Charging Facility Planning for Electric Vehicles

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***Abstract*—With the fast development and growth of Electric Vehicles (EV) in use, finding optimal locations for charging facilities became a critical issue since growth of EVs heavily depends on the availability of public charging facilities. Several researches have been done related to this topic considering optimal locations of charging stations on road networks. In this paper, we extend the problem by also taking into account optimal locations of charging pads which uses inductive charging technology. Flow Refueling Location Model (FRLM) was proposed to maximize the refueled traffic flow by allocating a fixed number of facilities, e.g., gas stations. This paper extends FRLM to consider both charging station and charging pad allocation to maximize the recharged EV flow. Evaluation on a sample network shows that deploying charging pads on road network enables us to capture more traffic flow compared to only locating charging stations. Charging pad deployment also significantly shortens the charging time spent by EV drivers.**

I. INTRODUCTION

Energy consumption and air pollution have become major concerns which lead to the development of electricity powered vehicles. Pure Electric Vehicle (EV) and Plugin Hybrid Electric Vehicle (PHEV) are two main types of vehicles being promoted to replace conventional fossil consuming vehicles [2]. It is forecasted that their market penetration will experience a significant increase in the following years [1], [6], [12], [14]. However, due to the limitation of driving range of a charged vehicle, the accessibility of public charging facilities is one key issue that restricts the widespread adoption of EVs [4].

Charging station is one type of charging facilities that is available on road network. However, the risks of charging stations such as electrocution and charger points become frozen on vehicles in extreme weathers advance the development of an inductive charging technique which is applied by charging pad [17]. The feature of charging pad is that it charges an EV wirelessly while an EV is driving above it, which overcomes the drawbacks of wired charging applied by charging stations. It is shown in [17] that charging pads provide a way to overcome the battery limitation.

In this paper, we focus on studying finding optimal locations both for charging stations and charging pads. The main difference between locating these two charging facilities is that charging stations are similar to conventional refueling stations, such as gas stations, and are assigned to intersections or points of interests of a road network. These locations are denoted by nodes in a graph. However, charging pads charge vehicles while they are in motion, meaning an EV is required to travel on a charging pad for a certain distance to get charged. This specific feature requires charging pads to be assigned to segments of roads instead of nodes.

The Flow Refueling Location Model (FRLM) [3], [9], [10] is a flow-based location-allocation model that aims at finding optimal locations for refueling stations. FRLM is categorized as a flow-based model because it treats serving demands as traffic flows between various origins and destinations with the goal of maximizing the amount of flows being refueled. One critical feature of this models is that it assumes vehicles stop at refueling stations on their preplanned trips instead of making a single purpose trip to refueling stations. Another feature is that the FRLM takes vehicle's driving range into consideration which is one crucial factor of EVs.

So far, several researches have concentrated on locating charging stations on road network [5], [8], [11], [15], [16]. To our best knowledge, this is the first paper studies locating charging pads on road network. In this paper, our main contributions are: 1) we extend FLRM in order to choose optimal locations for both charging station and charging pad on road network, 2) we compare the performances of locating charging pads and charging stations in terms of captured flow volumn, and 3) we discuss trade-offs of deploying charging pads compared to building charging stations.

This paper is structured as follows: in Section III we review the FRLM; in Section IV we introduce our extended FRLM to locate both charging stations and charging pads; in Section V we evaluate the extended FRLM on a 9-node network and compare its performance with the original FRLM that is capable of allocating only charging stations; and in Section VI we conclude the paper with a discussion on trade-offs between charging station and charging pad.

II. RELATED WORK

In [15], authors made decision on locations for new charging infrastructure by developing an agent-based decision support system which identifies patterns in residential EV ownership and driving activities. In [16], authors formulated a multi-objective optimization problem which considered EV owner's driving behavior to choose optimal locations for charging stations. The objective of the optimization problem consists of three sub-optimization problems with 3 goals: (i) minimizing the power losses; (ii) minimizing the node voltage deviations in the distribution network; and (iii) maximizing the utilization of charging stations. In [8], authors focused on finding optimal charging station locations for EVs in urbanized areas by developing a two-step model. The first step was transferring

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road information into data points and then clustering the data points into demand clusters. The second step was building an optimization problem given the clusters. In [5], researchers applied the flow capturing model to find optimal locations for charging stations. Two optimization problems were formulated separately. The first optimization problem followed the flow capturing approach to maximize the amount of flow that would be captured by the charging stations. The goal of the second optimization problem was to minimize the setup cost of charging stations while ensuring capture a minimum amount of flow. In [11], the authors formulated a mixed-integer linear programming problem to minimize the construction cost incurred when building stations. The constraints of the optimization problem ensured a minimum amount of flow being served.

