Effective circuit modelling and experimental realization of an ultra-compact self-rectifier flux pump

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Abstract
This paper presents experimental and modelling results of an ultra-compact self-rectifier flux pump (FP) energizing a superconducting coil. The device fits inside a volume of 65 × 65 × 50 mm and generates up to 320 A dc through the coil and a peak output voltage up to 60 mV. We also develop and present a full electromagnetic effective circuit model of the FP and compare its predictions to the experimental results. We show that our model can reproduce accurately the charging of the load coil and that it reproduces the systematic dependence of the maximum load coil current on the input current waveform. The experiments and modelling together show also the importance of dc-flux offsets in the transformer core on the final achievable current through the coil. The miniaturization possible for this class of FP and their minimal heat-leak into the cryogenic environment from thermal conduction make them attractive for applications with demanding size, weight and power limitations. Our effective circuit model is a useful tool in the understanding, design and optimization of such FPs which will accelerate their progression from research devices to their application.

Keywords: flux pumps, self-rectifier, effective circuit modelling, superconducting power electronics, wireless charging, HTS

(Some figures may appear in colour only in the online journal)

1. Introduction

Flux pumps (FP) are superconducting devices which output a large dc current to a superconducting magnet [1]. Self-rectifying FPs are a subset of such devices that rectify an asymmetric, alternating input current of a transformer to generate the dc current through a superconducting load [2–7]. Rectification is achieved by driving current larger than the critical current, \(I_c\), through part of the superconducting circuit (the ‘bridge’) for part of the input waveform cycle. This ‘self-rectification’ method was originally described for high-temperature superconductors by Vysotsky et al [8], and can be compared with FPs that employ various active switching mechanisms to vary the \(I_c\) of the bridge [1, 9–12]. Self-rectifying FPs are capable of delivering large currents at modest voltages [3] without a requirement for direct electrical and thermal connection between the superconducting load and an
ambient temperature power supply, which can lower the overall heat load on the cryogenic system when compared with a conventional power supply [1, 13, 14]. Furthermore, self-rectifying FPs do not contain moving parts, unlike dynamo-based FPs, and do not require additional electromagnets as ‘switching’ components [13, 14]. This makes self-rectifying FPs an attractive option for applications with demanding size, weight and power requirements, such as those found on spacecraft [15, 16] or as portable high-field electromagnets [17].

Previous experimental work on this class of FP has focused on demonstration of principle [2] or maximizing the delivered dc current [3] rather than its potential advantages, comprising a simple device architecture and physical compactness. What we believe to be the essential operating principles of the FP have already been fully described [3]. However, quantitative and accurate prediction of the performance of these FPs involves numerically solving the coupled equations describing them. Recent numerical modelling work utilizing an effective-circuit (or ‘lumped parameters’) methodology has been limited to exploring the influence of sub-components of the FP, such as the bridge [18] or the transformer [19]. Combining these subsystems into the same model has only just been reported by Zhai et al [20] with some explanatory success for an air-core transformer self-rectifier. What such modelling should enable however is; (i) quantitative performance prediction to facilitate model validation, and (ii) an understanding of the interplay between all subcomponents of the FP such as the input waveform, transformer and circuit impedances. Together these would allow for useful full-system design and optimization, which has been identified as an important issue to be addressed for FPs [14]. Such an effective-circuit approach for system-level modelling is utilized in other areas of superconducting power electronics as well [21–24].

In this work, we construct a simple prototype ‘ultra-compact’ self-rectifier FP and demonstrate its functionality. We then develop a system-level effective circuit model of the FP and compare its predictions to experimental results. Our first finding is that the FP does not require a superconducting secondary-winding and can deliver more than 300 A dc to a superconducting coil with up to 60 mV peak output voltage. The effect of modifying the input current waveform is explored and the implications on performance discussed. Our second finding is that our effective circuit model matches experimental behaviour. It is capable of describing the maximum load current and its dependence on the input current to the transformer and the magnitude and time dependence of the voltage across the load. The paper concludes with a discussion of insights from the model regarding the operation of self-rectifying FPs, particularly the effect of dc offsets of flux in the transformer core, and the limitations of our current model.

