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SEPIC-Fed BLDC Motor Drive with Tuned Voltage and Current Control of the DC Link

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ABSTRACT :

A brushless DC (BLDC) motor that runs from a battery needs a DC-link voltage that is often higher or lower than the battery voltage. This paper studies a drive in which a single-ended primary-inductor converter (SEPIC) sets the DC-link voltage of a six-step inverter, and the motor speed follows from that voltage and the load. The SEPIC is controlled by two nested PI loops, a DC-link voltage loop and an input-current loop, and no speed loop is used. The four gains are searched with particle swarm optimisation (PSO) on a cost made of time-weighted voltage error, peak voltage error and duty-cycle activity. The tuned controller is compared with a PI pair designed by crossover-frequency rules in an averaged-model simulation of a 48 V, 0.5 kW drive that covers motor start-up, a load step, a link-voltage reference step and a load release. After the load step the link voltage moved by 0.05 V with the tuned gains and by 0.39 V with the rule-based gains, and the link voltage settled to within 2 % about 9 ms after a 48 V to 60 V reference step against 14 ms. Under a battery sag from 48 V to 36 V the rms link-voltage error fell from 0.150 V to 0.016 V. The tuned gains were less tolerant of a simultaneous capacitance loss and resistance increase, which shows that the tuning should include parameter variations.

Keywords: SEPIC converter, BLDC motor, DC-link voltage control, input-current control, particle swarm optimization.

1. INTRODUCTION

BLDC motors are widely used in light electric vehicles, pumps, fans and robotic joints because they combine good efficiency with a simple construction and a high torque-to-weight ratio [1]. In most low-voltage systems the motor is supplied from a battery, and the battery voltage falls steadily as it discharges. A motor that needs a certain DC-link voltage for a given speed therefore cannot be connected to the battery directly if the speed is to stay constant over a full discharge cycle.

There are two ways to control the speed of a six-step BLDC drive. The inverter can chop its switches with a PWM duty ratio, which adds switching loss and torque ripple at every switching edge, or the DC-link voltage can be varied while the inverter switches only at the commutation instants. The second approach moves the regulation task to a DC–DC converter. A SEPIC is attractive in this role because it can raise or lower the voltage with a non-inverting output, has a continuous input current, and provides capacitive isolation between input and output, so a switch failure does not connect the battery directly to the motor [2], [3].

Once the converter is responsible for the link voltage, the control problem is that of a DC–DC converter feeding a variable load, and cascaded control with an inner current loop and an outer voltage loop is the usual solution [4], [5]. In this paper the motor speed is deliberately not fed back. The link voltage is the controlled quantity, the speed follows from the voltage and the load torque, and a speed loop can be added on top later if an application needs it. Rule-of-thumb gains designed at one operating point may behave poorly when the load or the battery voltage changes, and setting the gains by hand is slow. PSO is a population-based search that needs no gradient and has few settings [6]; here the cost can be computed directly from a simulation run, so it is easy to apply.

The authors have earlier studied a bidirectional synchronous SEPIC feeding a permanent-magnet synchronous motor in a regenerative-braking application [7]. The present paper deals with a different problem: a unidirectional SEPIC feeding a six-step BLDC drive, where the converter has to hold the link voltage against the inrush of a stationary motor and against load and reference steps. The contributions are:

- an averaged model of the SEPIC–inverter–BLDC chain that includes the diode constraint of the SEPIC and a current limit in the inverter;
- a PSO-based tuning of the voltage and current loops against a profile that contains motor start-up, a load step, a reference step and a load release;
- a comparison with crossover-based PI gains, including tests with a battery voltage sag and with changes of output capacitance and winding resistance.

2. SYSTEM DESCRIPTION AND MODEL

2.1 Power stage.

The drive is a chain of four stages. The battery feeds a SEPIC with two inductors L_1 and L_2, a coupling capacitor C_1 and an output capacitor C_o. The output of the SEPIC is the DC link of a three-phase six-step inverter that drives the BLDC motor in 120° conduction. A bleeder resistor R_b keeps a small load on the link so that it can discharge when the voltage reference is reduced. The DC-link voltage and the SEPIC input current are measured, and the two control loops of Section 3 act on the SEPIC duty ratio.

