Variable Speed Drive Design

ELEC4400 project report – 8/11/2020

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***Abstract*—Contained in this paper include the design methodology and component selection for a high power variable speed drive motor design. Selection of components was done on the merit of safety and efficiency according to the specification delivered by the course coordinator. Overall, the results delivered by the designed converter were shown to be satisfactory for the specification.**

I. Introduction

Amongst the realm of power electronics, power needs to be converted for various loads in an efficient manner. This report will detail the design of a power electronic converter to drive an resistor-inductor load of 1ohm and 0.1mH respectively. This power converter will be powered by a single phase mains voltage source of 220 V rms at a nominal frequency of 50Hz.

This power converter will be designed to following specifications:

- the current through the load must be between the values of 0A and 30A respectively.
- will drive the motor at frequencies between 500Hz and 5000Hz respectively

The motor will be driven according to the reference current in figure 4 of this report. Furthermore, the design of this converter will take into consideration applications of necessary safety features, fuses and harmonic distortion in order to create a suitable power converter.

II. AC-DC rectification

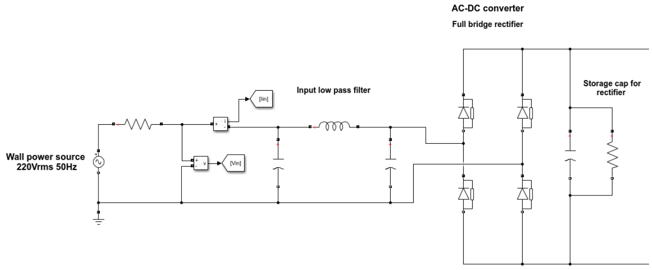

Figure 1: Input stage including low pass and full bridge rectifier

In order to safely and effectively convert voltage from the mains, the AC mains voltage must be converted to DC in order to be utilised in the PFC converter. Furthermore, this AC voltage source must be filtered from high frequency noise to protect other appliances connected to the local power grid are not distrubed and prevent excessive EMI emissions.

This was achieved through the use of a full bridge rectifier with a smoothing capacitor in regular configuration. The bridge rectifier was included as a single through hole package, model PB5006-E3/45 from Mouser. This part was relatively inexpensive, being only $5.19 hence there is little benefit for a discrete (4x) diode based rectifier.

The filter before the rectifier is a 3rd order LC filter with shunt capacitor values of 6.8μF and an inductor value of 500μH. The capacitor cost was negligible however the inductor needed to be capable of handling the high in-rush current. As such, the model 195C30 was chosen from mouser.com due to its max current rating of 30A. This component was $107.33.

This filter also aids the converter in reducing the harmonics of the grid side current.

III. Harmonic Filtering

Ensuring a good quality power factor at the grid-side is important to reduce total harmonic distortion (THD) in the input waveform and ensure that the device meets harmonics limits standards. Globally it is generally a requirement to obtain a grid-side THD below 4% on odd harmonics, however in this task the requirement is to obtain a THD below 40% on the third harmonic. To do this entirely with passive filters on the input would require a high-order LC filter and therefore have many components, which increases cost and PCB space; additionally the low grid-side frequencies mean the inductor values are quite large (~mH) and hence very bulky.

An alternative way to obtain very low THD's is to utilize an active filter, as shown in figure 1.

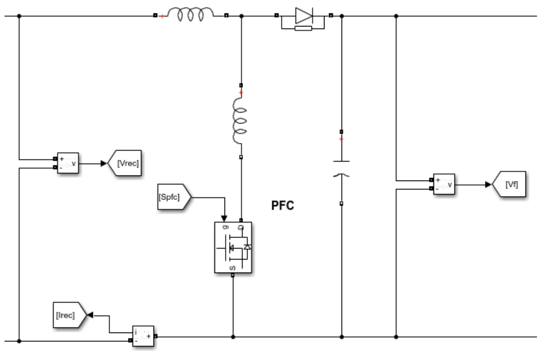

Figure 2. Boost converter connected after rectifier for active PFC correction (right).

In this project we utilised both a simple third order LC filter on the input grid-side as well as a boost converter after the rectifier to perform active filtering in order to obtain decent harmonic filtering. The switching device is operated at 100kHz, hence a mosfet is used since this can handle the high switching speed. The duty cycle of the mosfet is set by a controller which compares the dc-link voltage to a target value (300V), and then combines this to the rectified voltage and current waveforms to ensure the input waveform remains sinusoidal.