2. Methods

The self-rectifying FP studied in this work is shown in figure 1(a). It is built around an iron core made from 0.3 mm laminations with cross section of 20 mm × 20 mm and path length approximately 100 mm. The nominal saturation field at room temperature of the soft iron is \( B_{sat} = 1.7 \) T. The primary windings are made from 45 turns of Cu tape, wound as a double-pancake coil by hand. The secondary is made also from pure Cu and comprises a single strip, 12 mm wide, 35 mm long and 3 mm thick, bent in a U-shape around the core. Soldered to the secondary winding is a 100 mm long bridge made from commercial REBCO tape, which completes the loop around the core and results in a transformer turns ratio of \( N = 45 \). The coated conductor (CC) tape is SuNAM product code SCN12500-210222-01; 12 mm wide, stabilized by 20 \( \mu \)m of Cu and has a nominal self-field \( I_c \) of 500 A at 77 K with \( n = 35 \) (see equation (1) below for the definition of \( n \)). A small pancake coil of eight, dry-wound turns of the same REBCO tape was used as a ‘load’. It has a total length of 1.9 m and an inductance of 2.5 \( \mu \)H, measured at room temperature, and was soldered directly to the bridge.

In all experiments, the current through the primary windings was supplied by a Takasago BWS 40-15 bipolar linear
amplifier controlled via a National Instruments c-DAQ. Examples of the applied primary current waveform, \(i_1\), are shown in figure 1(b), where the maximum and minimum of the current are specified by the two numbers in braces in the legend. For example, \(i_1\{20, -2.7\}\) indicates an input waveform with a maximum current peaking at \(I_{1,\text{max}} = 20\ A\) and a current in the reverse direction of \(I_{1,\text{min}} = -2.7\ A\). All waveforms used in this work were driven at a frequency of 10 Hz, and all measurements were carried out in liquid nitrogen (approximately 77 K). Current through the load-coil was measured via the voltage developed across a thermally-sunk 1 Ω shunt resistor. The voltage across the primary and load were also measured.

The operation of the self-rectifying FP was modelled using the effective-circuit shown in figure 2. This circuit involves coupled electrical and magnetic circuits with non-linear componentry. It was implemented and solved within the Simulink package in MatLab. The current waveform input into the primary windings is specified, along with a parameterization of the circuit components.

The transformer is modelled as a variable reluctance, \(\mathcal{R}(H) = \mu(H)^{-1} \cdot A^{-1}\), resulting from a magnetic material with non-linear permeability, \(B(H) = \mu(H)H = B_{sat}\tanh(H/H_{sat})\), and the physical dimensions of the core length, \(l\), and cross sectional area, \(A\). In addition, we include in the model a leakage reluctance representing alternate paths outside of the transformer core that magnetic flux may take. This leakage reluctance is significant only as the flux in the transformer core approaches saturation. Ac-loss and hysteresis effects in the transformer core are not presently included in the model.

The superconducting components are treated as circuit elements with a resistance, \(R_{SC}\), that is a non-linear function of the current, \(I\) [25];

\[
R_{SC} = \frac{E_0I}{I_c} \left(\frac{I}{I_c}\right)^n
\]

Where \(E_0 = 1 \mu V \cdot cm^{-1}\) is the customary electric field criterion at which the critical current density of a superconductor, \(J_c\), is defined. \(n\) is obtained from fitting characteristic experimental data [26] and captures the steepness of the resistivity increase as \(I\) exceeds \(I_c\). \(l\) is the length of the REBCO tape. We use Cu-stabilized tape in which the Cu represents a parallel current path. This is included as a parallel resistor in the model, such that the full expression for the resistance of a component of CC tape in the model is:

\[
R_{CC}^{-1} = R_{Cu}^{-1} + R_{SC}^{-1}
\]

where

\[
R_{Cu} = \frac{\rho_{Cu}l}{\tau_{Cu}w}
\]

