Performing an electric vehicle conversion

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Abstract

This paper is written as the final activity of electric vehicle (EV) conversion trial done in our Center. Rooted from literature review and experience obtained from the retrofitting experiment, this paper explains what to be prepared in converting an EV, how to choose the components needed and how to assemble said components to form a retrofitted vehicle. By choosing suitable components appropriate with our needs, conversion can be done based on predicted vehicle performance we would like to achieve. Results recommends components to be prepared, the explanation for each component, and subsequently, steps to be conducted on performing an EV conversion.

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Keywords: electric vehicle; conversion, guidance; step by step; performance based

1. Introduction

As common knowledge, electric vehicle (EV) is promoted for its environmental friendly advantage in term of vehicle emission [1]. While debates are still running on the electricity source for its operation, EV in fact is gaining more support. Despite the energy source, EV benefit is clear [2]. Due to its range, EV is proven suitable for short distance travel like within city or within estate [3].

One major drawback of EV diffusion to local market is its high price [1]. That is one reason why conversion can be opted at the first place as reasonable solution to this problem. Moreover, since pioneer in EV adoption is actually endorse others application [4], it is important to start converting soon as it will exemplify others with real action. Hence promoting EV implementation and in turn supporting wider diffusion. Reflecting on high ownership cost of EV, retrofitting can be a made sense solution.

Retrofitting or converting conventional car to electric car offers several advantages. First, we still can use our old car, minimizing the cost of ownership of new electric car. Second, we promote greener life style, hence healthier environment. Speaking of drawback, like other electric vehicles, the available battery available now would not allow a long distance travel. Question arises is how to conduct an EV conversion? How to select vehicle spare parts and assemble them into a beautiful car called retrofitted EV?

This paper is written from experience, showing things to be prepared when conversion is about to be done and subsequently, the way to perform the conversion. It is aimed to provide a simple, easy to follow guidance on how to convert a traditional vehicle to its electric version. Further aim is to enrich the existing literature on retrofitting. Main topics covered are key components of EV and elaborated method to do a basic yet simple conversion.

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2. Material

The following components are parts used to convert a conventional car into electric vehicle in this study. There are several product choices available in the market for each component, actually. Therefore components should be chosen carefully according to kind of electric vehicle needed by the user. Components requirement for four passenger car would be different to those required by a truck.

2.1. Electric motor

In EV conversion, electric motor replaces ICE, delivering shaft forces from electrical energy conversion into mechanical energy to move transmission shaft. The advantage of using electric motor to ICE is the number of moving components becomes minimal. Electric motor possesses only three rotating components, which are rotor and two bearings[5]. ICE, on the other hand, employs tens of moving components. That is why electric motor is more efficient, simpler, durable and offering low maintenance cost.

There are three main electric motors for EV conversion purpose: DC motor, 3 phase induction motor, and Brushless DC (BLDC) motor. Those three are having different performance characteristics and efficiencies.

In general, motor DC used is from wound series. BLDC motor used is synchronous motor having permanent magnet for the rotor. Motor choice consideration should be based on their efficiency, power, wiring simplification and cost.

2.2. Motor controller

Motor controller specifically depends on the type of motor used. Motor controller functions to regulate the EV power requirement. Motor controller sometimes is called speed control due to the fact that visually indicated result on motor shaft is rotation variation caused by power regulation on motor controller. DC motor control is pulse-width modulation (PWM) duty drive given by motor controller.

To accommodate bigger power demand, beside power IC PWM amplifier can use transistor, MOSFET or IGBT[9]. Even several components already have IGBT power modules which make them simpler and more robust. Control for 3 phase induction motor and BLDC is similar in some way. Both of them use inverter transistor arrangement for all three phases. Difference lays on their inverter control strategy.

Every transistor is commanded by programmable control unit. Control is done based on input signal from acceleration pedal sensor, motor speed sensor, voltage and current. Control unit appropriately processes those signals into phases’ regulation of the electric motor.

