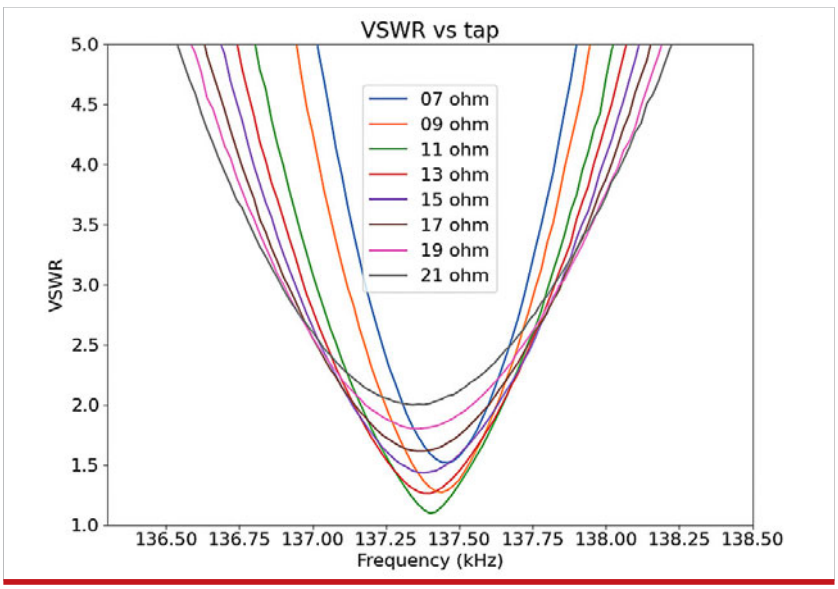

Figure 7. Family of tuning curves as the Mark 2 coupler impedance tap is switched sequentially to settings between 7 and 21 Ohms. In this case, the optimum match is at the 11 Ohm tap, corresponding to SWR = 1.1 (return loss = 26 dB) at the chosen centre frequency. This is close to a worst-case situation, with measured return loss often in the range 25 – 40 dB. Note the slight change in antenna resonant frequency as the transformer tap is moved. This is due mainly to change in the toroidal transformer's leakage inductance and, in practice, is countered by a small adjustment of the variometer.