In our case, we take \(\tau_{Cu} = 20 \mu m\) (the topmost stabilizing layer adjacent the superconductor only, as there is only a small cross-section of Cu connecting the bottom Cu layer to the superconductor), the width of the CC \(w = 12\ mm\). For high purity Cu, \(\rho_{Cu} \approx 1.9 \times 10^{-8} \Omega \cdot m\) at 77 K [27]. A look-up table is created during the initialization of the model for each CC element that relates its resistance to the current (and potentially additional variables) through the element. A fuller description of the model, for the more general case of a \(J_c(B)\) switched half-wave rectifier, is described elsewhere [28].

3. Results

We start by presenting the results of experiments conducted under an input current waveform \(i_1\{19.8, -4.45\}\). The current developed through the secondary by \(i_{1,max}\) constitutes the ‘charging phase’ of a current cycle as it is designed to drive current into the load rather than the bridge. The remainder of the cycle we call the ‘maintenance phase’ as it is designed to

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3 We note that the resistivity of Cu would become a temperature-dependent quantity in a effective circuit model that includes thermal-aspects, increasing approximately linearly with temperature under the effect of Joule heating.
compensate the flux accumulated in the transformer core during the charging phase. Simplified diagrams of the charging and maintenance phases are shown in figure 3. The current through the load coil as a function of time, \(i_L\), and voltage across the load coil, \(v_L\), are shown in figures 4(a) and (b) respectively as black lines. We estimate a 5% uncertainty in the accuracy of the measured load coil current. Also shown in the figure are the results from the effective circuit modelling, described above, as red lines. A full list of parameters used in the model can be found in appendix table 1, along with a estimates of the range of their values in the experiment.

Figure 4(a) shows that approximately 320 A was supplied to the load coil in under 3 s. The voltage across the load coil, shown in figure 4(b) was observed to peak up to 65 mV during the initial cycles, dropping to a peak voltage of 20 mV once \(i_i\) had reached its maximum of 320 A. These short spikes in the voltage each cycle are what firstly drive the increase in current through the load, and then maintain the saturation current (of 320 A in this case) against losses in the load-loop. The figure also shows that our effective-circuit model reproduces; (i) flux-pumping via self-rectification, (ii) the approximate maximum load-coil current and the magnitude of the voltage across the coil and (iii) the approximate waveform of the load-coil current and voltage.
Systematic experimental (black symbols) and modelling results (red line and symbols) of the maximum load-coil current. In panel (a) the positive amplitude of $i_{1}$ is varied for $i_{1,\min} = -4.45$ A, with panel (b) showing three of the $i_{1}$ waveforms. In panel (c) the negative amplitude of $i_{1}$ is varied for $i_{1,\max} = 19.8$ A, with panel (d) showing three of the $i_{1}$ waveforms. For the modelling results, the data points represent the average load-coil current at its maximum and the error bars represent the range of its current ripple.

Figure 5.

We note that there are several parameters within the model whose experimental value is not well known and were tuned to generate the agreement shown above. These include the series resistance, $R_{\text{series}}$, which in this particular FP design has the same physical origin as $R_{\text{secondary}}$, as well as the $n$-value and $I_{c}$ of the bridge (30 and 462 A respectively), for which we only know their nominal values (35 and 500 A respectively). The actual values may differ from the nominal ones due to tape inhomogeneities and/or mechanical strain during construction and thermal cycling. The resistance of the bridge and load-coil solder joints (450 nΩ) were estimated by matching the decay of current in the load coil once the primary current was turned off, see the data after 10 s in figure 4(a). For this estimate, we were guided by the 2.5 μH inductance of the load coil that was measured at room temperature. The behaviour of such FPs relies on the non-linearity of the resistance of the superconductor, equation (1). As such, the modelled results are also sensitive to uncertainties accuracy of the measured input current. Other model circuit parameters have similar uncertainties although it was found that the modelled load-coil current maxima and voltage was not as sensitive to them.

