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High Efficiency Modular DC-DC Power Converter for Adaption to Industrial & Hybrid Robotics

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Abstract – **The purpose of this paper is to address current issues in industrial robotics applications and to address also the current trends occurring in the industry regarding smaller mobile units in factory and external manufacturing processes relating to the battery powering of robotics devices. Specifically, we shall concentrate the efforts herein on "Mobile Industrial Robotics". The paper touches briefly on problems associated with both definitions of industrial robots and problems associated with power supply sources of mobile industrial robotics and provides an outline of future work with appropriate solution for smaller mobile industrial mobile units operating in the variable input range of 24V to 48v and outputs in the range of 3.3V to 12V @ 20A in three stages. The project required a fast, turn-key solution which did not allow for a "design from scratch" solution and so detailed herein is suitable design produced in other sectors and relating the details, design process, modelling and examination of a successful and efficient high current DC to DC switch mode power supply. Parameters have been adjusted to our own preferences in the design considerations regarding "Industrial Service Hybrids" [1] (ISH)[1]. Other design issues are under assessment and shall be included as the project moves forward.**

I. INTRODUCTION

According to the International Federation of Robotics (IFR), Projections for the period 2011-2014: about 14.4 million units of service robots for personal use to be sold and it is estimated that the worldwide stock of operational industrial robots will increase from about 1,035,000 units at the end of 2010 to 1,308,000 at the end of 2014 with one third as mobile manufacturing robots." consistent with most mobile robotic devices. [2]

The definition of an Industrial robot as defined by ISO 8373 is an automatically controlled, reprogrammable, multipurpose manipulator, programmable in three or more axes, which may either be, fixed in place or mobile for use in industrial automation applications.

- Reprogrammable - programmed motions or auxiliary functions may be changed without physical alteration.
- Multipurpose - capable of being adapted to a different application with physical alterations;
- Physical alterations - alteration of the mechanical structure or control system except for changes of programming disks or ROMs.
- Axis - direction used to specify the robot motion in a linear or rotary mode.

As can be seen, the definition of Industrial Robot is quite specific however a perusal of the definition of "Service Robot" within the same ISO *precludes* service robots from this industrial classification however *includes* industrial robots into the classification of Service Robots. We shall not expand on this further except to say that it may cause many problems when the specification of a robot's "dynamic range of power electronics", "limits placed on drives and converters" or limits "commonly imposed to protect the power devices" is required. In more simplistic terms, there is a requirement to account for those machines isolated from mains supplies.

There is a growing need for a stable, efficient, and versatile 24 to 48 volt power supply in the various emerging mobile robotics arenas capable of interoperation between various machine types.

There are many robotic systems requiring the use of two to six 12V lead acid batteries (or equivalent) for mobility, module operation, implement operation and requiring long operating lifetime. Within many projects there is insufficient research time available for the design from scratch power supply system accounting for the many and varied requirements of each component of the system. Therefore, the design of a power supply system specifically addressing the requirements of average machines would eliminate many concerns in power system design, much as a generic supply is available for the personal desktop computer.

The project attempts to eliminate the requirement of a power design in these systems by creating a highly efficient supply, capable of providing 3.3V, 5V, and 12V outputs, each capable of supplying up to 20 amps from a single 24V to 48V DC input. The power supply design utilizes three synchronous buck converters with a very small form factor.2

II. PREREQUISITE POWER SUPPLY PARAMETERS

Form Factor: Smaller than (W127mm x H80mm x L127mm)
Converters: (Initially Three)
Input voltage: 24 volts to 48 volts
Ideal input: 36Volts
Battery Configuration: 4 x 12 VDC Li-Ion 200Ah Batteries, series/parallel configuration: {24V @ 400Ah}, {36V @ 400Ah}, {48V @ 200Ah}
Output Voltage: Stable 3.3V, 5V, 12V.
Output Current: Maximum load current: 20A per converter.

The chosen parameters are in line with the current requirements for mobile robotics that operate on DC battery systems.

