A Design for Three Phase Electronic Controller for Electric Motor Cycle Equivalent to 100-125 Cc Engine Power with Regenerative Braking System

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Abstract. Technology always have the potential to disruptive the society, especially electronics since this technology follows Moore Law s. Electric vehicle is predicted to change how individuals are going to do their daily commute. Electric motor cycle is an answer to eco-friendly transportation, economical in the operation and will be more affordable in the future for the people. One of the main component for this vehicle is the 3 phase motor controller. Three phase electric motor has an advantage of being light weight, low cost and more compact compare with dc motors with a comparable power. The design is featuring a regenerative braking system which brings back the mechanical energy back to the system on braking time hence a significant advantage to increase energy efficiency, since a major power lost is happening during braking on conventional vehicle. The design on purpose is using 100-125 cc equivalent of gasoline engine since this engine has the most market in Indonesia. Which is about 10 to 15 KW 3 phase AC motor.

1. Introduction

Today battery technology is already at a point where their power density is acceptable enough so it can be applied as a power source for an electric cycle from an already popular segment for Indonesia market (equivalent to an engine of about 125 cc). For this purpose it is needed that an electric motor is installed on the vehicle as a replacement to the gasoline engine. Electric motor generally can be divided into three types: DC motor, AC 1 phase motor, AC multi-phase motor. From these types AC 3 phase motor has advantages of relatively small dimension and light weight to a comparable power output, also simple design and the absence of a permanent magnet can have advantage on longer term hence a total low cost of ownership. Other advantage is 3 phase AC motor already has long establishment in the industrial sector. On the other hand the drawback of using this motor are the requirement of a complex power controller electronics since this type of motor usually powered by utility power as compared to battery powered.

The complexity of using three phase AC motor can be describe as follows:
First, how to provide a three phase power source from a battery which is a low voltage DC source. Second, how to control the power provided to motor by a gas throttle which is turned by user as needed.

The last is how to provide a regenerative braking, which is available when the gas throttle is released or turned in the opposite direction the system would change into an AC electricity generator which can save the power back to batteries. The other problem to address is how the design can handle power up to 15 BHP, as it is equivalent to 125cc gasoline engine.

2. Literature Review
One of the considered successful implementer of 3 phase AC system for high performance vehicle is a company called TESLA. Despite its successful debut which changed people mind about electric vehicle which were thought as clumsy and slow, their specification are not an open specification, clearly it is not easy to cope with what TESLA did, their product performance is state of the art as can be seen in figure 1.below.

![Figure 1. Tesla with 3 phase AC motor 380V system compare to current fastest street legal car[1].](image)

In principles only motor power and big battery packs with a bigger power electronics are the differences between Tesla’s and our approach in the design. So although later we are in the right direction.

In the subsections below are the design requirements and characteristic of each modules as part of the plan.

2.1 3 Phase AC motor characteristics
A 3 phase AC motor does not require an additional starting device to start spin. The stator is consist of three coils. The coils are arranged 120 degrees to one another so they together is providing a rotating magnetic field. The speed of this rotating magnetic field for a utility power provided is usually 50 or 60 rotation per second comparable to the AC utility frequency of 50 or 60 Hz. But for this design this rotating magnetic field speed is controlled so the speed can be very slow when the rotor is starting to spin to provide high torque and is directly affected by the gas throttle position. The maximum rotation speed can also exceed more than fabricated specification of the standard 3 phase AC motor when it is used at high speed, so adequate cooling i.e. air circulation, air scoop might be needed and also good lubrication. The effect on high speed for long term use is subject to another study.

2.2 12 V DC Power Source
When this design is implemented, there will be several 12 volts power source available on the market, from the most common PB batteries to Lithium ion batteries. If we assume to use common high
capacity PB battery then a 100AH battery can have an energy storage equivalent to 1.2 KW. Raw estimation of the total distance for this single source is about 30km. This can be increased with the use of larger battery. If the weight of the battery is an important parameter, then the lithium ion version of the power source can be used so far of the same voltage rating.

The weight of the battery essentially in effect proportional to reduce the travel distance in total. But with the regenerative braking, the weight and velocity of the vehicle is linearly converted to chemical energy. So the loss resulted by the weight of the battery is compensated by the braking effect and this in total is reducing the effect of adding the weight of the battery.

2.3 12 V Capacitor Bank

Every motorist might have already aware that character of power consumption from a typical vehicle is that the throttle will be turned a bit a lot when the vehicle started to move. This would mean that the electric current draw would be very high at this moment on the battery. This would eventually cause the battery voltage to drop, the voltage drop should be avoided since the power which can be delivered will also drop.