Confidence in the descriptive ability of the model can however be taken from its ability to capture the dependence of the maximum load coil current on the input waveform. These results are shown in figure 5, for which panel (a) shows how the maximum load coil current varies with $i_{1,\max}$ for $i_{1,\min} = -4.45$ A, and panel (b) shows its dependence on $i_{1,\min}$ with $i_{1,\max} = 19.8$ A. The error bars for the modelling results represent the range of the current ripple at saturation, whilst the points represent the average value of the load coil current. In the effective-circuit model’s near quantitative reproduction of these data sets, only the input waveform was varied in the model to values of $i_{1}$ measured in the experiment.

4. Discussion

We start by discussing insights from our model regarding the achievable load-coil currents, as these appear to reliably reproduce the experimental results, before addressing some potential reasons for the discrepancies between the model predictions and experimental data seen in figures 4 and 5(b).

Firstly, the modelling results suggest that the maximum load coil current that we achieved experimentally, shown in figure 5(a), was not limited by the $I_{c}$ of the load-coil. The model instead shows that with an arbitrarily high coil $I_{c}$, the load current saturates at the same 320 A for $i_{1,\{19.8, -4.45\}}$. When the coil $I_{c}$ is the limiting factor within our model, the averaged load current saturates approximately 20 A below the coil $I_{c}$.

Rather, it appears to be the net dc voltage developed across bridge that limits our performance. This can be seen in figure 6, which shows in panel (a) the current across the bridge. A significant negative offset in the bridge current develops over the first second. This has two effects; firstly, the degree to which the bridge current exceeds the critical current of the bridge, $i_{b,\max}/I_{c,b}$, is reduced which in turn reduces the voltage developed across the bridge during the charging phase. Secondly, $i_{b,\min}/I_{c,b}$ is increased, increasing the negative voltage developed across the bridge during the longer maintenance phase. Panel (b) shows the net-voltage per
that there are two potential contributions to the offset in the load-coil current has saturated. Here, once the net voltage across the bridge reaches a threshold, the voltage developed across the load during the longer maintenance phase increases, reducing the net voltage across the bridge.

The dependence on the $i_{1,\text{min}}$ shown in figure 5(b) displays an optimum. For larger $i_{1,\text{min}}$, the decrease in the maximum load-coil current can be understood along similar lines to the situation described above and shown in figure 6; namely the voltage developed across the bridge during the maintenance phase increases, reducing the net voltage across the bridge. The more interesting case is the reduction of the maximum load coil current at smaller negative current maxima. According to our model, this is not due to transformer saturation, but rather relates to the net flux that develops in the transformer core over multiple cycles, as shown in figure 7(a). A net flux arises due to a non-zero integral of the input current waveform (and small resistance of the secondary loop) [29]. For $i_1 \{19.8, -5.34\}$ the integral is $-0.227$ Ampere seconds (A.s) per cycle, compared with $-0.014$ A.s for $i_1 \{19.8, -2.67\}$, the yellow curve in figure with the smaller $i_{1,\text{min}}$. This net flux corresponds to a net dc ‘offset’ current in the secondary loop, as seen in figure 7(b). That dc offset in the secondary current in turn directly affects the amount by which the bridge $I_c$ is exceeded in the charging phase and the voltage across the bridge, as shown in figure 7(c). For $i_1 \{19.8, -2.67\}$ (yellow curve) that positive dc offset is markedly less than for $i_1 \{19.8, -5.34\}$ (green curve) and leads to the reduced voltage across the load and lower maximum load current, figure 7(d).