[1] Industrial Service Hybrid Robot as coined by Leslie R. Adrian 2012

[2] The selection of output voltages is not fixed and reflects the required parameters of the authors.

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III. Wide Input Dual Synchronous Buck Controller

Uses high-voltage, wide input synchronous, step-down converters with design flexibility with a variety of user programmable functions, including soft-start, UVLO, operating frequency, voltage feed forward, high-side current limit, and loop compensation. Synchronizable to an external supply the LM5119Q incorporates MOSFET Gate Drivers for N-Chanel High side and synchronous rectifier (SR) Gate drive logic incorporates anti-cross conduction circuitry to prevent simultaneous high-side and synchronous rectifier conduction. The LM5119Q control method is based upon current mode control utilizing an emulated current ramp. Current mode control provides inherent line feed-forward, cycle-by-cycle current limiting and ease of loop compensation. The use of an emulated control ramp reduces noise sensitivity of the pulse-width modulation circuit, allowing reliable control of very small duty cycles necessary in high input voltage applications. (from LM5119 datasheet). Mosfets switching frequency is programmable from 50 kHz to 750Khz. The externally programmable current limit provides pulse by-pulse current limit, as well as a hiccup mode operation utilizing an internal fault counter for longer duration overloads.

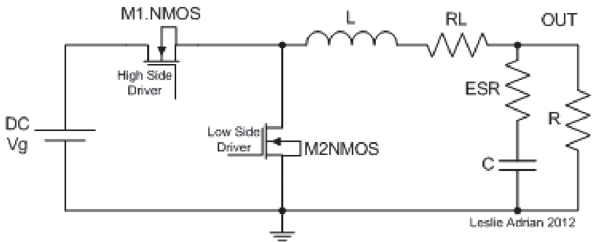

Fig.1. Remedial synchronous buck converter circuit.

With the switcher and method in mind the goal was to achieve a minimal form factor increasing the switching frequency through the use of GaN Mosfets, more specifically: GS61008T capable of driving up to 90A. It was decided to use a switching frequency of 635KHz. Those conditions gain the relevance of the circuit component thermal considerations were kept to a minimum, a remedial schema for the synchronous buck converter as seen in Fig.1 was investigated with the relevant equations governing the operation of the converter denoted in Formula 1,2 and 3:

$$\frac{di_L}{dt} = \frac{1}{L}\left(V_g \times d - i_L \times R_L - v_0\right) \tag{1}$$

$$\frac{dv_c}{dt} = \frac{1}{C}\left(i_L - i_0\right) \tag{2}$$

$$v_0 = v_C + ESR\left(i_L - i_0\right) \tag{3}$$

where:

- the desired output voltage is directly proportional to the duty cycle created by Mosfet M1 and Mosfet M2.
- a second order low pass filter is formed by the inductor and capacitor acting as energy storage elements forming a cut off frequency well below the switching frequency of the supply.
- A resultant smooth and filtered DC voltage is applied to the load as is in line with author required parameters.

Table 1

Adj. Input Voltage	Current Draw (Max)
24 -48 Volts	20 Amperes
Output Voltage (Fixed)	Output Current (Max)
3.3 Volt	20 Amperes
5 Volt	20 Amperes
12 Volt	20 Amperes

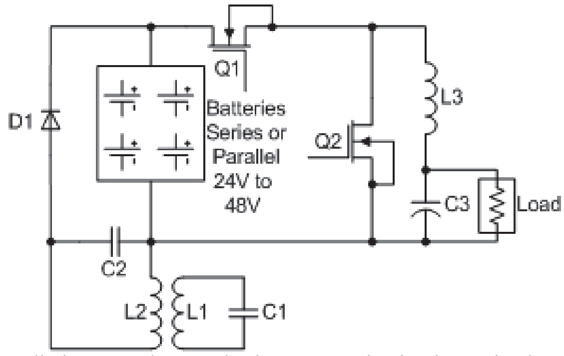

Fig.2. Preliminary synchronous buck converter circuit scheme simulate.

