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Rapid co-optimisation of turn-on and turn-off gate resistor values in DC:DC power converters

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Abstract — Both turn-on and turn-off gate resistance for switched power devices can significantly impact system EMI, switching loss, and device longevity. To determine the optimum resistor values, an exhaustive search through $m$ different turn-on values and $n$ different turn-off values would require $m \times n$ tests. This paper demonstrates a method that separates this process into $m+n-1$ experimental tests, followed by analysis of measured losses and time-domain waveforms in MATLAB. The methods allow loss and waveform spectral content to be highly accurately predicted for any of the possible $m \times n$ resistor combinations. Losses are predicted using 2D curve fitting, whilst automated edge-extraction and splicing is used on the time-domain waveforms for subsequent spectral analysis. Significant time savings are delivered through the reduction of repeated reworking to swap gate resistances, reconnection to test equipment, and the waiting for the converter to reach thermal steady state. All of the MATLAB code is made freely available to readers.

Keywords — Edge Detection, Edge Extraction, Waveform Splicing, Waveform Reconstruction, Gate Resistor Optimisation

I. INTRODUCTION

A key design aspect for tuning the performance of power electronic converters is the value of resistance used at the gate of power devices. Many gate drivers offer independent turn-on and turn-off paths (Fig. 1a) [1] – [3] and for those that don’t, simple networks external to the gate driver (Fig. 1b) can offer asymmetrical turn-on and turn-off gate-drive resistance.

![Fig. 1](image_url) — Gate driving with independent turn-on and turn-off resistance. (a) Using a driver with independent pull-up and pull-down outputs, (b) Using networks external to the gate driver.

Independent turn-on and turn-off gate drive resistance gives designers maximum flexibility, allowing independent adjustment of the controlled device’s turn-on and turn-off behaviour. When selecting the values of gate drive resistance, the designer will typically have to trade-off power losses against other performance factors such as spectral content of voltage and current switching waveforms (for electromagnetic compatibility), overshoots, and ringing. The optimum values of gate resistance are usually determined experimentally [4],[5] rather than via simulation, due to a number of simulation challenges:

1. Simulation models can require a large investment of person-hours to deliver an acceptable match to reality, requiring experimental validation.
2. The execution time of accurate circuit models can be very high.

Taken together, the total time taken to perform an evaluation of gate drive resistances in simulation can exceed that of performing it experimentally. An exhaustive evaluation of gate drive resistance combinations would require $m \times n$ experiments for $m$ different turn-on resistances and $n$ different turn-off resistances. For each change in resistor value, the circuit under test must be disconnected from test equipment, have a resistor removed and replaced with another, be re-connected to the test equipment, and be operated until it reaches a thermal steady-state. Not only is this a lengthy process, the repeated reworking of the circuit board to remove and replace the resistors can eventually lead to irrecoverable physical damage such as lifted solder pads and obliterated solder resist.

Even for small $m,n$, the time required to perform a complete exhaustive evaluation can be prohibitive, forcing measurements over a smaller solution space and thereby potentially missing the optimum value combination. This paper presents methods to allow an accurate, exhaustive performance evaluation across all $m+n$ resistor value combinations, whilst only requiring $m+n-1$ experiments. This significant reduction in experimentation time for a given solution space raises the possibility of expanding the number of candidate turn-on and turn-off resistors, to give confidence that the best combination of resistor values will be found. Optimum resistor values may be determined for a given target system performance, such as minimisation of losses for a given maximum acceptable spectral content in voltages and/or currents in the converter.

For each experiment, power-circuit time-domain waveforms are acquired and saved, together with measured power losses. The power losses for any of the $m \times n$ resistor value combinations can be predicted via standard 2D curve fitting — splicing, waveform reconstruction, and optimisation of turn-on and turn-off gate drive resistance gives designers maximum flexibility, allowing independent adjustment of the controlled device’s turn-on and turn-off behaviour. When selecting the values of gate drive resistance, the designer will typically have to trade-off power losses against other performance factors such as spectral content of voltage and current switching waveforms (for electromagnetic compatibility), overshoots, and ringing. The optimum values of gate resistance are usually determined experimentally [4],[5] rather than via simulation, due to a number of simulation challenges:

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fitting [6]. An overview of the automated process of the time-
domain data analysis by an edge extraction and splicing method
is provided in Section II. At present, the method relies on the
switch-mode waveforms being steady-state, such as those
found in a DC:DC converter when input and output conditions
are not changing, but similar methods could be used in an
ehanced scheme with time-varying switching waveforms such
as those found in an inverter. This paper presents the methods
used for:

- The automated switching-edge detection and extraction,
  which minimises the amount of leading data extracted
  before the start of the edge, and maximises the amount of
  trailing data extracted following the edge, as explained in
  Section III.