2.2 SEPIC averaged model.

In continuous conduction the state equations averaged over a switching period are

$$L_1 \frac{di_1}{dt} = V_{in} - (1-d)(v_{C1} + v_o) - r\, i_1 \qquad (1)$$

$$L_2 \frac{di_2}{dt} = d\, v_{C1} - (1-d)\, v_o - r\, i_2 \qquad (2)$$

$$C_1 \frac{dv_{C1}}{dt} = (1-d)\, i_1 - d\, i_2 \qquad (3)$$

$$C_o \frac{dv_o}{dt} = (1-d)(i_1 + i_2) - i_o \qquad (4)$$

where d is the duty ratio, r the inductor resistance and i_o the current drawn by the inverter and bleeder. At steady state the conversion ratio and the duty ratio are

$$\frac{V_o}{V_{in}} = \frac{D}{1-D}, \qquad D = \frac{V_o}{V_{in} + V_o} \qquad (5)$$

Because the output diode cannot carry reverse current, the model enforces $i_1 \geq 0$ and $i_1 + i_2 \geq 0$; otherwise the averaged equations would let the link voltage go negative at start-up. The peak-to-peak ripples used to size the components are

$$\Delta i_{L1} = \frac{V_{in} D}{L_1 f_s}, \quad \Delta v_{C1} = \frac{I_o D}{C_1 f_s}, \quad \Delta V_o = \frac{I_o D}{C_o f_s} \qquad (6)$$

2.3 BLDC motor and inverter.

With 120° conduction two phases carry current at any time. The line-to-line back EMF is $E_{ll} = K_e \omega$ and, for the trapezoidal machine, the electromagnetic torque is $T_e = K_e i_m$. The averaged motor equations are

$$2L_m \frac{di_m}{dt} = m\, v_o - 2R\, i_m - K_e\, \omega \qquad (7)$$

$$J \frac{d\omega}{dt} = K_e\, i_m - B\, \omega - T_L \qquad (8)$$

where R and L_m are the phase resistance and inductance, J the inertia, B the friction coefficient and T_L the load torque. The factor $m \in [0, 1]$ represents the inverter's current limiter, which reduces the average voltage applied to the motor when the current approaches its limit I_{lim}:

$$m = \min\left(1, \max\left(0, \frac{I_{lim} - i_m}{\Delta I}\right)\right), \qquad i_o = m\, i_m + \frac{v_o}{R_b} \qquad (9)$$

Without this limit a stationary motor would draw $V_{dc}/2R$ from the link, which is far above what the SEPIC can supply, and the model would collapse the link voltage at start-up.

Table 1. Drive parameters

Parameter	Value
Battery voltage V_{in}	48 V (36–48 V)
$L_1 = L_2$, r	300 µH, 50 mΩ
C_1, C_o	100 µF, 470 µF
Switching frequency f_s	40 kHz
Bleeder R_b	150 Ω
Phase resistance R, inductance L_m	0.35 Ω, 1.2 mH
K_e (line-to-line)	0.17 V·s/rad
J, B	0.003 kg·m², 5×10^{-4} N·m·s
Current limit I_{lim}, band ΔI	20 A, 8 A

Parameter	Value
Inductor-current reference limit	30 A
Duty-ratio limits	0.05 – 0.85

Table 2. SEPIC design values at 48 V in, 60 V out, 10 A load

Quantity	Value
Duty ratio D	0.556
Average i_1 / i_2	12.5 A / 10 A
$\Delta i_{L1} = \Delta i_{L2}$	2.22 A
Δv_{C1}	1.39 V
ΔV_o	0.30 V

3. CONTROL AND TUNING

3.1 Control loops.

The outer loop compares the link voltage with its reference V_{dc}^* and produces a reference for the SEPIC input current i_1, and the inner loop sets the duty ratio:

$$i_1^* = \mathrm{sat}\left(K_{pv}e_v + K_{iv}\int e_v dt\right) \qquad (10)$$

$$d = \frac{V_{dc}^*}{V_{in} + V_{dc}^*} + K_{pi}e_i + K_{ii}\int e_i dt \qquad (11)$$

with $e_v = V_{dc}^* - v_o$ and $e_i = i_1^* - i_1$. The first term of (11) is the feed-forward duty from (5). The current reference is limited to 0 – 30 A, the duty to 0.05–0.85, and each integrator stops accumulating while its output is saturated. No signal from the motor is used by the controller.

