Optimum design of an EV/PHEV charging station with DC bus and storage system

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***Abstract* -- In this paper the optimum design of a fast-charging station for PHEVs and EVs is proposed to minimize the strain on the power grid while supplying the vehicles with the required power. By studying the power demand of the charging station, a conclusion is reached that the size of the grid tie can be reduced substantially by sizing the grid tie for the average rather than the peak power demand. Therefore the charging station architecture with a single AC/DC conversion and a DC distribution to DC/DC charging units is proposed. An energy storage system is connected to the DC bus to supply power when the demand exceeds the average that can be provided from the grid. Various topologies for both the AC/DC and DC/DC conversion are studied to find the optimum design for this application.**

Index Terms-- AC/DC conversion, bi-directional DC/DC converter charging station, energy storage system, EV PHEV.

I. Introduction

While electrically powered vehicles provide a promising solution for fuel economy improvement and emission reduction, the lack of recharging infrastructure is posing a problem to their mainstream acceptance. Due to the limited energy storage capacity of the on-board battery, the PHEVs will operate mostly in a blended mode thus limiting the environmental benefit and cost savings associated with the electric propulsion. On the other hand, in the case of an all electric vehicle the recharging issues make the use of the vehicle limited to short distances unless the recharging problem can be addressed. Therefore for electrically powered vehicles to provide the convenience of conventional vehicles with the environmental benefits there has to be a network of fast charging stations that can replenish the batteries in a time comparable to tank filling on conventional vehicles.

In this study we show that the grid tie capacity of the charging station can be significantly decreased by using architecture with common DC bus and energy storage system. A detailed procedure of optimization is given to find out the optimal value of the capacity of the charging station and the energy storage system. A cost efficient solution for AC/DC conversion is proposed, which has high power factor and low current distortion. A comparison of different topologies for DC/DC chargers is also presented and the most suitable topology for this application is chosen.

II. Study of Power Demand on EV/PHEV Charging Station

The SAE J1772 [1] defined common electric vehicle conductive charging system architecture. It covers the general physical, electrical, and performance requirements for the electric vehicle conductive charging system and coupler for use in North America. According to this SAE Recommended Practice, the charging methods for electrical vehicle are classified into three types, which are AC level 1, AC level 2 and DC charging. Table I summarizes the electrical requirements of the three charging levels.

The proposed charging station is comparable to gas station, which means it should be able to provide fast charging. The maximum power that can be provided by AC level charging is 7.7 kVA. For PHEVs and EVs, the capacity of the storage system can be as high as 60kWh, as described later, which makes it impossible to provide fast charging with AC level charging methods. So the DC charging leaves to be the only choice for the proposed charging station.

The capacity of the storage system in future PHEVs and EVs is kind of a mystery, since there is still no commercialized PHEV or EV in North America market by now. However, by considering the characteristics of the state-of-the-art energy sources, as shown in Table II, the capacity of the storage systems in regular vehicles can be estimated. For the middle size sedans, such as Chevrolet Impala, the vehicle glider mass is around 1000kg. We assume any storage system weighed more than 40% of the vehicle glider mass is unacceptable. So the maximum weight of the storage system is 400kg. With this assumption, the maximum capacity is given as 60kWh by using Li-ion battery which has the maximum energy density (150Wh/kg is used here).

To be comparable to the gas station, the charging station should be capable of fast charging with a charging rate of 3C to 5C. For the 60 kWh battery pack, the maximum charging rate should be 4C because the maximum power of the charger is limited to 240 kW, as shown in Table I. Suppose there are 10 charging slots in the charging station, then the worst case is that all 10 vehicles, each of which has a battery pack of 60 kWh with the State-of-Charge (SoC) of 20%, arrive at the same time and begin to charge with the charging rate of 4C.