III. REVIEW OF FRLM

Due to space constraints we only briefly review the Flow Refueling Location Model (FRLM) in this section, and refer the readers to [9] for detailed description.

The FRLM is a flow-based model which treats serving demands of road networks as traffic flows with various Origin-Destination (OD) pairs. Traffic flow is defined as the traffic flow volume passing a reference point during a given time period. The goal of FRLM is to serve as many flow as possible under specified constraints. FRLM applies a critical concept, combination, which is first introduced in [9]. A candidate combination is defined as a set of candidate locations to locate refueling facilities. Each candidate combination is either eligible or ineligible in terms of a specified OD pair. An eligible combination is a combination that can refuel vehicles driving a round trip between the OD pair without running out of fuel. Otherwise, the candidate combination is ineligible.

The FRLM consists of two major steps which are described in detail in [9] : 1) Generate and record all eligible combinations for all OD pairs on road network and outputs two matrices $\{a_{hp}\}$ and $\{b_{qh}\}$. Matrix $\{a_{hp}\}$ stores configuration of each combination with each row indicating a distinct combination and each column representing a candidate location. Entry $a_{hp} = 1$ if a refueling facility is located at location p, otherwise 0. Matrix $\{b_{qh}\}$ keeps track of eligibility of each combination in terms of each OD pair with each row of matrix $\{b_{qh}\}$ representing an OD pair, and each column representing a combination whose configuration is stored in matrix $\{a_{hp}\}$. Entry $b_{qh} = 1$ if combination h is eligible for OD pair q, otherwise 0. 2) Given the combinations generated, build an optimization problem to select combination(s).

IV. EXTENDED FRLM

As discussed in [2], charging stations share the same feature as traditional refueling stations that they can be assigned to nodes of a road network. However, charging pads charge EVs while EVs are driving above them [17] which implies that the charging capability of a charging pad depends on its length. Therefore, we assign charging stations to nodes (points of interest) and charging pads to links (roads).

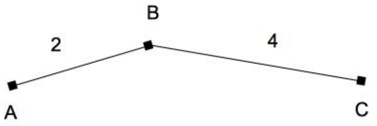

Fig. 1. A path consists of two links and three nodes.

To clarify the meaning of combination, we use the short path in Figure 1 as an example. Number two and four indicate the length of corresponding links. All candidate combinations are listed under the following three situation:

- If we only locate charging stations, then the candidate combinations are {A}, {B}, {C}, {A,B}, {A,C}, {B,C}, {A,B,C}. Candidate combination {A} means that a charging station is assigned to node A.
- If we only locate charging pads, then the following subset of links constitute all candidate combinations {AB}, {BC}, {AB,BC}. Candidate combination {AB} means that a charging pad is assigned to link AB.
- If we locate both charging stations and charging pads, then candidate combinations are all possible combinations of two candidate combinations, each from the above two separate lists. Note that we exclude the combinations where we assign charging pads to a link and charging station to one of its end-point. For example, combination {A,AB} is not considered a candidate combination since node A is assigned with a charging station and is on link AB where has a charging pad.
  The reason of setting this criteria is to decrease the size of the set of candidate combinations. The intuition behind this is the maximum flow refueling objective will not be achieved by having overlapping charging facilities since spreading them would have a higher chance of serving more flows. Thus we suspect that, even though all candidate combinations including those with overlapping facilities were fed into the optimization solver, they should be eliminated eventually.Therefore, we are pre-excluding these combinations to reduce the burden of optimization solver.

To test eligibility of candidate combinations, we need to consider the driving range of EVs. Since an EV can be charged while moving above charging pads, we assume that the State-of-Charge (SoC) of EV's battery remains the same while moving on links with charging pads. In addition, we make the following three assumptions about EV battery status before or after charging: 1) Assume the vehicle's driving range is five units when fully refueled. In other words, the full fuel range is five. 2) A vehicle gets fully refueled after passing a refueling station. 3) A vehicle's starting fuel range is full fuel range if a refueling station is located at the origin of its trip. Otherwise, its starting fuel range is half the full fuel range.

