The EV market has grown substantially over the last decade. This market is likely to continue to grow as concerns over global warming rise. Thus, it is imperative to further develop EV systems. Perhaps the most important of these systems is the inverter. Since most EVs use an AC motor, inverters are needed to convert the battery DC to AC. Currently EVs use a single inverter, however multilevel converters have shown promise as a potential replacement in EVs. The purpose of this project was to design, simulate, and analyze the efficiency of a multilevel converter for an automotive engine.

Modular multilevel converters (MMC's) are commonly used in renewable energy applications. They are used to invert a DC power source into an AC source. Traditionally, this is done with a single inverter switching the full DC voltage on and off at a very high frequency. Since the whole DC source is turned on at once it creates harmonic distortion, and requires heavier filtering. By breaking the DC source into sections and switching each section sequentially, then there will be less distortion at the output. Figure 1 shows a typical output for a MMC with a with only twenty switches per reference wave cycle.

The submodule can be seen in figure 2 along with the control scheme.

Control Scheme

The tiered sine wave was generated by comparing the desired output waveform with carrier waves of different amplitude. The high-side of the half bridge will switch on when the sign wave is greater than its carrier wave. For the first module the switching will occur when the absolute value of the sign wave is greater than its carrier wave, and off it is less than its carrier wave. When the desired sign wave increases beyond the module voltage it will remain on while the next module begins switching based on its carrier wave. Figure 3 (a) shows an example of a four module carrier wave and desired sign wave. (b) shows the tiered module output as it increases/decreases beyond the carrier wave amplitudes.

Efficiency

The main efficiency advantage of an MMC is that it uses soft switching. In our model we used twelve submodules switching eight volts as opposed to 96V. This greatly reduces the switching losses. Since there is only one module switching at high frequency at a time the number of switches is nearly the same for a single inverter. Unfortunately, this comes at the cost of increased conduction losses as the output current will travel through all switches during peak voltage. Selecting good components is extremely important to increase efficiency. Since our main losses were conduction losses, choosing mosfets with low on resistance was a high priority.

For our model we chose the NVM15S19N40C4L mosfet for our submodules. This mosfet has extremely low on resistance at just .84 miliohms. It is rated at 40V/650A, and continuous 56A. We selected the UF3SC65007K4S 3C model for our inverter. This has a breakdown voltage of 650V and a continuous current of 120A. It also has a low on resistance of just 11 miliohms.

Efficiency will then be simulated using the following equation, \( \frac{\int \text{Voltage} \times \text{Current} \, dt}{\int \text{Voltage} \, dt} \). This will give us the efficiency of the system under typical driving cycle, as opposed to four separate efficiency data at different loads. Efficiency will be dependent on driving profile as not all users will drive the same driving cycle.

The DC bus was created by utilizing each of the three phases during high voltage periods. By putting the output of each tiered DC through a diode we ensured even load distribution between phases. The three phases also helps stabilize the DC bus as the input is essentially three evenly spaced ripples. A large capacitance is required to adequately stabilize the bus during load conditions. As the HVAC system draws more power the voltage ripple within the DC bus grows, however this can be mitigated with another DC to DC converter, or a larger capacitor.

Our MMC produced a very nice motor voltage sine wave with minimal harmonic distortion. This sine wave was produced without any filtering. However, it does resemble the reference wave as twelve submodules create 23 different voltage outcomes. Lower harmonic distortion given to the motor will increase the motor performance, in addition to reducing the filtering, and at switching frequency. The three phase voltage to the motor (no load) can be seen in figure 4 (a).

This output is affected by the efficiency of the system. As motor draws more current the voltage will decrease slightly. This can be seen in figure 4 (b). This is due to small voltage drops across each resistor. As \( I_{loads} \) increases the small voltage drops increase in each of the 28 mosfets. Additionally, the DC current draw will also increase the 24 submodule voltage drops. At full load the voltage drop is only about two volts bringing the peak voltage to 94V.

High current draw also has a big affect on the DC bus stabilization. As the HVAC system draws more power from the DC bus its voltage ripple increases. The DC bus in figure 5 has an HVAC load of 1KW drawing current from it and a ripple of 1.5V (bottom graph). The current supplied to the DC bus is evenly distributed amongst the three motor phases as seen in the top three graphs of figure 5.

To analyze the effects of MMC’s in an automotive environment a behavioral simulation will be used (Simulink). Using common parameters for light electric vehicles a twelve sub-module three phase model was created. Since driving conditions vary load demands will also vary. To accommodate this a driving profile was created to test the model under 1KW, 3KW, 6KW, and 10KW loads. The model parameters can be seen below:

- Motor=96V AC, 3phases, 0-10KW Load
- DC Bus=96V DC 0
- Motor=96V AC, 3phase, 0-10KW Load
- DC Bus=96V DC 0

We decided on a single star chopper topology (half bridge) to reduce switches/conduction losses, and a single inverter. The module voltage becomes 96/12 Submodules = 8V per Submodule. This enabled us to find lower voltage rated mosfets for each of our submodule. The submodules were connected in series to generate the 96V amplitude wave.

The overall efficiency of this system under can be seen in figure 6. The efficiency starts at low as power is needed to charge the DC bus capacitor, however, it quickly rises to above 99%. This occurs when the motor is drawing only 1KW of power. As the motor goes through its profile the efficiency begins to fall with higher load, however it ends at 98.5% at the end of the driving cycle.

**Analysis and Results**

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**Summary/Conclusions**

Modular multilevel converters have great potential in electric vehicle drive systems. Using SOC algorithms, they have the capability to aid in cell balancing, and have significantly less harmonic distortion. If properly implemented the efficiency can be as good or better than a single inverter due to soft switching. More work would need to be done in SOC estimation, cell balancing, module efficiency/component analysis, as well as using DC/DC converters to further stabilize the DC bus.

**Key References**


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