TABLE I
ELECTRICAL RATINGS OF DIFFERENT CHARGE METHOD (NORTH AMERICA) [1]

Charge Method	Nominal Supply Voltage(Volts)	Max. Current (Amps-continuous)	Max. Power (kW)	Branch Circuit Breaker rating (Amps)
AC Level 1	120 V AC, 1-phase	12 A	1.44	15 A (Min.)
AC Level 2	208 to 240 V AC, 1-phase	32 A	7.7	40 A
DC Charging	600 V DC maximum	400 A maximum	240	As required

TABLE II
CHARACTERISTIC OF ENERGY SOURCES [13-14]

Type	Energy Efficiency (%)	Energy Density (Wh/kg)	Power Density Sustained (W/kg)
Pb-Acid	70-80	20-35	25
Ni-Cd	60	40-60	140
Ni-MH	50-80	60-80	220
Li-ion	70-85	100-200	300-2000
Li-polymer	70	100-200	300-2000
Electrochemical cap.	90+	25-75	5,000-20,000

After one group finishing the charging, another group of vehicles with the same battery pack begin to charge with the same charging rate. However, it takes 1 minute for the transition of the two groups, during which all chargers are not working. Assume that Battery voltage is linearly proportional to battery SoC, and battery voltage is 80% of rated voltage when SoC is 0. Then the power demand profile for this worst case can be obtained, as shown in Fig. 1, from which it can be seen that the peak power demand is 2.4 MW and the average power demand is 2.05 MW.

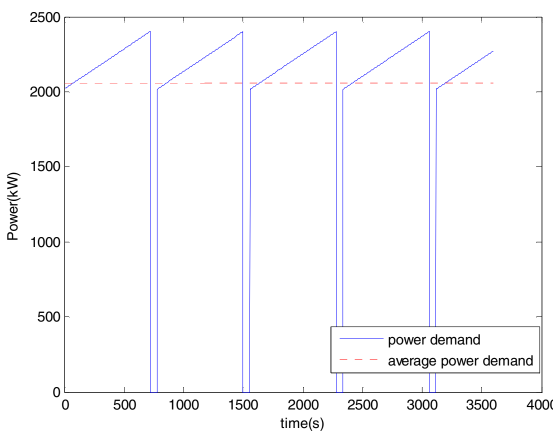


Fig. 1. Worst case scenario

Although it is highly unlikely to have such a worst case scenario in reality, it gives a preliminary understanding of the size of the charging station. If we are to install such stations throughout the city, the strain on the grid, and the hardware investment would be overwhelming. There would be a need to put in place additional capacity just to supply this unregulated and highly variable load.

III. OPTIMUM DESIGN OF THE POWER DELIVERY ARCHITECTURE

To sum up, the charging station will have 10 charging slots, and each of them has a capacity of 240 kW. To study the power demand of this charging station in a more realistic sense, the following assumptions are made:

(1) Battery State-of-Charge (SoC) range is 20%-50% (normally distributed with the mean of 35% and standard deviation of 7.5%).
(2) Battery voltage is linearly proportional to battery SoC, and battery voltage is 80% of rated voltage when SoC is zero.
(3) Battery capacity range is between 5kWh-60kWh (normally distributed with the mean of 32.5kWh and standard deviation of 13.75 kWh).
(4) Charge rate is between 3C-5C (normally distributed with the mean of 4C and standard deviation of 0.5C).
(5) The efficiency of the power transformation is not considered.
(6) All chargers will be working all the time except for the interval between one vehicle leaving and next vehicle starting to charge, which takes 3 minutes.

Based on these assumptions, a preliminary simulation of the operation of this system is performed to get the profile of the power demand. Fig. 2 is the simulation result which gives the power demand of this system in a cycle of 12 hours' operation. It should be mentioned that this scenario based on the assumptions above is going to happen in reality, however, it is not likely that it will last for 12 hours. In fact we expect this scenario to represent the worst case scenario that occurs during the peak use of the charging station.

From Fig. 2 it can be seen that the average power demand (942 kW) is significantly lower than the peak power demand (1678 kW). This profile suggests the possibility to 'smooth' the power demand and thus substantially reduce the grid tie