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Table 1. Performance and efficiency of electric motors example

<table>
<thead>
<tr>
<th>Electric Motor type</th>
<th>efficiency (%)</th>
<th>max.power (kW)</th>
<th>max.torque (Nm)</th>
<th>battery (Vdc)</th>
<th>max.current (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC motor [6]</td>
<td>88</td>
<td>52</td>
<td>150</td>
<td>144</td>
<td>500</td>
</tr>
<tr>
<td>3 phase induction motor[7]</td>
<td>88</td>
<td>47</td>
<td>163</td>
<td>96</td>
<td>650</td>
</tr>
<tr>
<td>BLDC motor[8]</td>
<td>95</td>
<td>30</td>
<td>150</td>
<td>144</td>
<td>250</td>
</tr>
</tbody>
</table>
2.3. **Battery**

Battery works as the component for electricity energy storage. Like fuel tank for ICE, there are a number of batteries for EV applicable as EV conversion components. Every battery has its own advantages and disadvantages, depends on its characteristics and energy cost.

Lithium polymer would be the best choice since it has the highest energy specific, energy density and power density among others. For same capacity, battery with higher energy density creates more compact volume. However, its management system complexity is higher compared to lead acid. Lead acid merely embraces electrochemical reaction which does not need special arrangement to regulate the reaction. The reaction will naturally balance the potential in each cell of the battery.

![Three-phase inverter using gate controlled switches](image)

**Fig. 2.** Three-phase inverter using gate controlled switches[10]

Table 1. Main characteristics of various batteries[11]

<table>
<thead>
<tr>
<th>System</th>
<th>Voltage (V)</th>
<th>Specific Energy (Whkg⁻¹)</th>
<th>Energy Density (WhL⁻¹)</th>
<th>Power Density (Wkg⁻¹)</th>
<th>Specific Energy of Cell (Whkg⁻¹)</th>
<th>Specific Energy of Battery (100%SOC)(Whkg⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sealed lead-acid (LA)</td>
<td>2.1</td>
<td>30-40</td>
<td>60-75</td>
<td>180</td>
<td>20-35</td>
<td>20-35</td>
</tr>
<tr>
<td>Nickel-cadmium (Ni-Cd)</td>
<td>1.2</td>
<td>40-60</td>
<td>50-150</td>
<td>150</td>
<td>40-60</td>
<td>40-60</td>
</tr>
<tr>
<td>Nickel-metal hydride (Ni-MH)</td>
<td>1.2</td>
<td>30-80</td>
<td>140-300</td>
<td>250-1000</td>
<td>50-70</td>
<td>40-70</td>
</tr>
<tr>
<td>Lithium-ion LiCoO₂</td>
<td>3.6</td>
<td>160</td>
<td>270</td>
<td>1800</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lithium polymer</td>
<td>3.7</td>
<td>130-200</td>
<td>300</td>
<td>3000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lithium-ion LiFePO₄</td>
<td>3.25</td>
<td>80-120</td>
<td>170</td>
<td>1400</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2. Energy cost, advantages and disadvantages of various batteries

<table>
<thead>
<tr>
<th>System</th>
<th>Voltage(V)</th>
<th>Energy Cost (WhS⁻¹)</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sealed lead-acid (LA)</td>
<td>2.1</td>
<td>5-8</td>
<td>Cheap</td>
<td>Heavy</td>
</tr>
<tr>
<td>Nickel-cadmium (Ni-Cd)</td>
<td>1.2</td>
<td>2-4</td>
<td>Reliable, inexpensive, high discharge rate, good low temperature behaviour</td>
<td>Heavy, toxic material, memory effect</td>
</tr>
<tr>
<td>Nickel-metal hydride (Ni-MH)</td>
<td>1.2</td>
<td>1.4-2.8</td>
<td>High energy density, environment friendly</td>
<td>Higher internal resistance, gas formation, self-discharge</td>
</tr>
<tr>
<td>Lithium-ion LiCoO₂</td>
<td>3.6</td>
<td>3-5</td>
<td>High specific energy, lowself-discharge</td>
<td>Expensive, requires safety electronics</td>
</tr>
<tr>
<td>Lithium polymer</td>
<td>3.7</td>
<td>3-5</td>
<td>High specific energy, lowself-discharge</td>
<td>Expensive, requires safety electronics</td>
</tr>
<tr>
<td>Lithium-ion LiFePO₄</td>
<td>3.25</td>
<td>0.7-1.6</td>
<td>Safe</td>
<td>Technology in development</td>
</tr>
</tbody>
</table>
2.4. **Gearbox adapter plate**

The EV conversion base concept is substituting ICE drive system with electric drive system, hence all components, from transmission to wheel, still use OEM components. Adapter plate is a component that connects OEM transmission with electric motor. This component should be able to hold electric motor and transmission in its straight position. The shape and dimension of adapter plate vary for each vehicle.