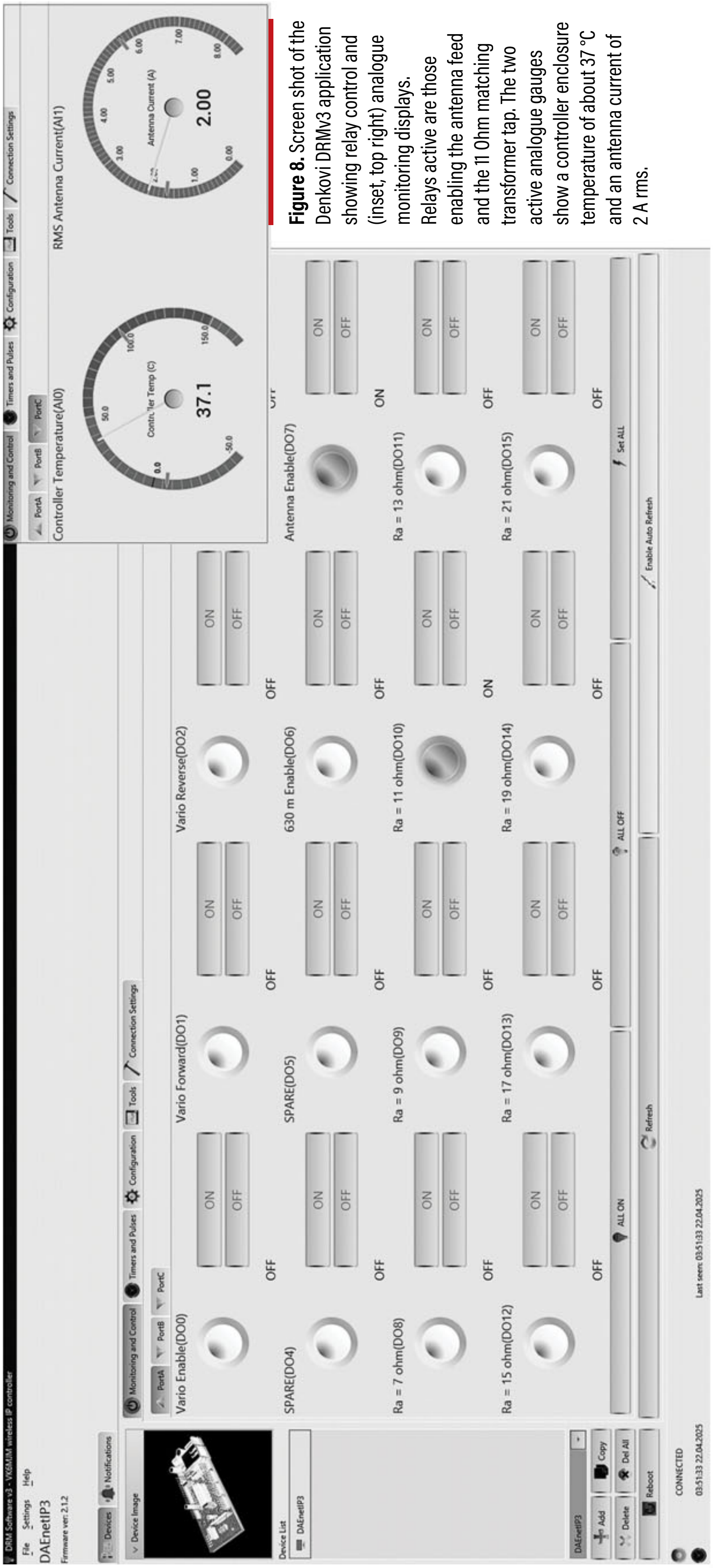

Figure 8. Screen shot of the Denkovi DRMv3 application showing relay control and (inset, top right) analogue monitoring displays. Relays active are those enabling the antenna feed and the 11 Ohm matching transformer tap. The two active analogue gauges show a controller enclosure temperature of about 37 °C and an antenna current of 2 A rms.

many display options but it is also quite practical to operate the coupler using only the DAEnetIP3 web server in a browser window.

With the remote desktop running, operation of VK6MJM is the same at Manjimup, Perth or anywhere else. Internet latency takes a little getting used to when moving the variometer motor but, with a bit of practice, antenna tuning to better than 50 Hz at 136 kHz is straightforward.

Good matching of the antenna to the switching power amplifiers results in efficiencies >85% and also helps in maintaining C/N ratio. Remote monitoring of the antenna current allows reliable EIRP setting and, less technically, minimizes tuning anguish as the current remains essentially constant in the face of tweaks by a bored operator!

The next operational feature to be added to the Mark 2 coupler will be selectable relay by-passing of the whole coupler RF path and the use of a commercial auto-tuner for 160m and HF band operation.

On another front, 18 months experience in remote station operation means there has now been sufficient experience to develop an integrated VK6MJM control software application. The Mark 2 coupler and other station hardware have good general interfacing credentials and customized software will open up several new paths, including optional coupler auto-tuning.

Conclusion

This article has described the use of a versatile IoT controller to enable the remote operation of an LF/MF antenna coupler. The coupler and controller aspects are likely to be useful to amateurs interested in our lowest bands, while the controller alone may be interesting to those looking for easy automation of other devices in their station.

References and Resources

1. Hall, P. J. VK6MJM – New Life for an Old Non-Directional Beacon, QEX July/August 2024, pp. 9 – 13. Available via https://highqradio.com/publications-and-notes
2. Hall, P. J. Radio Engineering, https://highqradio.com/
3. Denkovi Assembly Electronics, DAEnetIP3 User Manual, https://denkovi.com/