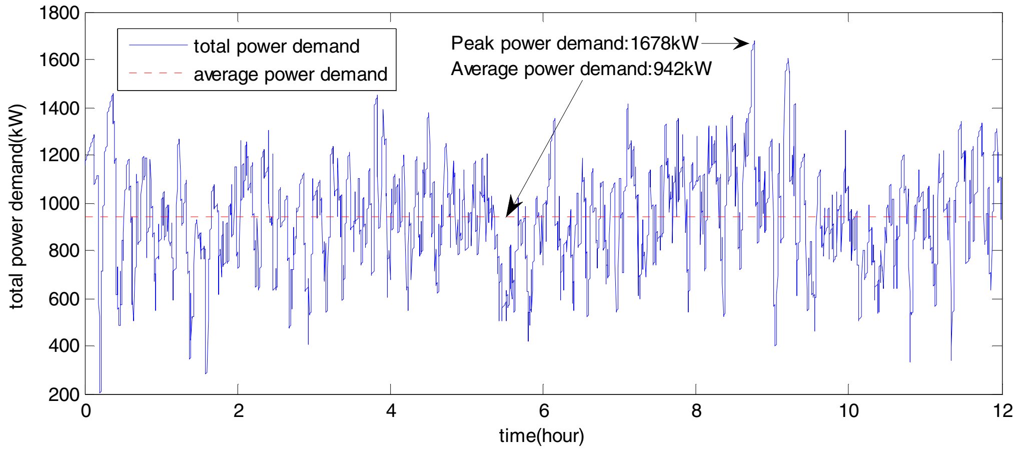


Fig. 2. Power requirement of the charging station

capacity. A straight forward way to achieve this is to size the grid tie at the average power demand level and have energy storage to 'smooth' power demand from grid. The energy storage will provide extra power when power demand is higher than the grid tie capacity, and will be charged when power demand is lower than the grid tie capacity.

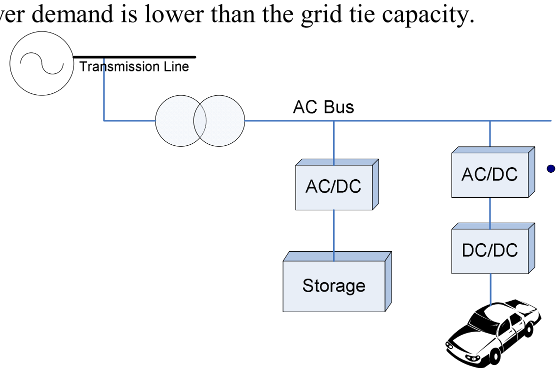


Fig. 3. Charging station architecture using AC bus

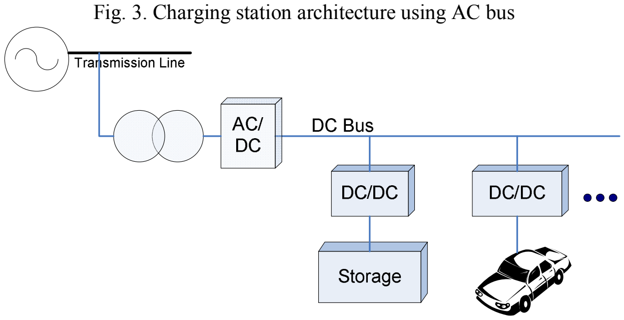


Fig. 4. Charging station architecture using DC bus

A bus is a necessity in this system to enable energy sharing between chargers. Fig. 3 and Fig. 4 give two candidate architectures based on AC bus and DC bus, respectively. From the practical point of view, the AC bus based system is preferred because AC system has been used for years and there are well developed standards and technologies available. However, DC bus based system provides a more convenient way to integrate renewable energy sources. Because both the sources and the DC loads are interfaced to a common DC bus, it requires fewer stages of power conversion and thus reduces losses and hardware costs. Moreover, the DC system utilizes one AC/DC converter instead of 10 smaller ones in the AC system, which is beneficial in terms of both efficiency and cost. So the DC bus based architecture is chosen for the charging station in question.

Some parameters need to be determined for the charging station, as given in Fig. 4. For the transformer primary voltage, 4160 V is recommended for plants with loads of less than 10 MVA [15]. For the secondary voltage and the DC bus voltage, application oriented considerations need to be taken into account. Generally, for high power load, higher voltage level is preferred to reduce the current. But for this application, the output voltage of the charger could be as low as 100V. If higher DC bus voltage is used, the charger would have to use a transformer to match the voltage level, which will significantly complicate the topology of the charger and increase the hardware cost. Therefore, the 480V line-to-line grid tie is considered, which gives 678V on the DC bus.

Based on the simulation result as given in Fig. 2, the power rating of the AC/DC converter is sized as 1.1 MW, which is slightly higher than the average power demand.