2.5. **Accelerator sensor**

Accelerator sensor analogy in EV is throttle to ICE. The accelerator sensor functions to give input signal from driver’s feet to motor controller. Motor controller will regulate power produced by the motor proportionally to input received from acceleratorsensor. This sensor construction commonly is made from a potentiometer or Hall effect sensor. For potentiometer typed sensor is often called pot box.

2.6. **Power cable**

Power cable acts to transmit high power electrical energy from battery to motor controller. Power cable is different from vehicle body wiring due to its ability to transmit high voltage electricity and high current. Cable that can be applied for EV conversion is welding cable. Welding cable owns high current characteristics and flexible fibers, which eases installation within the vehicle. Cable choice should be made based on the requirement of current channel between battery and motor controller. Table 3 displays the recommended cable measure for EV conversion according to American Wire Gauge (AWG). More attention should be put on voltage decline ($V_D$) from cable resistance and power dissipation ($W_D$) which causes cable heat. When battery used is of high voltage, voltage decline will be insignificant; therefore AWG 2/0 can be used. Cable test of 1000 A for several seconds to one minute will increase cable heat extensively. Temperature upsurge will enlarge cable resistance which in turn will amplify the existing power dissipation[14].
Table 3. Cable parameters and calculated values

<table>
<thead>
<tr>
<th>AWG</th>
<th>Diameter</th>
<th>Ohm/1Kft</th>
<th>V_D†/10ft</th>
<th>W_D†/ft</th>
<th>Area/ft</th>
<th>W†/in²</th>
</tr>
</thead>
<tbody>
<tr>
<td>2/0</td>
<td>0.47” – 0.53”</td>
<td>0.0779</td>
<td>0.78V</td>
<td>78W</td>
<td>18 in²</td>
<td>4.3 W/in²</td>
</tr>
<tr>
<td>4/0</td>
<td>0.60” – 0.66”</td>
<td>0.0490</td>
<td>0.49V</td>
<td>49W</td>
<td>24.1 in²</td>
<td>2 W/in²</td>
</tr>
</tbody>
</table>

† at 1000 Amps of current

2.7. EV fuses and circuit breaker

EV fuses and circuit breaker are used as battery circuit protection when short circuit, component breakdown or too much current take place. When short circuit happens, fuses will stop the electric connection hence fire can be avoided. What differs EV fuses to another other fuses is its specific function in handling high DC voltage. Moreover, its ability to hold DC current is more dominant that for AC voltage.

2.8. Contactor

Contactor is the primary gate of electricity from battery to motor controller. Contactor is controlled electronically using control from motor controller or using ignition key activation. It works like relay, only that its electricity connector component enables high current delivery.

2.9. DC to DC converter

Electrical system in EV conversion should be provided according to vehicle standard. Headlamp, sign, dashboard and other features still use conventional vehicle system rule which is 12 VDC. For that reason, electricity supply for the energy source should be available. Electricity supply in EV conversion is fulfilled by DC to DC converter. This converter operates like alternator in ICE drive system, functions to supply electricity for lamps and battery accessories (12 V or 24 V).