One way to reduce is by using a capacitor bank as a buffer. A PB battery would have a full charge open circuit voltage about 12.8V (100 percent charged) and empty at about 11.8 Volt. If the battery voltage drop which can be caused by load from the throttle which opened, the supply would eventually be cut off. The capacitor bank is calculated for this purpose to have a minimum energy stored up to 10Kwatts during 10 seconds of acceleration, or about 1000 Amps @12 volts. This is equivalent to 30-50 Farad of capacitance. This can be implemented using high performance capacitor bank or a supercapacitor.

Below in figure 2. The electronic system design is break into several modules.

![Figure 2. Modules of the Electronic Controller](image)

In subsections below are descriptions of each module on figure 2.

2.4 Inverter Module 12 V DC – 400 V DC

This module is needed to change low voltage power source into voltage that is used by 3 phase motor. This higher voltage means a thinner and lighter coil for the same power rating, and a more readily available 3 phase motor that is already available in the market. This also means a less bulky cabling
and connectors. The actual voltage used is 380V rated AC, a 400V is a DC voltage which is a peak voltage when converted to AC.

Inverter works by changing the DC 12V input into an AC 12 volts with tens of thousands hertz frequency. It is achievable by using high efficiency MOSFETs with a high frequency oscillators. This AC voltage then feed into a high frequency transformer with 400 AC output. The advantage of using high frequency is a smaller and lighter transformer since it is also using a ferrite core, and the energy which is converted is directly related to its working frequency resulting to a small but powerful transformer works in the tens of thousands of watts.

2.5 (Optional) 400 DC Power Supply
The main input is the 12 Volts supply, but beside it a direct 400 DC volts input also can be implemented with a potential to eliminate the previous inverter module. This is achievable with a 400DC battery, a battery with a voltage this high can be made by serially connect 100 lithium ion batteries of the popular 16850 series. Lithium-ion (Li-ion) battery has a 3 times power density of PB batteries at the same weight. A maximum one cell voltage (at full charge) of Li-ion is 4.2 volts and at empty the open circuit voltage is 3.6 volts. As a consequences at full charge the voltage of 100 li-ion connected serially is about 420 volts. This higher voltage can be ramped of by programming the arduino on the PWM conversion so there would be no full width conversion during a full charge battery condition to avoid over powering the 3 phase motor and overheating it. This also can be seen as an advantage of having a turbo-mode for the motor so far as its temperature is continually monitored. As we know from experience that full throttle from a motorist is happen only a couple of seconds during acceleration.

2.6 400 V DC – 3 phase AC 380 V Power Converter
This converter is an Arduino based with a script designed to representing a pseudo sinusoid of AC to the output of the arduino into the power MOSFETs which are connected each to a 400 DC source. The efficiency of the design is more than 95 percent, so the MOSFETs can be safely bolted into aluminium heat sinks to keep it at the operational level temperature (less than 85 degrees Celsius maximum). Since there are 3 phases of 120 degrees rotational cycle each, there are 3 pair of MOSFETS, 1 for each phase. Also there are 3 outputs from the Arduino controller one for each phase. The frequency is a 60 hertz as available in the market with 3 phase AC motors.

The converter can also set to be operated on a frequency variable mode. This means that the throttle control is achievable thru changing of the AC frequency. This can be implemented if it is enough testing and studying that the 3 phase motor selected can withstand AC frequency changing and able to operate at least on impulse to about 300 Hz or equivalent to 18000 RPM peak. Also might be achievable by changing the bearing and its lubrication on the motor axis with high performance one. Nevertheless both mode is programmed on the chip and can be selected as needed.

2.7 Arduino Based 3 phase AC Power Control (Throttle)
As its been stated, that the throttle can be used in two modes, first mode is using variable width of the Pulse Width Modulation (PWM) signal, also means the length of the signal activated per short pulse in one cycle, in one fix frequency cycle of 60 hertz. This mode is guaranteed to be compatible with most of available 3 phase AC motors on the market. This mode means that the energy is equivalent to be delivered in the small pulses in the active cycle of the sinusoid.

In the second mode, the throttle position is translated into the frequency of rotational AC sinusoid cycle, it is also means the rotational speed of the rotor inside the 3 phase motor which is following the rotational of the power cycling on the cage coil.

The throttle handle is made of a potentiometer, can be analogue or digital. Can be made directly in the axis of the throttle of the vehicle or indirectly connected with the cable as in conventional vehicle.