Another important component in this system is the energy storage, which has a significant impact on the load shape. A simulation was conducted to determine a proper capacity of the energy storage. The scenario for this simulation is that 10 vehicles, with different arrival time, come to the charging station for battery charging. The simulation ends when all 10 vehicles finish charging. Assumptions (1)-(5) in the beginning of this section apply here, with additional assumption that vehicle arrival time is between 0-5 minutes (normally distributed with the mean of 2.5 minutes and standard deviation of 1.25 minutes). During the simulation, if the power demand exceeds available power from DC bus, the extra power needed which should be provided by energy storage will be recorded, and finally get the needed storage power and capacity rating. Monte Carlo method is used here to get statistical results, as given in Table III. The results from each row of the table are based on 1000 simulations. For both

TABLE III
MONTE CARLO SIMULATION RESULTS FOR ENERGY STORAGE RATINGS

No.	Needed storage capacity (kWh)			Needed storage power (kW)		
	max.	mean	median	max.	mean	median
1	66.68	13.01	9.72	646.81	170.18	163.58
2	88.79	12.77	8.51	741.20	166.96	145.62
3	84.15	12.88	9.42	779.07	169.18	155.38
4	72.07	12.63	8.59	694.85	166.59	144.60
5	74.62	13.42	10.13	698.88	173.48	159.28

TABLE IV
OPERATION PERFORMANCE OF THE CHARGING STATION

No. of simulation	Average power demand(kW)	Delivered power over total power demand	Total customer served	Percentage of customers been delayed	Max. delay time(sec)	Average delay time(sec)
1	954	98.78%	515	66.99%	142	10.0
2	936	98.94%	516	63.95%	127	9.1
3	942	98.97%	511	61.64%	100	9.8
4	935	99.10%	516	65.50%	87	8.1
5	924	99.53%	511	59.10%	77	4.7

the storage power and capacity, the mean value is much lower than the maximum value. So it is not reasonable to size the storage with the maximum value to guarantee 100% satisfaction. Instead, sizing the storage based on the mean value would be much more cost-efficient. The mean value for needed storage capacity is roughly 13 kWh, and 170 kW for needed storage power. With this capacity-power combination, the best choice for the energy storage will be ultracapacitor. Because there will be a large voltage drop as the ultracapacitor discharges, it is assumed that only 50% of the voltage range is usable due to the limitations of the power electronics. With the 50% of the capacitor voltage range in use, 75% of the available energy is accessible. Based on the results from Table III, the capacity is chosen as 20 kWh, with 15 kWh are usable. The power limitation for ultracapacitors comes from the power electronics since ultracapacitors can be used at very high discharge rates, much above the 10C. According to Table III, the DC/DC converter for the ultracapacitor will be sized at 180 kW.

With the configurations as stated above, and assumption (1)-(6) as given in the beginning of this section, the operation of this charging station can be simulated. Table IV summarized the simulation results. Each simulation simulates a 12-hour operation of the charging station. It can be seen that with relatively small storage system (20 kWh with 15 kWh being usable) and AC/DC converter (1.1MW), more than 98% of the power demand is satisfied. The percentage of customers been delayed is pretty high, however, the average delayed time is no more than 10 seconds.

A further Monte Carlo simulation shows that if there is no energy storage, only 93.7% of the power demand can be delivered, and the average delayed time is 35.7 seconds (average value based on 10 operation cycles).

IV. TOPOLOGY SELECTION FOR AC/DC CONVERTER

The AC/DC converter has the power rating of 1.1 MW. At this power rating, the high frequency switching power converters may not be a good choice when considering the cost of high power high frequency switches. Several converters can be used in parallel to provide higher power, but this will complicate the system and thus deteriorate the reliability.

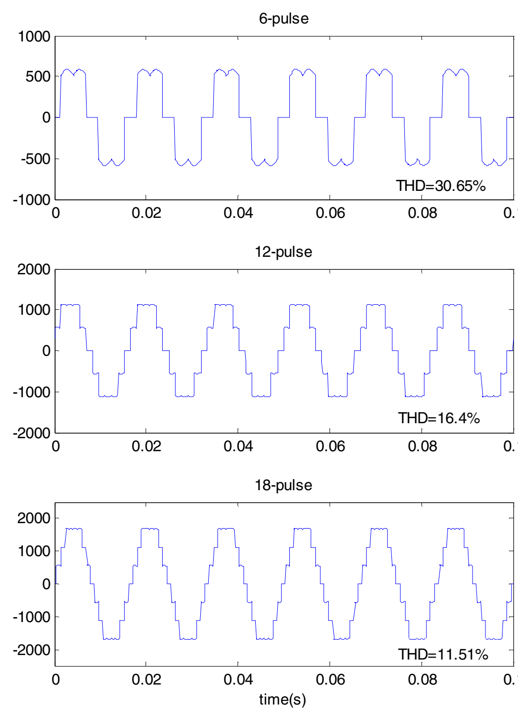
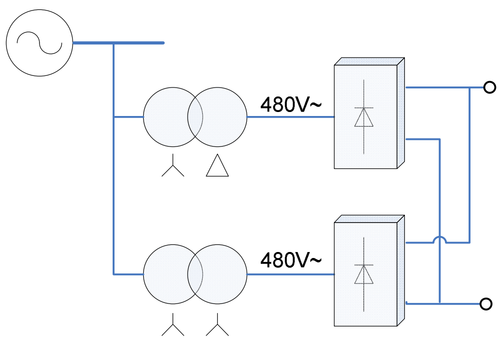