3.2 Rule-based design.

The comparison design follows the usual crossover rule [4], [8]. The inner plant is approximated as $i_1/d \approx (V_{in}+V_o)/(sL_1)$, so a 2 kHz crossover ω_{ci} gives $K_{pi} = \omega_{ci}L_1/(V_{in}+V_o)$ and $K_{ii} = K_{pi}\omega_{ci}/10$. With the voltage-loop plant approximated as $(V_{in}/V_o)/(sC_o)$, a 150 Hz crossover ω_{cv} gives $K_{pv} = \omega_{cv}C_o/(V_{in}/V_o)$ and $K_{iv} = K_{pv}\omega_{cv}/5$. The design point is $V_o = 60$ V.

3.3 Particle swarm tuning.

The four gains form the vector $\mathbf{x} = [K_{pv}, K_{iv}, K_{pi}, K_{ii}]$, searched on a logarithmic scale between the limits $K_{pv} \in [0.05, 5]$, $K_{iv} \in [5, 1000]$, $K_{pi} \in [0.005, 0.2]$ and $K_{ii} \in [5, 500]$. Particle k is updated by [6]

$$\mathbf{v}_k \leftarrow \omega_p\mathbf{v}_k + c_1r_1(\mathbf{p}_k - \mathbf{x}_k) + c_2r_2(\mathbf{g} - \mathbf{x}_k), \qquad \mathbf{x}_k \leftarrow \mathbf{x}_k + \mathbf{v}_k \qquad (12)$$

where $\mathbf{p}_k$ is the best position of the particle, $\mathbf{g}$ the best position of the swarm and r_1, r_2 are uniform random numbers. The settings were 20 particles, 30 iterations, $\omega_p = 0.72$ and $c_1 = c_2 = 1.5$, and one particle was started at the rule-based gains. Each candidate is judged by simulating the whole profile of Section 4 and evaluating

$$J = 10\int_0^T \tau\,(t)\,|e_v(t)|\,dt + 0.1\sum_{k=1}^{4}\max_{t\in E_k}|e_v(t)| + 2\sum_n (d_{n+1} - d_n)^2 + 5\max\left(0,\, i_{1,max} - 35\right) \qquad (13)$$

where the voltage error is in volts, $\tau(t)$ is the time since the start of the current event window E_k, and the last term penalises inductor-current peaks above 35 A. A run in which the link voltage exceeds 200 V is given a very large cost.

4. SIMULATION SETUP

The averaged model (1)–(9) was integrated in Python with a semi-implicit scheme at 20 µs, updating the currents before the voltages, and with a one-sample delay between the duty command and its application. The motor starts at rest with the SEPIC output precharged to the battery voltage through the output diode. The link-voltage reference is 48 V until 0.6 s and 60 V afterwards. The load torque is 0.4 N·m until 0.3 s, 1.2 N·m until 0.9 s, and 0.5 N·m afterwards. These give four event windows of 300 ms each: motor start-up, load step, reference step and load release. Two further tests were run. In the first the battery voltage falls from 48 V to 36 V between 0.3 s and 0.8 s with the reference held at 48 V and a load torque of 1.0 N·m. In the second the output capacitance is reduced by 30 % and the phase resistance increased by 30 % on the main profile. Since the model is averaged, switching ripple and commutation torque ripple are not represented.

5. RESULTS AND DISCUSSION

5.1 Tuning outcome.

The best cost of the swarm fell from 2.58 at the start to 2.12 after five iterations and to 2.05 after thirty. The rule-based gains score 2.92 on the same measure. Table 3 lists both gain sets. Two of the four PSO gains finished on a bound, K_{iv} at its upper limit and K_{ii} at its lower limit, so a wider range might give a lower cost; it would also push the voltage-loop integral action toward the inner-loop bandwidth, which is why the limits were kept.

Table 3. Controller gains and cost

Parameter	Rule-based	PSO-tuned
K_{pv}	0.554	3.02
K_{iv}	104.4	1000
K_{pi}	0.0349	0.00967
K_{ii}	43.9	5.00
J	2.92	2.05

5.2 Link-voltage response.

Table 4 gives, for each event, the largest deviation of the link voltage from its reference and the time taken to settle within ±2 % of the final reference. At motor start-up the link voltage dipped by 5.4 V with the tuned gains and by 10.9 V with the rule-based gains, and returned to the band after 5.9 ms and 13.2 ms respectively. The load step from 0.4 to 1.2 N·m moved the link voltage by only 0.05 V with the tuned gains against 0.39 V; the same load release gave 0.08 V against 0.62 V. In both cases the voltage never left the ±2 % band, which is 0.96 V at 48 V and 1.2 V at 60 V. For the 48 V to 60 V reference step the deviation is simply the 12 V step size, so only the settling time is compared: 9.3 ms for the tuned gains and 14.1 ms for the rule-based ones.