IV. Dynamic Range of Power Electronics (DRPE)

DRPE refers to the limits placed on drives and converters and although commonly imposed in the interest of protecting the power devices are not usually consistent with the needs of most robotic applications.

In most classical drive control structures in use today a classical, cascaded loop, control structure is used. The innermost loop is the current loop, which is driven in cascade by the field oriented controller, which in turn is driven by the motion controller. The feed-forward controller functions are included to meet the dynamic motion control accuracy requirements for the most demanding automation applications.

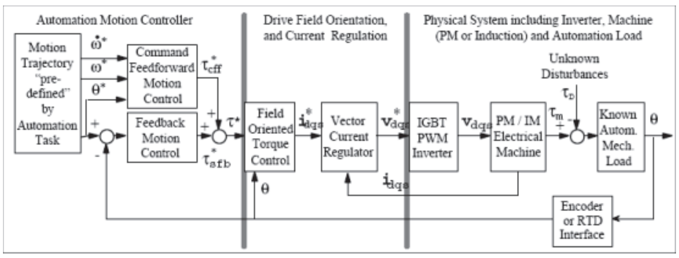

Fig.3. The classical drive control structure.

Actual process intervals are often quite slow because of process limits, e.g. paint cannot be applied with a fire hose. During actual process intervals, the torque demands are often quite low. To minimize the non-productive time, all non-process motion would ideally be accomplished in "nearly zero" time. This implies that an extremely high torque profile should be provided by the controller for a short period to achieve the desired non-process motion. An ideally designed feed-forward controller would immediately request such torque. The power electronic switches are not ideal and have very real temperature limits that dictate the losses which they can sustain. This limit is most commonly designed to be twice the rated, steady state current of the drive. It is well recognized that this limit cannot always be met, especially at high speeds because of bus voltage limitations, unless dynamic control of field weakening is implemented. Assuming dynamic control of field weakening is implemented, various methods of control have been suggested to handle the current limit. One method simply modifies the current reference to make it feasible, given the inductance of the motor and the bus voltage [3]. Another method uses artificial intelligence to select the best possible inverter output voltage [4].

In summary, the dynamic range limitation, as currently implemented in power converters, is not well suited to automation and robotics applications. Real opportunities however exist for improved automation performance if the physical properties of the devices and electrical machine are more fully included in the limiting functions.

Fig.4. COBHAM's heavy duty EOD robot, similar in autonomy and power requirements to the ISH robots outlined within the paper.

V. Power Electronic Equipment in (ISH) Robotics

The reliability of the energy systems for the Industrial Service Hybrid robot is of paramount importance, moreover due to the demand for a high energy system non-mains connected system. A system shutdown due to inefficient power systems is unacceptable. The existing controls for power electronic converters are primarily designed for shutdown style protection of the power electronics and not for sustained limited capacity operation of the process. Multiple causes for failures exist, but two causes are thermal overload and unexpected application dependent problems. This requirement suggests active control of the temperature and cycles of devices in the power converter. Actively controlling temperatures and temperature cycles of devices, interconnections, interfaces, and components would become the innermost loops and power conversion and motion control would be subordinate to these capacity reducing constraints. One such idea is where the thermal mechatronics of both the power electronics converter and the machine are regulated, and actively limit the power conversion of the drive including both conduction losses and switching losses. In summary, reliability of power electronics could strongly benefit from a control-oriented solution whereby failure causes are actively regulated and power conversion subordinated. This solution methodology is indeed a major focus of ongoing research addressing reliability of power electronic systems [5].