Using a net offset of flux in the transformer core to improve the performance of a self-rectifying FP has been qualitatively described earlier [3], and this work now shows a quantitative description of this strategy.

A strategy of increasing the $i_1$ current amplitude to increase the maximum load-coil current may not be desirable. For example, the heat dissipated across various parts of the circuit rapidly increases, as shown in figure 8. Figure 8(a) shows the heat dissipated per cycle across the bridge as estimated from experimental results. This is regarded as an estimate because it was not possible to directly measure the experimental current through either element. Instead, determination of the bridge current required the approximation that the current across the secondary is $N$ times that of the primary. This approximation is imperfect, as we do not have an ideal transformer. Also shown in the panel is the heat dissipated by the various elements on the secondary side of the transformer, the ‘cryogenic side’ (see figure 2), as calculated within our model. Figure 8(b) shows the degree to which the total heat dissipated on the cryogenic side, calculated after the load current has saturated at $t = 5$ s, increases with input current maxima.

We have shown that the model behaviour and experimental results show broad agreement, and now we discuss their discrepancies. Most noticeable is the ramp-rate of the dc component of the load-coil current, in particular the very first cycle of operation, as highlighted in the inset to figure 4(a). There is also some quantitative inaccuracy in the dependence of $i_{1,\text{max}}$ on $i_{1,\text{min}}$ predicted by the model, as shown in figure 5(b).

Figure 6. Modelling results of the (a) current across the bridge, with the magnitude of the critical current of the bridge indicated by horizontal dotted lines and (b) average voltage per cycle across the load for the experimental conditions presented in figure 4. The dotted blue line indicates the product of the cycle-averaged load current and the load-loop resistance of 450 nΩ.

cycle across the bridge, which quantifies the two effects above. Once the net voltage across the bridge reaches $v_l = i_l(R_l + R_b)$, the load-coil current has saturated. Here, $R_l + R_b$ is the ‘load loop’ resistance, modelled as 450 nΩ, that accounts for joint-resistances and flux creep.

The dependence of the maximum load current on $i_{1,\text{max}}$ is then straightforward to understand, as $i_{1,\text{max}}$ drives current through the bridge in the charging phase to exceed the $I_c$ of the bridge, generating voltage that charges load. For $i_{1,\text{max}} > 20$ A, the model shows there is no longer a significant increase in the maximum load-coil current. This is due to a voltage developed across the load during the longer maintenance phase where $i_{b,\text{min}}/I_c,\text{bridge} \approx 1$, and which compensates the voltage developed across the shorter charging phase of the waveform.

The description above aligns with that previously discussed in the literature [2, 3, 6, 18], however it is important to note that there are two potential contributions to the offset in the bridge current. The first is the load current as previously discussed in the literature, and there is a second contribution from an offset-current in the secondary loop. This second component, discussed below, can be manipulated in self-rectifying FPs through modification of the $i_1$ (or $v_1$) input.
Figure 7. Understanding the maximum \( i_1 \) as \( i_{1,\text{min}} \) is varied. Modelling results of; (a) flux density in the transformer core, \( B \), with the magnitude of the saturation flux density of the core, \( B_{\text{sat}} \), indicated by a dotted line, (b) secondary current \( i_2 \), (c) the average load voltage per cycle, and (d) the load current, \( i_l \).

Figure 8. (a) Energy dissipation across various device elements under \( i_1 \{ 19.8, -4.45 \} \) current input; black symbols for the bridge as estimated from experimental data (see text), red lines show results from the model. (b) Total heat dissipation into the cryogenic environment as a function of \( i_{1,\text{max}} \) with \( i_{1,\text{min}} = -4.45 \) A once the maximum \( i_1 \) has been reached \((t = 5 \text{ s})\)—modelling results only.