Fig. 5. (a)High current fuse[15]; (b)Airpax Circuit Breaker 250A/160V[16]

Fig. 6. Kilovac LEV200 contactors[17]

Fig. 7. BRUSA BSC623-12V[18]
2.10. Volt meter, Ampere meter and SOC-meter

Indicators and meters are standardized equipments should be present in a vehicle. For a converted vehicle, beside basic meters and indicators like speedometer, odometer, rpm meter, and sign and lamp indicators, other meters should be added to make sure the driver get enough information for vehicle operation. They are voltmeter, ampere-meter and State Of Charge-meter/SOC-meter. Voltmeter is useful for the driver to find out the remaining voltage in the battery. Ampere-meter will show the current transmitted back and forth from the battery. SOC meter is like fuel meter in conventional vehicle. SOC monitors battery capacity in real time. Those three components are the minimum display should be placed in dashboard. Other meters and indicators can be attached to dashboard are indicators for motor temperature, motor controller, charging state, SOH, Time to Full during charging, Distance to Empty prediction and DCDC.

2.11. Auxiliary parts (vacuum pump, power steering pump and air conditioner compressor)

Auxiliary parts are optional components for EV conversion. This means some OEM vehicles could need those components while some other maybe not. Modern vehicles usually use vacuum booster as braking assist to strengthen braking forces. To keep braking optimum, EV conversion requires a vacuum pump functions similarly to its OEM counterparts. Thus an electric typed vacuum pump which takes energy from DC to DC converter supply is utilized. For vehicle with power steering, modification should be done on hydraulic pump component. Hydraulic pump driven by ICE pulley (OEM) is replaced by one moved by electric motor which called Electro-Hydraulic Power Steering (EHPS). One alternative is using Electric Power Steering (EPS) that has many advantages in optimizing the energy usage for power steering.

3. Method

EV conversion stands for changing ICE propulsion with electric propulsion. Therefore, practical steps are needed to ensure trouble free conversion. The following steps elaborated below are simple steps recommended in performing EV conversion. Some might view these steps as too many or too few.

3.1. Defining EV conversion kit

The vehicle to be converted determines the proper EV conversion kit that is about to use. Simple way to decide proper conversion kit is by finding out the GVWR (Gross Vehicle Weight Rating) or vehicle’s gross weight [12]. By knowing GVWR, we know the vehicle ability to get load. Based on GVWR threshold, the suitable voltage for the drive system can be calculated. System voltage influences battery specification. Normally, the higher the system voltage, the bigger battery capacity, hence bigger mass. This will put GVWR beyond one set by OEM. This condition is dangerous since suspension and vehicle frame structure can be damaged. Below is conversion example for some vehicle brands based on the voltage of propulsion system.

![Fig. 8. EV display - SOC [19]](image)

![Fig. 9. (1) Hella UP28 Vacuum Pump [20]; (2)EHPS pump[21]; (3) Masterflux air conditioner compressor[22]](image)
After voltage of the propulsion system is set, the next step is to select components for vehicle propulsion. On the whole conversion kit comprises of components mentioned in Chapter 2, main components for EV conversion minus auxiliary parts. Kit depends on the type of electric motor used. When DC brush motor is chosen, DC conversion kit should be used. In the case inductive AC motor is used, AC Induction Motor (ACIM) conversion kit should be employed. Furthermore, if BLDC motor is used, then the conversion kit should be BLDC package.

3.2. Preparing vehicle to be converted

Preparation is a crucial part in conversion step. This stage determines the smoothness of the next steps. Better preparation leads to time saving.

Things to be prepared are:

- IC engine overhaul
- detaching fuel tank and the channel
- removing radiator and the coolant
- tidying up cable around engine compartment

Once preparation is done, room dimensions to place battery and electrical component can be measured.

3.3. Designing the layout of conversion components

To obtain a good vehicle control, mass of conversion components should be distributed evenly to each vehicle axis, especially battery which has the biggest mass. Battery can be distributed to several centers of gravity of the vehicle. For instance, when the vehicle to be converted is a sedan with front wheel drive, 55% battery can be placed in engine compartment and 45% in the luggage compartment that will yield 55% front and 45% rear balances. Those number will in general offer good control to sedan.