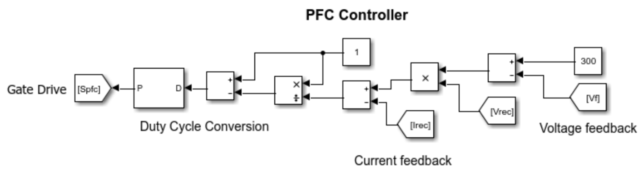

Figure 3. Control system for the PFC boost converter

The IPW60R031CFD7XKSA1 is a silicon based n-channel enhancement mosfet with a Vds breakdown voltage of 650V (sufficiently over the maximum operating voltage), very low on-state resistance (max 31mΩ) and a low gate charge of 141nC (important at high switching frequencies where it is directly proportional to gate-charge losses in bootstrapping circuit); additionally it comes in a small through-hole TO-247 package which can be directly mounted to a heat sink.

To choose a suitable diode, we must consider the power handling capability, hence the maximum current flowing through the diode is equivalent to the maximum output current, likewise the voltage rating should be above the maximum output voltage. Ideally a Schottky diode is preferred for this application due to the lower forward & reverse recovery losses versus a traditional pn diode. To obtain maximum efficiency from the converter we desire a diode with low forward voltage, hence the SBRT25U60SLP-13 with a forward voltage of 0.55V was chosen.

As for the inductor, assuming CCM operation, the inductance value selected for a given amount of current ripple on the output is,

$$L = V_{in}D/(2f_{sw}\Delta i_L)$$

Therefore if we assume the duty cycle is 50% (actually controlled by the controller), for a 100kHz switching frequency the minimum inductance value is 94uH, however in testing (and for supply reasons) this was set to 150uH. The part chosen for this role was the DKIH-3252-50D2 150uH inductor which has a maximum current rating of 50A.

The value of the capacitor used in this converter (ALS70A102KF630, 1000uF, 630VDC) was chosen based on simulation results of the output waveform but was also selected so it's rated voltage is well above the maximum output voltage and has a long ripple lifetime. As for the type of capacitor, a Aluminium electrolytic was used since they are better at handling transient behaviour, though typically have a much higher series impedance than film capacitors.

IV. DC-AC inverter

The DC-AC inverter is needed to regulate both the frequency and the amplitude of the load current. The inverter is shown on the figure below:

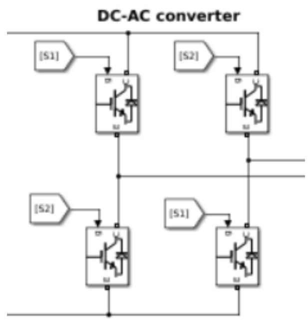

Figure 4. DC-AC inverter simulation model. Connected to the load on the right side

The control logic of the inverter is based on a relay scheme in order to keep the load current within a certain range of a reference signal. The computation of S1 and S2, the gate signals of the inverter, is done as follows:

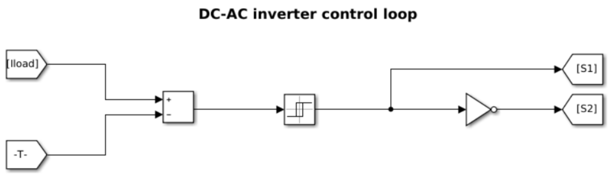

Figure 5. Control scheme of the inverter

The load current is compared to the reference signal created according to the specifications of the load current which are shown on the figure below:

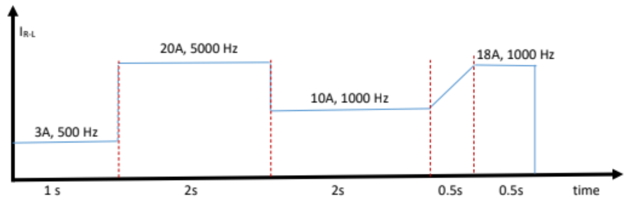

Figure 6. Load current characteristics

The relay specifies some upper and lower limits around the reference level, and if the load current reaches the lower limit then S1 becomes 1 and the voltage across the load becomes positive. Since

$$v = L\,\frac{di}{dt}$$

the current increases when the load voltage is positive. Once the load current reaches the upper limit set by the relay, S1 becomes 0 and S2 becomes 1, thus creating a negative voltage across the load and decreasing the load current. The only condition for this control logic to be functional is that the load current must have a rate of change high enough to keep up with the variations of the reference signal. In this case the fastest rate of change required is when the load current should have an amplitude of 20A at a 5kHz frequency. The highest derivative of a sine function with those characteristics is approximately 20A/(T/4)=400 000A/s since sin(x)<=x. The load inductance is L=0.1mH, so the necessary voltage to obtain that rate of change is given by Vl=400 000/L= 40V if we neglect the resistor. The voltage at the input of the converter is much higher than this approximated value so the load current will be able to keep up with the reference signal.