VI. System Schema

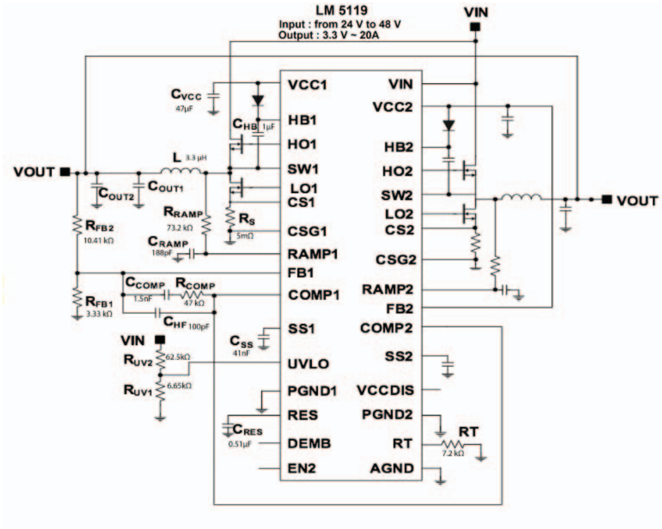

Fig. 5. Converter circuit schematic reflects the (24V to 48V input) to (3.3V @>20A) Converter.

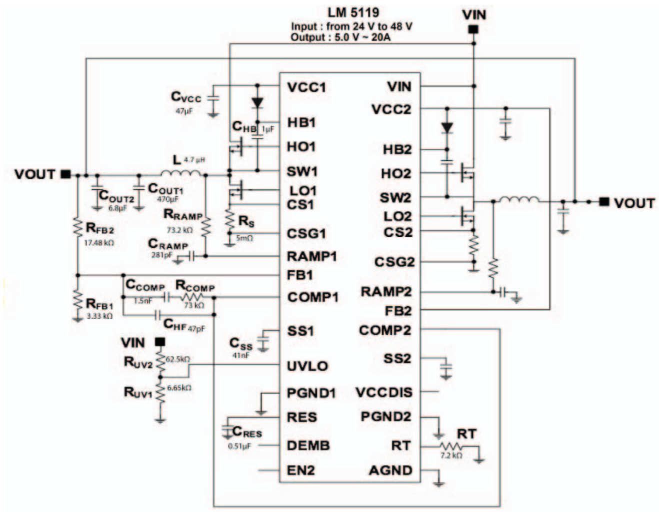

Fig. 6. Converter circuit schematic reflects the (24V to 48V input) to (5V @>20A) Converter.

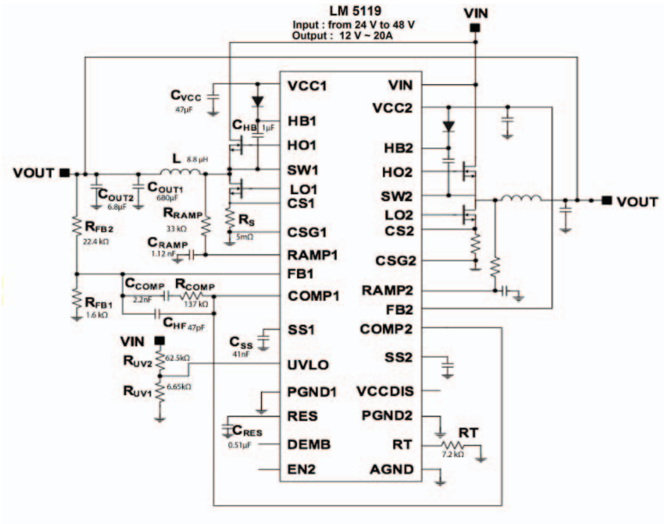

Fig. 7. Converter circuit schematic reflects the (24V to 48V input) to (12V @>20A) Converter.

VII. Circuit Thermal Considerations

Thermally, the above circuit has only three components generating significant amounts of current flow. Both the MOSFETs and the inductor have the output current flow through them and as such require thermal consideration. Utilizing design tools we can evaluate that the Mosfets can reach temperature, under full load and using only PCB layers for heat sink, above 180^{0}C [6].