Moment balance (M) equation in static condition can be used as guidance deciding the layout of conversion components.

\[ \sum M = 0 \]  

(1)

If F and R are the centers of front and rear wheel axis, then balance moments on those two points are \( M_F \) and \( M_R \).

\[ \sum M_F = 0 \]  

(2)

\[ \sum M_R = 0 \]  

(3)

Fig.10. Reactions produced by wheel due to vehicle gravity are \( M_F \) dan \( M_R \)
3.4. Creating adapter plate and battery pack

To achieve the appropriate shape and dimension of adapter plate, the shape and dimension of transmission that is about to be used should be known. Material strength and spaces between transmission shaft and electric motor, and flywheel position should be taken into account in designing adapter plate [23]. The cross section of transmission and electric motor can be identified using CNC indicator dial or manually by obtaining surface image to be processed using CAD afterward.

Battery pack is component acts as ‘container’ for primary battery. Besides being the pedestal structure for battery, this component functions as protector from collision, vibration and thermal conductor during battery charging and discharging. However, thing should be noted when designing battery pack are:

- When using flooded lead acid battery, always provide adequate room above the battery for air circulation, aquades refilling, and maintenance access. Room for air circulation is needed since throughout charging and discharging battery will release corrosive gas as the side result of reaction. That gas should be taken out as it will destruct steel construction or to avoid sulfation.
- In the event flooded lead acid battery is used, provide outlet for excess fluid. All through charging and discharging process gas emitted from the battery will be condensed and very cold, leaving residue among the batteries. That fluid is acid, hence corrosive. For that reason fluid outlet should be made available.
- A special protector which is corrosion resistant due to acid fluid from flooded lead acid battery is needed. That protector will lengthen economic life of the battery pack structure.

The above guidance is required when battery pack is made from metal substance that is sensitive to acid liquid.

3.5. Wiring

After all components are assembled to the converted vehicle, the subsequent step is wiring. First thing to be done is power cable installation. Sections use power cables are:

- Battery poles in series circuit
- Battery poles to motor controller
- Motor controller to electric motor
- Auxiliary parts using high current, like EHPS

When power cable is attached already, the next part to handle is control cables with low current. In this condition, do not turn fuse on and leave the circuit breaker off. Depends on conversion kit motor used, a start module might be necessary. Start module is used to activate EV conversion components using key of OEM standard. The components that should be active when key on are:

- motor controller
- DC to DC converter
- auxiliary parts covering electric vacuum pump, EHPS or EPS and ready state air conditioner

Several other functions can be added in start module are charger protector, Battery Management System (BMS) activation and security system. During wiring process, connections to primary battery and accessory battery (12V) are the last connections to be made to prevent short circuit coming from accident or wrong linkage.
3.6. First run and first test

When all is done, components, installation and wiring rechecking is important. The next step is first run which means the EV conversion operation for the first time. For first run guidance:

- Before turning the key on, pull the drive wheel (front or rear, depend on vehicle wheel drive) until it is above the the ground.
- Perform battery charging to make sure charger and wiring function properly.
- After charging is complete, release the charging plug then turn the key on. Make sure transmission in neutral position and parking brake is released. Push acceleration pedal slowly and observe the electric motor. Watch and take note of all abnormal indications on the motor like when motor shaft does not rotate, motor shaft rotates twisted or motor shaft moves abruptly. Those signs indicate that motor controller need tuning. If motor controller has tuning feature, then perform a tuning. Otherwise, an additional component is needed in order to perform tuning. If motor shaft rotates normally when wheel position is still pulled, perform clutch and transmission tests. Add gear and release clutch. Watch and take note when a problem takes place during gear shift. Perform clutch tuning when needed. Test and tune all components like vacuum pump, EHPS or EPS, air conditioner and BMS if lithium battery is used.
- After all seem normal, next stage is first test. Release the jack, move all wheel grips to make the wheel free. Add gear, push acceleration pedal slowly. Perform tests on some conditions like motor response, hilly road, big load and braking forces.
- After all are performed with satisfying result, EV conversion process is finished. Next procedure is establishing operation and maintenance manuals to make certain that users can gain full benefit.

4. Conclusion

Converting an EV can be a challenging task. However, when type of converted EV is already decided, all steps are understood, and requisite materials are already considered accordingly; initial phase can be started immediately. Choosing the right spare parts for every functional module should be done appropriately. Testing is the important step to be conducted once component assembly is finished. Further recommendation for EV conversion can be made on topics regarding best right spare parts for every functional module should be done appropr.

References