The quality of the signal can be adjusted by changing the values of the relay: a very narrow bandwidth in the relay will create a waveform very close to that of a sine wave (since the reference is a sine wave), but induces more switching operations, thus increasing the losses and potentially some parasitic noise. In this work we chose the limits of the relay to be +/-0.25 A from the reference value in order to have a reasonably sinusoidal waveform and as few switching operations as possible since it impacts the harmonies on the rest of the circuit.

The results are as expected matching to the created reference signal:

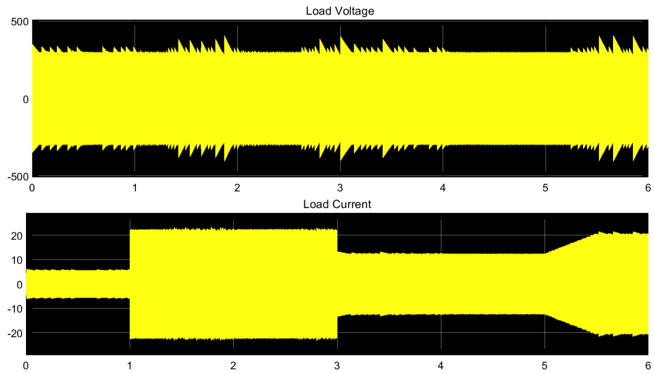

Figure 7: Load voltage and current

A close up shows that the waveform is close enough to a sine wave:

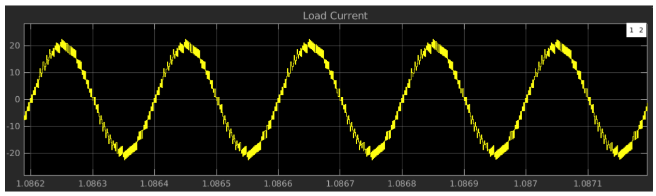

Figure 8: Close up on the load current

The cost of the inverter is not very high, 4 IGBT switches and 4 Schottky diodes are necessary, handling up to 400V and 40A. Each lot of IGBT switch plus diode costs around $7, so the total cost of the inverter would be around $28.

V. Protection Scheme

Included in the converter is a protection scheme that is controlled by the amplitude of the voltage between the PFC Converter and DC-AC converter. This circuit can be seen below:

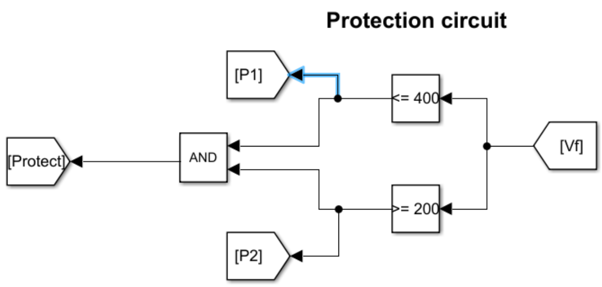

Figure 9: Protection Circuit for between main converters stages.

This protection scheme simply reads the DC-link voltage (across the capacitor of the PFC converter) and checks if it is greater than 400V or lower than 200V respectively. This then feeds the signal to a relay which would open the circuit if these conditions are met. Physical design of this would require a high-side ADC to measure this voltage.

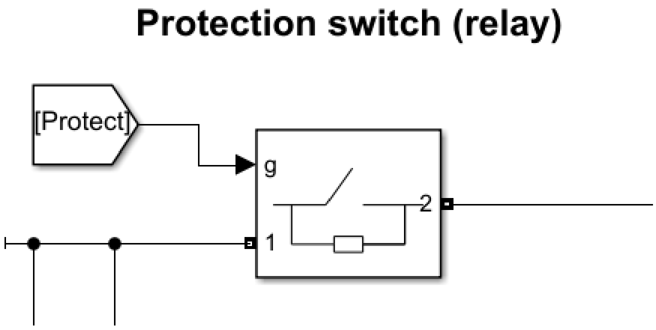

Figure 10: Protection relay connecting the PFC and Inverter stages of the converter.