TABLE II

Circuit Input	Mosfet	Est.Temp.@20A Using only PCB for Heat sink	Est.Temp.@20A Using SMD heatsink and forced air Flow
Output 3.3V	Q1	160~185 `C	62.5~ 87.5
Output 3.3V	Q2	160~185'C	62.5~ 87.5
Output 5V	Q1	160~185 `C	62.5~ 87.5
Output 5V	Q2	160~185 `C	62.5~ 87.5
Output 12V	Q1	160~185 `C	62.5~ 87.5
Output 12V	Q2	160~185 `C	62.5~ 87.5

GS61008T is a SMD Mosfet that contains a thermal pad on the top and allows the use of electric pad, on the bottom side, as limited thermal pad. Those pads connected to the copper planes within the board, achieves heat dispersion across PCB layers. In order to reach acceptable working temperature ratings (that takes in account also extra current transients that occurs during DC motor switching on operations), Power converters will utilize SMD Heat sinks for Mosfet top layers and fan cooling in addition to the PCB thermal layers. The temperature of the inductor is not a significant factor due to the nature of inductors. This power supply will require cooling when operating in the higher load regime. To increase efficiency, it is preferable that the cooling is not continuous but active only when required. To achieve this, a simple circuit has been created using a thermal sensing part and a P channel MOSFET. The AD6501 and AD6502, are analogue thermal sensing devices with hysteresis that is factory designed for a certain temperature. When this temperature is reached the voltage on the output then drops from logic high to logic low at a level of 5 volts to 0 volts. The technology used is an open drain transistor so this device requires a pull up on the output to operate correctly. A fail safe mechanism is envisaged as the image below depicts.

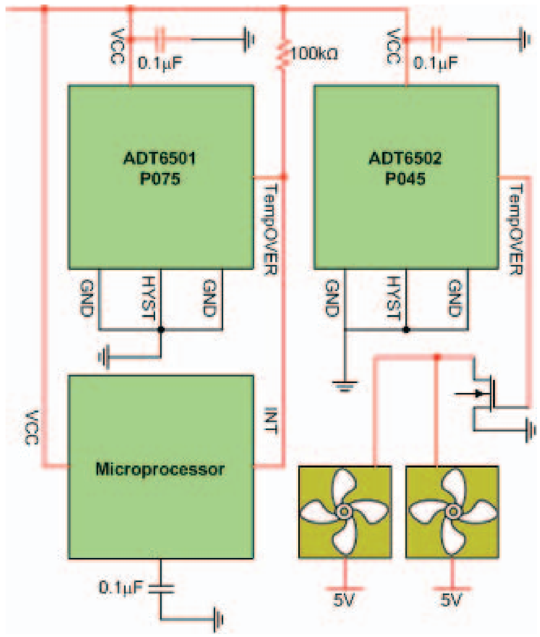

Fig.8. Flow through fan model for improvement of overall system thermal considerations.

The design tool was able to quickly calculate the expected characteristics of the three converters. The converters all had output voltage ripples below 25 mV, and an on time less than 3 microseconds. This will of course have to be tested in the final product to ensure the design is achieving its goals.

Overall, there are no expected issues in the regulation of this design. It is also expected for all designs to have greater than 90% efficiency in standard operation but this will also need to be verified. This efficiency is excellent and should far exceed commercially available products.

VIII. Phase Gain Analysis

The circuitry and design is an excellent industry standard component but as may be seen in the schematics of Figures 5 to 7 of the LM-5119 (circuit similar product) requires additional components in order to compensate for the error amplifier and to ensure stability. Correcting poles and zeros in the frequency domain to achieve the correct roll off and to filter out high frequency signals to maintain steady output without no spikes or instabilities is necessary. The graphs in Fig.8 are a representation of the gain and phase of error amplifier.

The design tool utilized allows for rapid selection of values for components and although the gain plot is not ideal it is well and truly adequate for stable operation. The Phase and Gain plots were simulated for the 3.3V, 5V and the 12V rails.