- The automated edge splicing method used to build a
  “predicted” time-domain waveform for the desired turn-on
  and turn-off resistor combination, as detailed in Section IV.
  The method avoids introducing discontinuities in the
  reconstructed waveform that would otherwise corrupt its
  high-frequency content.

- The reconstruction of multiple different time-domain
  waveforms from a single circuit (i.e. voltages and currents
  at various points in the circuit) including non-switching
  waveforms that exhibit disturbances (for example the output
  of a converter can exhibit disturbances when the power
devices switch), as detailed in Section V. The reconstruction
  maintains the correct relative timing of all waveforms.
Once time-domain waveforms have been constructed, they
  can be transformed into the frequency domain for spectral
analysis, and these data subsequently used for the gate resistor
value co-optimisation. In Section V, the results of using the
  edge extraction and splicing methods on waveforms acquired
  from a SiC-based boost converter are presented, demonstrating
  that the spectral content of reconstructed waveforms, and
  predicted system loss, closely match actual measurements.

In Section VII, the reconstructed waveforms and
  interpolated losses are used to automatically determine the
  optimum gate resistor value combination, based on a set of
  user-defined selection criteria such as an acceptable limit for
  the spectral envelopes of switching waveforms.
Section VII draws conclusions, noting some limitations of
  the present implementation and making suggestions for further
work.

II. OVERVIEW OF EXPERIMENTAL PROCEDURE AND
  SUBSEQUENT EDGE EXTRACTION AND SPlicing

For this paper, the method is used on an open-loop 300 W,
600 V output non-synchronous 1:10 SiC boost converter
operating with 100 kHz switching frequency, as shown in Fig.
2. Time-domain waveforms of $v_{GS}$, $v_{SW}$ and $v_{OUT}$ are captured
  on a 10 GSa/s, 4 GHz Rhode & Schwarz RTO1044
oscilloscope, and input and output power (for loss calculation)
are measured using three 6.5-digit Fluke 8845A multimeters
  (for $V_{IN}$, $V_{OUT}$, and $I_{OUT}$) and one 6.5 digit GW PCS-1000
precision current shunt (for $I_{IN}$). It is desired to optimise the gate
resistor values over a range of
  2.7 Ω to 47 Ω for turn-on, and
  2.7 Ω to 100 Ω for turn-off, to find
the best compromise between
  losses and spectral content of the
measured $v_{SW}$ and $v_{OUT}$
waveforms. The first step of the
  process is to acquire measurement
data for the turn-on and turn-off
resistor value combinations shown
in Table I. 11 turn-off and 9 turn-
on resistor values are evaluated
  with 19 tests. Whilst all resistor
values could be used in a
  minimum of 11 tests (by simultaneously changing both
  turn-on and turn-off resistor values), this would give too small
  a measurement space to go into
  the 2D loss curve fitting, and
  adversely affect the accuracy of
  loss predictions for untested
  resistor combinations.

For each resistor combination,
  the converter is operated until it
  reaches thermal steady state, at
  which point losses and time-
domain signals are measured and
  acquired. The oscilloscope is set
to capture and average multiple
  successive waveforms to give a
  high signal to noise ratio, with each capture duration equal to
  exactly one complete switching cycle (i.e. 1/100 kHz = 10 μs).
Triggering is set so that the switching edges occur well away
from the start and end points of the capture. Loss measurements
  and time-domain waveforms are transferred to a host PC for
  offline analysis in MATLAB.

To determine the time-domain waveforms that would occur
  for any gate drive resistor combination that is not part of the
measurement space, e.g. 6.8 Ω turn-on with 33 Ω turn-off,
  the procedure outlined in Fig. 3 is followed. Firstly, edges are
extracted from the relevant measured data (in this case the
  waveforms for 47 Ω on with 33 Ω off, and 6.8 Ω on with 10 Ω
  off) and then spliced to form a new “reconstructed” waveform.