We identify three general potential reasons for these discrepancies. Firstly, we may have model parameter values that inadequately represent the experiment. This is likely to be the case to some degree. However after investigating several different parameter configurations that reproduce the experimental data sets, we find that the same physical interpretations from the model that are discussed above. Secondly, our electromagnetic effective-circuit model may be missing important circuit elements. We do not believe this to be the case. Thirdly, our effective circuit model may be missing important physics. Perhaps the most salient effects not accounted for within our effective circuit model are thermal effects (for example, heating of superconducting components due to the energy dissipation highlighted in figure 8) and ac loss or hysteresis in the transformer core [29]. In this regard, it is noteworthy that the heat dissipation across the bridge estimated from experiments is approximately twice that calculated by the model, figure 8(a). We expect loss relating to the current ramp...
rate, \( di/dt \), in the superconducting components to be relatively minor [30], however we note that we have large \( di/dt \) values of up to approximately \( 9 \times 10^4 \, A \cdot s^{-1} \) and our asymmetric waveform presents additional complications over the standard analysis presented in literature, see e.g. [31, 32]. We also note that the degree to which these effects are significant will depend on the details of the experimental set up. Future experiments and extensions to the current effective circuit model will look to quantitatively incorporate such physics, as has recently been done in other areas of superconductor power electronics [33], and assess the degree to which they improve agreement with experiment.

5. Summary

In summary, we demonstrated the operation of an ultra-compact self-rectifier FP that supplied up to 320 A dc to a superconducting coil and a peak output voltage of up to 60 mV. Whilst that is not the largest current or voltage demonstrated from a self-rectifier to date, our device is exceptionally compact, simple in architecture and demonstrated that the secondary winding need not be made from a superconductor. These features, along with their minimal heat-leak into the cryogenic environment from thermal conduction, highlight how attractive this class of FP is for applications with demanding size, weight and power limitations. We also developed an electromagnetic effective-circuit model of the FP, encompassing the transformer and all superconducting components, in order to understand and predict the behaviour of this class of FP. A comparison of its predictions to the experimental results showed that many key aspects of the experiment are captured by this model, such as the maximum load current and its dependence on the input current to the transformer. Work is currently ongoing to understand why certain aspects of the experiment were not accurately reproduced by the model, such as the load current ramp rate, with this work including investigations into the effect of including additional physics into the model. Nevertheless, the predictive successes of our model and its inclusion of all key components of the FP system, show it to be a powerful tool in the design and optimization for applications of this class of FP.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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Appendix

In the table below we present a comparison of model parameters used in this work and experimental estimates where available.

Table 1. A comparison of model input parameters and estimates for the range of experimental values of those parameters.

| Circuit element | Parameter [units] | Experimental range | Value in model |
|-----------------|-------------------|--------------------|---------------|
| Bridge          | \( I_1 \, [A] \) | 470–550            | 462           |
|                 | \( n \)           | 25–35              | 30            |
| Load            | \( I_2 \, [A] \) | 400–550            | 360           |
|                 | \( n \)           | 15–35              | 20            |
|                 | \( \tau \, [\mu m] \) | 18–22            | 20            |
|                 | \( L \, [\mu H] \) | 0.01–0.2           | 0.01          |
| Secondary       | \( N \)           | 1                  | 1             |
| Resistances     | \( R_{\text{series}} \, [\Omega] \) | —                | 100           |
|                 | \( R_{\text{bridge}} \, [\Omega] \) | 150–750          | 400           |
|                 | \( R_{\text{load}} \, [\Omega] \) | 50–600            | 50            |
| Core            | \( A \, [\text{mm}^2] \) | 3.5–450           | 400           |
|                 | \( l \, [\text{mm}] \) | 90–110            | 100           |
|                 | \( B_{\text{sat}} \, [T] \) | 1.5–2.1          | 1.7           |
|                 | \( H_{\text{sat}} \, [A \cdot \text{m}^{-1}] \) | 200–400         | 300           |
| Leakage reluctance | (0.01 – 1) \times 10^9 | 0.1 \times 10^9 |

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