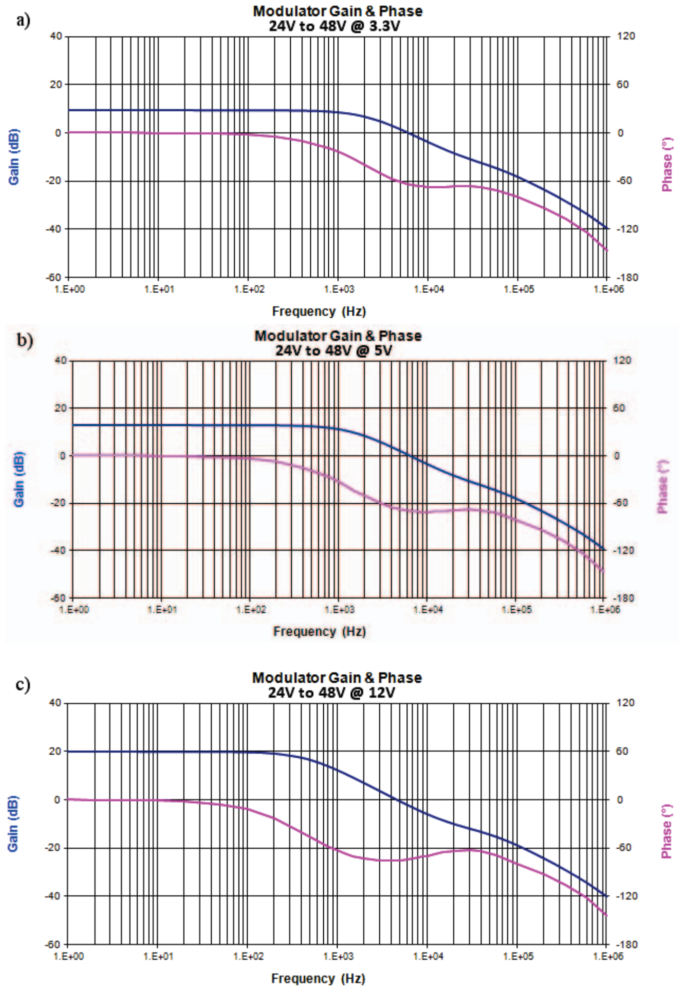

Fig.9. Phase and Gain Plots for 3.3v, 5v and 12v Rails.

IX. PCB Implementation

The system will be implemented utilizing surface mount devices on a four layer printed circuit board, which will be designed to allow sufficient onboard thermal relief in addition to surface mounted components. The printed circuit board for this device will be four layers of heavy layer copper. The top layer containing the majority of signal traces as well as a large amount of copper power planes to help reduce noise and increase thermal dissipation. The printed circuit boards must be hand assembled, easy to work on, dissipate the heat and be of a standard size. The size chosen for the circuit boards will be the approximate base size of a standard ATX power supply. Prior to commencement of the board an analysis must be done to consider all the energy requirements of the robot. ie: ensuring that all necessary voltage and current needs are met in the first stage of production. An example of this would be to evaluate the need for a forth converter as a variable input / variable output supply for ancillary or rather unforeseeable auxiliary systems.

It is clear from investigations that voltage outputs at the three indicated levels cover a majority of drives, microprocessor and manipulator requirement, however it may be prudent to consider further needs such as onboard visual, wireless accessories or sensor or lighting requirements.

X. Conclusion

The results of those various methods tested, combined with research of results obtained from other references have indicated that results should be more than satisfactory and are indicative that the methods proposed are sound and worthy of further research. As can be seen in Section VI the necessary PCBs have been produced and work continues to complete those parts. Completed construction of the prototype will allow accurate definitions of the mathematical allowances needed for the correct evaluation of the system in comparison to our previously performed analysis. Future work will continue with focus on completion of this work which adds to the efficacy of autonomous robots in open environments.

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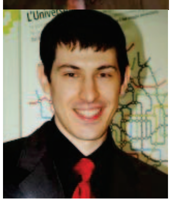
Biographies

Leslie Adrian received his Bachelors Diploma, Master's Diploma and Doctoral Degree at Riga Technical University, within the Faculties of Electronics and Telecommunications (FET) and Power and Electrical Engineering, Department of Power Electronics and Electrical Technologies (EEF).



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