Because the source data from each edge has been captured
under the influence of minor test-to-test variations, and due to

<table>
<thead>
<tr>
<th>Table I. TURN-ON AND TURN-OFF RESISTOR VALUE COMBINATIONS USED WHEN ACQUIRING CIRCUIT MEASUREMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turn-on resistor value (Ω)</td>
</tr>
<tr>
<td>-----------------------------</td>
</tr>
<tr>
<td>10</td>
</tr>
<tr>
<td>10</td>
</tr>
<tr>
<td>47</td>
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<tr>
<td>47</td>
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<td>47</td>
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<tr>
<td>33</td>
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<tr>
<td>22</td>
</tr>
<tr>
<td>15</td>
</tr>
<tr>
<td>10</td>
</tr>
<tr>
<td>6.8</td>
</tr>
<tr>
<td>4.7</td>
</tr>
<tr>
<td>3.3</td>
</tr>
<tr>
<td>2.7</td>
</tr>
</tbody>
</table>
small time- and temperature- dependent variations in the inaccuracies of the waveform acquisition, the high and low steady-state values of the edges to be spliced will not be exactly equal. The splicing process must account for this, so as not to introduce discontinuities which would corrupt the high-frequency content of the reconstructed waveforms.

### III. EDGE EXTRACTION METHOD

#### A. Sliding-window Linear Regression

To extract edges from a measured waveform, first the vertical midpoint of the waveform is found:

```
midpoint = (max(timeData)-min(timeData))/2;
```

The first edge is located by searching forwards from the start of the waveform, looking for the first index where the data crosses the midpoint value. For example, if the initial waveform value is below midpoint, the index of the transient of the first edge is located at:

```
firstEdgeIndex = find(timeData>midPoint,1);
```

and the index of the second edge’s transient is located by searching backwards from the end of the waveform:

```
secondEdgeIndex = find(timeData>midPoint,1,'last');
```

If the edge to be extracted is the first edge, the start of its transient must be located; this will define the initial edge extraction point. The final edge extraction point is found by searching backwards from the second edge transient, looking for the point where that transient starts.

The starts of transients are found using the process illustrated in Fig. 4. A sliding window, equal in length to 0.5% of the total switching period, defines the region over which a linear regression is performed on the data. Initially, the window is placed at the relevant edgeIndex point, and is then slid backwards one index at a time, once the linear regression has been performed. The process is repeated until the slope of the best-fit line in the window is below a fixed threshold, indicating that a steady-state has been located.

If the edge to be extracted from the data is the second edge, the waveform is first “shuffled”, as shown in Fig. 5, before performing the steady-state searching process to find the start and end points for the edge extraction.

#### B. Alternative Edge Extraction Method

Edges could potentially be identified using a high-pass filtering and smoothing process depicted in Fig. 6. Here, the
Fig. 6  Edge detection with high-pass filtering and smoothing.

switching waveform has been processed by a high-pass filter with a stopband (80 dB attenuation) width of 250 kHz and a passband (0 dB ± 1 dB) starting at 10 MHz. The absolute values of the filtered waveform are then passed through a 255-point moving-average filter to give the smoothed line in Fig. 6. If the value of this line is above a pre-determined threshold, the source waveform can be considered to be undergoing a transition.

Although this edge-detection method can be faster than the sliding-linear-regression method, both methods are fast – taking the order of tens of milliseconds to detect edge start and end points in a 100,000-point waveform. The linear regression method also requires only two parameters to be configured: the sliding window length and a “flatness” threshold. The filtering method requires the high-pass and moving-average filter characteristics to be tuned to the input waveforms, definition of a threshold for the smoothed filtered waveform to define when a transition is occurring, and a definition of the number of samples that should be extracted prior to the detected edge (unlike the linear regression method, the filter method will not find a long enough steady-state prior to the edge such that the extracted edges are ready for splicing). The linear regression method was therefore selected as the edge detection method in this work.

IV. EDGE SPLICING METHOD

When the edges are to be spliced together to form a “reconstructed” time-domain waveform, it is vital that discontinuities are not introduced, as these would create spurious high-frequency content. However, because the source data for the edges to be spliced are acquired under the influence of minor test-to-test variations, and due to small time- and temperature- dependent variations in the inaccuracies of the equipment, if the waveform high-level amplitudes (e.g. the 600 V level of the example \( v_{SW} \) waveforms shown in Fig. 3) are aligned, there may still be a discontinuity at the low level. The edge-alignment conflict is handled by aligning the pulses at the steady-state value found in-between the two edges (e.g. 600 V for the example \( v_{SW} \) waveforms), and then windowing the data to accommodate any discontinuity in the waveform end-points. The pulse-alignment process follows the procedure illustrated in Fig. 7, and the windowing process follows the procedure illustrated in Fig. 8.