Once this switch is opened, the load is disconnected from the grid and no current flows, ensuring safety. In order to handle the high currents and voltages from this region of the converter, a solution with high quality/reliability as well as high power handling capability was needed. A decision was made on the PM6760D50P model Solid-state Relay to handle this task. This component is priced roughly at $256.57 through Mouser.

VI. Conclusion

The specifications asked for a THD below 48% at the grid side, along with a DC component of the grid side's current below 1% and the 3rd harmonic of the current at the grid side should be below 40%. Figure 11, shows that the THD requirements are exceeded in every criteria with a THD of 4.55% and a 3rd order harmonic of 2%. It should be noted that this simulation did not take into account the parasitic resistances/capacitances/inductances involved with the different components or packages selected hence the real world performance of the system still needs to be verified.

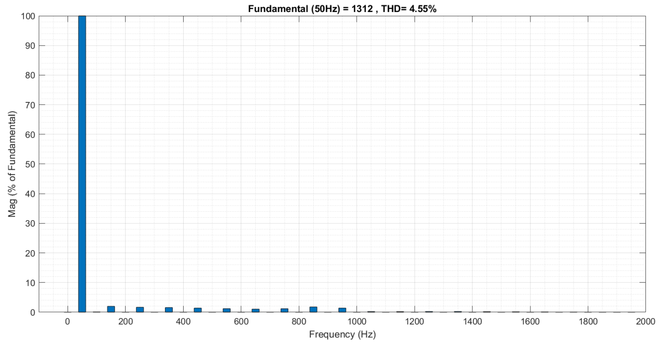

Figure 11: THD of the current at the grid side

The total cost of the design is $613.24. A full layout of the bill of materials can be seen in appendix 1. Commercially sold variable speed drives with comparable power ratings typically cost between $800-$2000 [8] hence our solution presents an attractive alternative (minus extra costs for heat-sinks, enclosures, manufacturing, ect.).

VII. References

[1] https://au.mouser.com/ProductDetail/Vishay-General-Semiconductor/PB5006-E3-45?qs=B7e2WOII5TrRZdGCClGdYg%3D%3D

[2] https://au.rs-online.com/web/p/igbts/1687071/

[3] https://au.rs-online.com/web/p/rectifier-diodes-schottky-diodes/1454280/71–350.

[4] https://au.rs-online.com/web/p/solid-state-relays/7761796/

[5] https://au.rs-online.com/web/p/polypropylene-film-capacitors/8829212/

[6] https://au.mouser.com/ProductDetail/Hammond-Manufacturing/195C30?qs=xaYn2CMR%2FYwcksgau7g37g%3D%3D

[7] https://au.mouser.com/ProductDetail/Crydom/PM6760D50P?qs=OTrKUuiFdkaJOIy8Bu%2FBTA%3D%3D

[8] https://mtmwarehouse.com.au/productlist/2800

VIII. Appendices

Appendix 1: Bill of Materials

Section	Component	Part number	SMD/Thru-Hole	Maximum voltage rating	Quantity	Unit Price (AUD)	Total Price (AUD)	Source	Link/RoHS
Rectifier	Bridge rectifier	PB5006-E3/45	Thru-Hole	600V	1	5.19	5.19	Mouser	
Buck converter	n-channel enhancement power mosfet	FDMS86350ET80	SMD		1	5.04	5.04	Mouser	RoHs compliant
	Schottky diode	SBRT25U60SLP-13	SMD		1	1.32	1.32	Mouser	RoHs compliant
	Power inductor	DKIH-3252-50D2	SMD		2	29.62	59.24	Mouser	RoHs compliant
	Bulk storage capacitor	ALS70A102KF630	Screw-in		1	40.96	40.96	Mouser	RoHs compliant
	Input film capacitor	ECW-FD2J185JB	Thru-Hole		1	2.09	2.09	Mouser	RoHs compliant
Inverter	IGBT	STGP20V60F	Thru-Hole	600V 40A	4	2.96	11.84	RS	RoHs compliant
	Diode	RURG3060	Thru-Hole	600V 30A	4	3.32	13.28	RS	RoHs compliant
Miscellaneous	Solid-state relay	CWU4850-10	Panel mount		1	107	107.00		
Low pass filter	Capacitor	B32672L1333J000	Thru-Hole	1.6 kV dc, 600 V ac	2	1.54	3.08	RS	RoHs compliant
	Inductor	195C30	chassis mount	30A	1	107.33	107.33	Mouser	RoHs compliant
Old	Solid-state Relay	PM6760D50P	Panel mount	600VAC/50A	1	256.87	256.87		
							0.00		
						Product cost:	613.24		
Total									