Fig. 5. Typical waveform of 6-pulse, 12-pulse, and 18-pulse diode rectifier

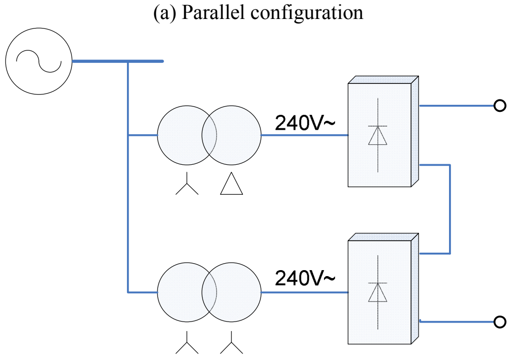
Diode rectifier is the simplest way in practice to convert AC source to DC source. Its high reliability and low cost makes it very competitive in high power rating applications.

However, it suffers from the high level input current harmonics and unregulated output voltage. For the charging station in question, a certain level of fluctuation on the DC bus is acceptable because the DC/DC charger can work under a large range of input voltage. So the only problem with the diode rectifier is how to eliminate harmonics.

One way to reduce harmonics is to increase the pulse number of the diode rectifier. Fig. 5 gives the typical input current waveform of the 6-pulse, 12-pulse and 18-pulse diode rectifier. The improvement of the rectifier by increasing the pulse is significant. However, neither of them can meet the IEEE 519 standard [12]. By using a dedicatedly designed transformer, the 18-pulse rectifier can have less than 3% total input current distortion [6]. But this kind of dedicatedly designed transformer is not easy to be manufactured in practice.



(a) Parallel configuration



(b) Series configuration
Fig. 6. Two types of configuration for 12-pulse diode

By introducing some modifications to the 12-pulse rectifier, the Total Harmonic Distortion (THD) of the input current can be reduced to less than 5% [2-5]. Thus 12-pulse rectifier along with harmonic control methods gives the most suitable solution for this application.

The 12-pulse diode rectifier utilizes two 6-pulse diode rectifiers to achieve harmonic cancellation. There are two ways to configure these two 6-pulse rectifiers, as shown in Fig. 6. In comparison with the series configuration, the parallel one has lower diode forward voltage drop, and thus is suitable for high current applications. However, proper measures need to be taken to balance the current between the paralleled rectifiers. The interphase transformer can be used to prevent instantaneous uneven DC voltages from two paralleled rectifiers [6]. But it has no effect on the steady state uneven DC voltage. Considering that the pre-existing voltage distortion in the AC source is the main reason for uneven DC output voltage, the Harmonic Blocking Reactors (HBR) can be used to block the pre-existing harmonics [2]. Note that the interphase transformer is inserted into the DC output and the HBRs are inserted into the AC input lines, which means all the load current will flow through the interphase transformer and all the input current will flow through the HBRs. Therefore, an increased conduction loss is expected and this may cancel out the advantage of lower diode conduction loss than series configuration.

On the other hand, the series configuration does not have the current sharing problem, and the increase in diode conduction loss may not be so significant. To confirm this, the diodes for both configurations are selected and their losses are calculated, as given in Table V. All the results are given under full load condition. Assume that the difference of reverse recovery and switching losses between these two setups is negligible. Then the total loss difference is 3938W. For a 1.1 MW system, this will cause a decrease of the efficiency by less than 0.36%. This is acceptable when considering the simplicity of the series configuration, not to mention that the interphase transformer and HBRs for the parallel configuration will also bring additional losses. So the series configuration of the 12-pulse diode rectifier is preferred for this charging station.