When the process is complete, the waveform gently tapers to/from equal values at the start and end of the waveform, ensuring no discontinuity is present when the frequency content is calculated via the FFT.
V. RECONSTRUCTION OF MULTIPLE WAVEFORMS

A. Overview

Often there will be multiple waveforms of interest in a power converter. The techniques presented can be applied to multiple waveforms, but additional processing is required to ensure that predicted waveforms maintain the correct relative timing. Additionally, some waveforms may not be “switching” waveforms like the $v_{SW}$ waveform used thus far as an example, but may instead exhibit disturbances when a power device switches. For the circuit used in this work, an example of such “disturbance” waveform is the output voltage $(v_{OUT})$ in Fig. 2.

B. Reconstruction of Disturbance Waveforms

As a disturbance waveform is non-switching, the sliding-window linear regression method described in Section III.A cannot be used on such waveforms. Instead, a switching waveform is used as a “reference”, whereby the start and end indices for edges extracted from the source reference waveforms are saved during the edge extraction process, and are then used to define the indices at which data should be extracted from the source disturbance waveforms. Once fragments have been extracted from the source disturbance waveforms, they are spliced together using the process described in Section IV. It must be noted that this method requires that the disturbances do not occur before the transients in the reference switching waveform. In the example provided here, $v_{SW}$ is a suitable candidate to act as the reference, because the $v_{OUT}$ disturbances are occurring as a direct result of the $v_{SW}$ transients and therefore cannot occur before them.

If no switching waveforms are available to act as a reference, disturbances could be detected using a method based on that described in Section III.B. However, it is most probable that the switching waveform responsible for the disturbances would be of interest and therefore would be measured and available to act as a reference. In this case, extracting the disturbances from non-switching waveforms is very rapid as no additional computation is required to determine the extraction points.
C. Maintaining Synchronisation of Multiple Switching Waveforms

When reconstructing multiple switching waveforms, one of the switching waveforms acts as a reference. Edges are extracted from the reference waveform first, with the index of the vertical midpoint of each edge being saved for later reference. Edges are then extracted from the other switching waveforms, and during this process the time delay to the reference waveform edges are calculated and saved, as illustrated in Fig. 10. Reconstruction of the waveforms then proceeds as follows:

1. The reference waveform is reconstructed according to the steps outlined in Section IV, with the additional proviso that the amount of data moved from the end of the waveform to the start (as per Fig. 8(b)) is now based on the earliest-occurring edge across all the switching waveforms. This is because all reconstructed waveforms must have sufficient lead-in data such that no edge will be affected by the Tukey windows that will be applied later to accommodate any end-to-start discontinuities. For the example $v_{SW}$ and $v_{GS}$ waveforms, the $v_{GS}$ falling edge starts before the $v_{SW}$ rising edge, as shown in Fig. 10. So, in this case, the amount of lead-in data required is determined by the time position of the $v_{GS}$ falling edge.

2. The edges of any non-reference switching waveforms are now positioned according to the time-delays saved during the edge extractions, as shown in Fig. 11.

3. For each of the non-reference switching waveforms, the end of the first edge may now overlap with the start of the second edge, or there may be a gap between the edges such as shown in Fig. 11, bottom. If there is overlap, data are removed from the first edge. If there is a gap, it is filled by repeating data from the end of the first edge.

4. The pulse amplitudes of each of the non-reference switching waveforms are aligned according to the steps shown in Fig. 7.

5. For each of the non-reference switching waveforms, those that are too long are truncated, and those that are too short are extended by repeating data at the end of the second edge.

6. Data are moved from the end of the waveforms to the start, as illustrated in Fig. 12.

7. The waveforms are windowed according to the steps shown in Fig. 8(c) and (d).

---

Fig. 10 Maintaining synchronisation across multiple predicted switching waveforms: during edge extraction process, the time delays between the measured switching edges in the source waveforms are calculated and saved. $v_{SW}$ and $v_{GS}$ switching edges for circuit of Fig. 2 used as an example here.