Table 4. Largest link-voltage deviation and ±2 % settling time per event

Event	Rule-based dev. (V)	Rule-based time (ms)	PSO dev. (V)	PSO time (ms)
Motor start-up (48 V)	10.88	13.2	5.44	5.9
Load 0.4 → 1.2 N·m	0.389	0	0.051	0
Reference 48 → 60 V	–	14.1	–	9.3
Load 1.2 → 0.5 N·m	0.622	0	0.077	0

The faster response was not free. At start-up the peak SEPIC input current was 18.5 A with the tuned gains against 12.3 A, and in the reference step it was 33.7 A against 17.6 A. The 30 A limit applies to the current reference, not to the actual current, so the tuned value can pass it; it stays below the 35 A level that the cost function penalises. The peak motor current was nearly the same for both controllers, 17.9 A against 17.7 A, since it is set by the inverter current limit.

Table 5 shows the state of the tuned drive at the end of each event window. The speed is not regulated, so it settles with the motor time constant and depends on the link voltage and load: 2383 rpm at 48 V and 1.2 N·m, and 3214 rpm at 60 V and 0.5 N·m. At the end of the first window the motor was still accelerating, so the figures for that row are not steady-state values.

Table 5. State of the PSO-tuned drive at the end of each event window

Window	V_{dc} (V)	Speed (rpm)	i_1 (A)	i_m (A)
Start-up, 0.4 N·m	47.99	2002	12.28	12.60
Load step, 1.2 N·m	48.00	2383	8.46	7.99
Reference step, 60 V	60.02	3018	12.06	9.05
Load release, 0.5 N·m	60.00	3214	5.54	3.99

5.3 Robustness.

During the battery sag from 48 V to 36 V the largest link-voltage error after 0.2 s was 0.481 V with the rule-based gains and 0.066 V with the tuned gains, and the rms error was 0.150 V against 0.016 V. The result was different with the second test, in which the output capacitance was reduced by 30 % and the phase resistance raised by 30 %. The largest link-voltage deviation in the load-step window was 9.58 V with the tuned gains and 0.33 V with the rule-based ones; in the reference-step window both were close to 12.5 V because of the step itself; and in the load-release window the figures were 4.29 V and 0.52 V. The tuned gains, which rely on a high integral gain K_{iv}, were therefore much less tolerant of this combined change than the more conservative rule-based gains.

5.4 Limitations.

The model is averaged, so switching ripple, commutation torque ripple and the lower efficiency of the real inverter are not included, and no loss or

efficiency results are reported. The speed is not regulated, so it varies with the load and the battery voltage. The SEPIC is unidirectional, so the drive cannot regenerate: braking energy is absorbed by the bleeder and the rotor friction. The rule-based design is a simple textbook choice and a more carefully tuned conventional controller would narrow the gap shown here. The tuned gains were obtained from the nominal profile alone and, as Section 5.3 shows, they do not transfer well to a plant with lower capacitance and higher resistance. Including such cases in the cost, or limiting K_{iv}, is the obvious remedy. A switched model and a hardware test are needed before these gains are used on a real drive.

6. CONCLUSION

A SEPIC-fed BLDC drive whose DC-link voltage is regulated by a voltage loop and an input-current loop, with no speed feedback, was modelled with an averaged description that includes the SEPIC output diode and an inverter current limit. The four PI gains were tuned with particle swarm optimisation. Compared with gains obtained by crossover rules, the tuned controller held the link voltage much more tightly during load steps and load release, settled faster after a change of the voltage reference, and was far less affected by a falling battery voltage. The price was a higher peak input current during the reference step and a poorer tolerance of a combined loss of output capacitance and rise of winding resistance, which shows that parameter variations belong in the tuning cost. Future work will include such variations in the cost, run the gains in a switched model, add the converter losses to the cost, provide a regenerative path, and add an outer speed loop for applications that need a fixed speed.

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