The throttle since software based can be made to include an electronic speed control to avoid speeding, and is hard to bypass since it is directly embedded in the core controller.
2.8 Regenerative Brake Power Converter (AC-> DC)
From our experience on riding conventional vehicle, motorist when do braking action is also put throttle at minimum position also. So this is also applied when the throttle at minimal position then the AC motor is not given power. At the same time the Arduino controller on the section of Regenerative Power module [2]will connect circuits on minimum one of the 3 phase electric motor terminal to the terminals of the regenerative power converter. When the brake light switch is ON then the rectifier diode circuit will rectify AC power generated on the motor and naturally the AC motor become an electric generator[3]. It might be on the next phase of research the braking power can be made variable according to the power of the user hand which applying brake with an intermediate electronic coupling module.

When the vehicle speed is more than 5 km/hour the brake effect is put maximally on the regenerative brake so the conversion power from mechanical to electricity is maximum[1]. But when the speed is lower than 5 km/hour and when the brake lever is push immediate and with maximum power then the conventional braking is working maximum also to avoid crash.

The high voltage generated from the motor is converted using a conventional power transformer for current design for simplicity reason directly to about 16 volts AC. The efficiency rating of the transformer is about 95% at 60Hz or 3600RPM, and better at lower speed. This low voltage AC is then converted to DC using standard diode bridge. This DC voltage is directly connected to Capacitor Bank Module.

2.9 Capacitor Bank Module
Capacitor Bank in the Regenerative Braking sub system is used as an energy accumulator[4]. This is required since the duration of the braking is relatively short or in pulses whereas the energy which can be gathered is equivalent to the momentum of the vehicle, which is relatively big, in the order of kilowatts per second. Since the AC motor is now functioning as generator, then as an assumption if the total masses of the vehicle plus the rider is 250 kg and total braking is 10 seconds, the braking is decelerating at 0.2 G, and then the calculation result about 10-20 Farad capacitor is required. The rated voltage for the capacitor is 16 volts related to 12 volt power supply system voltage.

During the time when there is no braking applied, an electronic switch automatically will transfer the energy from the capacitor to the battery[5], so the capacitor would be empty and ready for next braking session. An electronic circuit which stabilizes the output to about 12.8 volt is required regarding of the input voltage on the capacitor. This will make sure that all of the available power juice can be transferred optimally and make the capacitor empty to make sure its greatest room availability during next brake.

2.10 Electronic Switch for the Capacitor Bank
This electronic switch consist of a power MOSFETs which connected their gate pin to the output of Arduino (a might be independent than other, later all the arduinos might be merged into one), The Arduino in essence is monitoring the voltage of the capacitor bank and its rate of voltage increase. If the voltage is close to 16 volts then the power MOSFET is commanded by Arduino to open and transfer its energy to power circuit which translate any voltage in its input (0-16 volt) to a stabilized 12.8 volts output and this is connected directly to the 12 volt power supply.

With this kind of conversion then it can be guaranteed that the condition of the capacitor bank is always empty to be able to maximize the power storage availability on it. This is due to the fact that in capacitor, the percentage of energy stored is comparable to its voltage. So the capacitor should be emptied (0 volt) and all of its available energy is transferred to the power supply batteries.

Below are some of the integration and testing which is done after completing the modules above.

2.11 Module Level Testing & Integration
All of the modules mentioned above have been made passing criterions for them as part of the testing as in table 1. Voltage stability level shall be within 10 percent of the value stated during maximum
load, since some of these module is not the full scale module, especially the power modules. For example the IGBT MOSFETS used are rated for maximum 1000 W instead of 20KW for the full scale, the gate inputs the same for both and shall not affect the design. Load is made from a full resistive load of big resistors, capable to sink up to 1500 watts of power.

**Table 1. Some Testing Criterion for Modules**

| Voltage (open circuit /Full Load 1000 W) | Inverter 12V-400V DC | 400V DC – 3 phase AC 380 V Power Converter | AC Power Control (Throttle Power Electronics) | Regenerative Brake Power Converter (AC-> DC) | Electronic Switch for Capacitor Bank |
|----------------------------------------|----------------------|---------------------------------------------|----------------------------------------------|---------------------------------------------|-------------------------------------|
| 392V/355V                             | 378V/320V            | 360V (Full throttle)                        | N/A /not tested                              | 16 Volts max/ 0 V empty                    |
| Temperature (no load/full load) max spec. 85°C | 37°C/70°C | 42°C/73°C | 38°C/70°C | 37°C/70°C | 37°C/70°C |
| Currents (Max)                         | 3.2 Amps             | 3.1 Amps                                     | 2.9 Amps                                     | 3 Amps                                     | 124 Amps (Burst)                    |

3. **Discussion & Conclusion**

The design has been made into separate modules, to simplify mass production on the final design it is suggested to implement this on one PCB for compactness, efficiency and more robust product. Also suggested that the PCB is a multi-layered ground to protect against EMI. Current design also requires 5 different Arduinos. This might be simplified into one, or better replace the arduino with similar chipset.

4. **Acknowledgement**

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