Fig. 11 Edges of non-reference waveforms, $v_{GS}$ in this case, positioned to maintain the previously saved time delays. The bottom graph shows a horizontal zoom of the middle graph.

Fig. 12 Pulses aligned, and data moved from end of waveform to start, ready for the final stage of reconstruction: windowing as per Fig. 8.
VI. COMPARISON OF THE FREQUENCY-DOMAIN CONTENT OF PREDICTED AND MEASURED WAVEFORMS FOR A SiC-BASED BOOST CONVERTER

The presented waveform analysis methods have been used to reconstruct $v_{SW}$ and $v_{OUT}$ waveforms for two resistor combinations not covered by those listed in Table I: 6.8 $\Omega$ on with 33 $\Omega$ off, and 33 $\Omega$ on with 33 $\Omega$ off. Also, 2D curve fitting is used to predict the losses for these resistor combinations. Subsequently, the real circuit has been operated with these two additional resistor value combinations, to validate the analysis method. The loss comparison is provided in Table II. In both cases, the error between predicted loss and measured loss is within the measurement error band.

Fig. 13 through Fig. 16 show comparisons between the spectral envelopes for $v_{SW}$ and $v_{OUT}$, calculated from the time-domain waveforms. In all cases, the spectral content of the predicted waveforms matches closely to the actual measured waveforms.

VII. OPTIMISING THE GATE RESISTORS FOR BEST LOSS VS. SPECTRAL CONTENT TRADEOFF

Using the presented methods, MATLAB can be used to search across all $m \times n$ gate resistor value combinations, calculating predicted losses and circuit waveform spectral content. If acceptable spectral content limits are defined, it can then be determined which gate resistor value combination meets the defined limit with the minimum losses.

For example, if the $v_{OUT}$ and $v_{SW}$ spectral content limits are defined as in Fig. 17 and Fig. 18 respectively, it is determined

<table>
<thead>
<tr>
<th>Turn-on resistor value ($\Omega$)</th>
<th>Turn-off resistor value ($\Omega$)</th>
<th>Predicted loss (W)</th>
<th>Measured loss (W)</th>
<th>Error (W, (%))</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.8</td>
<td>33</td>
<td>14.50</td>
<td>14.23</td>
<td>0.27 (1.9%)</td>
</tr>
<tr>
<td>33</td>
<td>33</td>
<td>16.45</td>
<td>16.32</td>
<td>0.13 (0.8%)</td>
</tr>
</tbody>
</table>
19 different combinations of turn-on and turn-off resistor values meet these limits. One of these combinations is 33 Ω turn-on with 6.8 Ω turn-off, as shown in Fig. 19. With power circuit losses of 15.51 W, this is the lowest-loss resistor combination to meet the limit.

The total execution time of the optimisation is 3.3 seconds when run on a 2.6 GHz Intel Core i3 system with 16 GiB RAM running MATLAB R2016a.

VIII. CONCLUSIONS AND FURTHER WORK

Automated methods for extracting and splicing edges from measured time-domain waveforms have been presented. These form the key part of a process for determining the optimum values of a power device’s turn-on and turn-off gate drive resistances with a minimum number of experiments required. Exhaustive evaluation of all of the \( m \times n \) resistor value combinations, for \( m \) different candidate turn-on values and \( n \) candidate turn-off values, is possible whilst only requiring \( m+n-1 \) experiments. Once suitably-formatted data have been experimentally acquired, the analysis is highly automated and extremely rapid.

Currently, the analysis methods are only applicable to DC-DC converters with fixed operating conditions, but the concept could potentially be expanded to accommodate variable conditions such as changing load current. Switching waveforms must have a pulse duration of at least 0.5% of the switching cycle, and noisy waveforms or those that do not reach a steady-state between edges, for example a waveform with extensive post-edge ringing, are not currently supported.

The edge extraction and splicing methods presented have other potential uses beyond gate resistor optimisation. They could form the basis of experimentally-informed circuit simulation, whereby a database of measured waveforms for a range of operating conditions is created using a test circuit, and then the simulation tool extracts and splices edges from the database to create simulated waveforms for any scenario.

MATLAB code that implements the presented methods is available at [7], together with a set of example data.

REFERENCES

[7] University of Bristol, MATLAB waveform splicing tools, [online: http://tiny.cc/waveformSplicing]