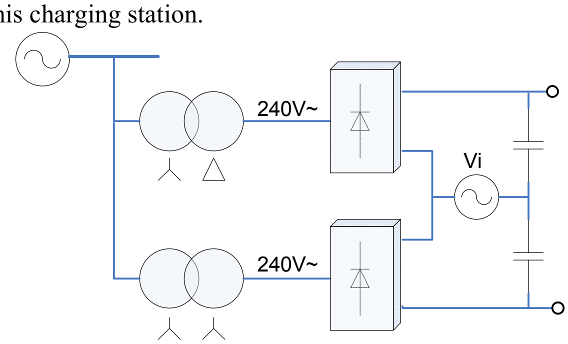


Fig. 7. 12-pulse diode rectifier with auxiliary-supply-assisted harmonic reduction

The next issue is the harmonic elimination of the rectifier. Fig. 5 shows that for a traditional 12-pulse diode rectifier the THD is still as high as 16.4%. A lot of work has been done to further eliminate harmonics in 12-pulse rectifier [3-5], [7-8]. A straight forward way is to have passive and/or active filters along with the rectifier [7-8]. This approach is not favorable because of the bulky passive components and the design complexity of the active filers. Other methods dedicatedly designed for the 12-pulse diode rectifiers are also proposed [3-5]. For the series connected 12-pulse diode rectifier, an Auxiliary Voltage Supply (AVS) can be inserted into the midpoint of the two 6-pulse rectifiers to shape the input current [5], as shown in Fig. 7. The AVS only needs to

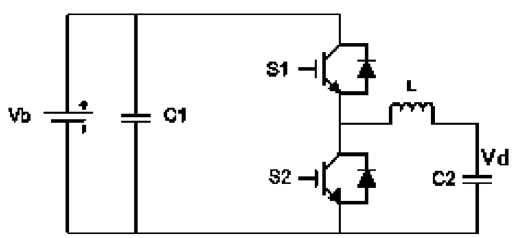
TABLE V
COMPARASION OF THE DIODE LOSSES FOR TWO CONFIGURATIONS

Rectifier configuration	Diode type	Diode current(rms)	Diode forward voltage drop	Conduction loss	Reverse leakage current	Reverse leakage loss	Total loss difference
Parallel	PD411211 (1100A/1200V)	382A	0.717V	3287W	200mA	768W	3938W
Series	PS410625 (2500A/600V)	764A	0.83V	7609W	200mA	384W	

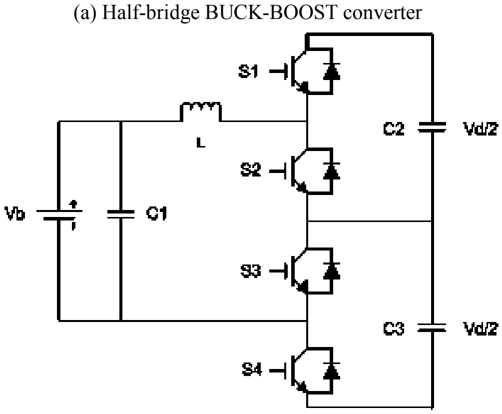
generate a rectangular voltage pulse with a frequency of 6 times of the line frequency, and the VA rating is less than 5% of the rectifier capacity. With this setup, the harmonic can be reduced to less than 5% at full load.

V. TOPOLOGY SELECTION FOR DC/DC CHARGERS

There are two types of chargers in this charging station. One is for charging/discharging the energy storage which should be a bi-directional converter. Another one is for charging the batteries, which could be unidirectional converter. Although V2G (Vehicle to Grid) technique is expected to be implemented in EVs and PHEVs in the near future, it is not likely that people will prefer to feed back power at a roadside charging station.



(a) Half-bridge BUCK-BOOST converter



(b) Three-level BUCK-BOOST converter

Fig. 8. Bi-directional DC/DC converters

For the bi-directional DC/DC converters, two topologies which are half-bridge BUCK-BOOST converter and three-level BUCK-BOOST converter, as shown in Fig. 8, are studied in detail [16] and the conclusions are:

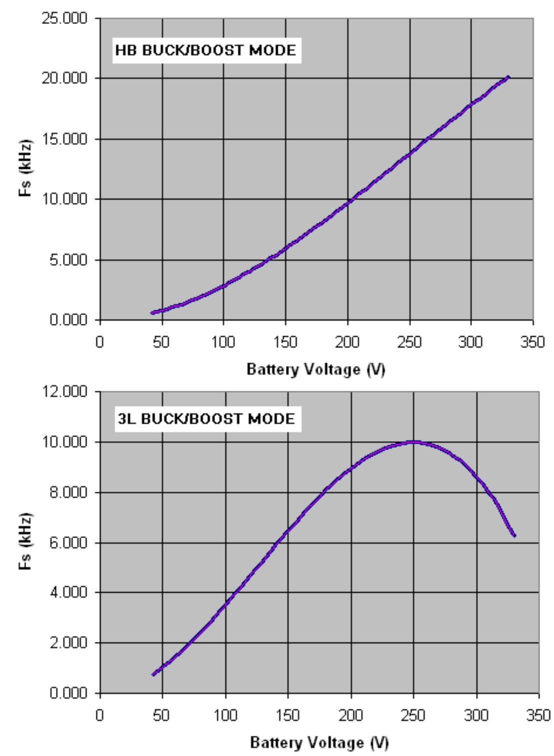


Fig. 9. Variable switching frequency strategy

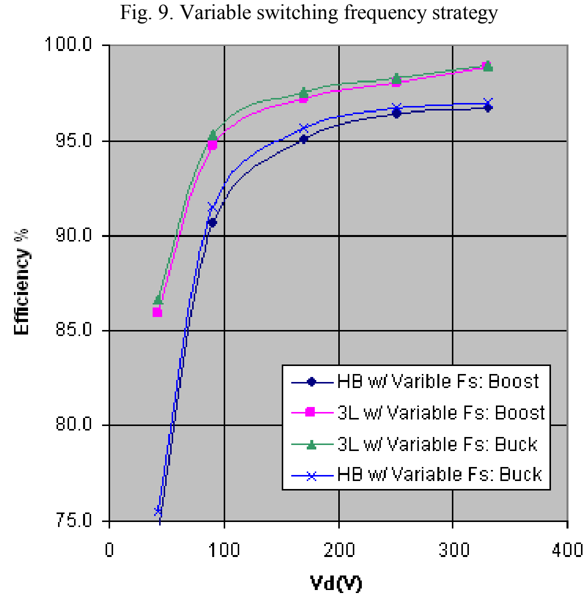


Fig. 10. Efficiency comparison of the three-level and Half bridge converter

- The voltage stress of switch and diode in three-level converter is half of that in half-bridge converter.

- To maintain the same inductor current ripple ratio, e.g. 30%.
  (a) The switching frequency in three-level converter can be much lower than that of half-bridge converter.
  (b) The inductor size in three-level converter is much smaller than that of half-bridge converter, e.g. 1/3.
- The current stress for power semiconductor devices and passive devices is similar in three-level and half-bridge converter.

Since this bi-directional DC/DC converter will be used to charge/discharge the ultracapacitor, the voltage range of V_d in Fig. 8 will be very large. When V_d is low the performance of the converter will get worse. For example, the inductor current ripple will increase because the duty ratio is small, and the efficiency will decrease because the output power is decreased but the losses do not decrease proportionally. To solve this problem, a variable frequency strategy is proposed [16]. Fig. 9 gives the relationship between switching frequency and battery voltage. With this frequency profile, the output current ripple is maintained constant with any output voltage. Fig. 10 gives the efficiency comparison of these two converters. It is clear that the three-level converter has higher efficiency both in BUCK and Boost mode.

By considering all the comparisons of these two converters, the three-level DC/DC converter has better performance almost in all aspects. So it will be chosen as the charger/discharger of the energy storage. One obvious disadvantage of the three-level converter is that it needs four switches while the half bridge converter only needs two. But the voltage stress on the switches used in half bridge converter is two times larger than that in three-level converter.

VI. CONCLUSIONS

The optimum design of a PHEV/EV charging station is proposed in this paper. The power demand of the charging station is studied. The results show that the power rating of this charging station can be reduced substantially by sizing it with the average rather than the peak power demand. By using an energy storage system, the charging station sized based on the average power demand can satisfy the power demand during most of the time. The 12-pulse diode rectifier is justified to be the most suitable topology for this application. To meet IEEE 519 standards, an Auxiliary Voltage Supply (AVS) is used to shape the input current and eliminate harmonics. For the DC/DC converters, the half bridge and three-level bi-directional converters are studied in detail. And the three-level converter shows better performance in almost all aspects. A variable switching frequency strategy is proposed to get better performance of the DC/DC converter.

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