The extended FRLM shares the same two steps as the FRLM which are discussed in detail in the two following sections.

A. Eligible combination generation

An algorithm is developed in [9] which considers combinations only consists of nodes. In this section, we extend the algorithm so that it takes both nodes and links into consideration in order to model charging station and charging pad allocation.

Due to the effect that considering all possible combinations of links and nodes, the number of candidate combinations explodes which results in a large decision space for the optimization problem formulated in the second step. Instead of treating each single link as a candidate site to assign charging pads, we treat each OD pair as an entity to assign charging pads. To be more specific, in Figure 1, we do not consider assigning charging pads to either link AB or link AC but to assign charging pads to the entire AC path. As long as the OD pair AC is chosen to assign charging pads, link AB and link AC both get assigned.

Inputs of the algorithm are the network topology and driving range of EV, and produces two matrices $\{a_{hp}\}$ and $\{b_{qh}\}$ which have the same meaning as in Section III. The algorithm is as follows:

Step 1: initialization. Generate shortest paths for all OD pairs and store their corresponding nodes and links. Keep a list of all OD pairs Q.

Step 2: select OD pairs as candidate paths to assign charging pads. Given a network with more than one OD pair, select a subset of OD pairs, R, to be candidate paths.

Step 3: initialize matrix $\{\mathbf{a_{hp}}\}$ ***as an empty matrix with number of*** $\mathbf{n}$ ***columns where*** $\mathbf{n}$ ***is the summation of the number of candidate nodes and the number of candidate paths.***

Step 4: generate candidate combinations for all OD pairs.

1) Begin with the first OD pair q on the list of Q.
2) List all candidate combinations when assigning charging stations only.
3) If q is one of the candidate paths, list the combinations of q assigned with charging pads only and the combinations of assigning both charging pads and charing stations.
4) Repeat the above two steps until candidate combinations are generated for all OD pairs in Q. And record all combinations in matrix a_{hp}.

Step 5: check eligibility for all combinations.

1) Initialize matrix b_{qh} with entries all zero. And Initialize the starting fuel range.
2) Begin with the first candidate combination h and the first OD pair q. Generate a round trip q_r for OD pair q.
3) If any links of path q_r in combination h is assigned with charging pad, update the energy cost of corresponding links to zero.
4) Check if combination h is eligible for OD pair q.
    - Start from origin node and move to the next node on the round trip path q_r. Update the remaining fuel range by subtracting the fuel cost from the remaining fuel range at previous node.
    - If the remaining fuel range is negative. We reached the conclusion that the combination h is not able to refuel path q. Leave $b_{qh} = 0$ as initialized. Go check the next combination for path q.
    - If the remaining fuel range is nonnegative, check the three followings: 1) If the current node is destination node of path q and there is a charging station at the destination node, this combination is eligible. Set $b_{qh} = 1$ and proceed to the next combination. 2) If the current node is the origin then this is an eligible combination. Set $b_{qh} = 1$ and continue with the next combination. 3) If the current node has a charging station, update the remaining fuel range to full fuel range.
    - Move to the next node and repeat the same procedures until the round trip is checked.
5) Repeat the above steps until the eligibility of all combinations have been evaluated for all OD pairs.

Step 6: remove combinations which are supersets of any other remaining combination. For instance, in Figure 1, combination {A,B,C} is a superset of combination {A,C}.

B. Optimization problem

After generating matrices $\{a_{hp}\}$ and $\{b_{qh}\}$, we formulate the problem into an optimization problem described below:

$$\text{maximize } Z = \sum_{q} f_q^T x_q \tag{1}$$

$$\text{s.t.} \sum_{h \in H} b_{qh} v_h \geq x_q, \ \forall q \in Q \tag{2}$$

$$a_{hp} y_p \geq v_h, \ \forall h \in H, \forall p \in P \tag{3}$$

$$\sum_{p \in P} y_p = c, \tag{4}$$

$$y_{p_n} + y_{p_r} \leq 1, \ \forall p_n \in p_r, \forall p_n \in P, \forall p_r \in P \tag{5}$$

$$x_q, y_p, v_h \in \{0, 1\}, \ \forall q, \forall h, \forall p \tag{6}$$

where q is index of OD pairs, Q is a set of all OD pairs, f_q is traffic flow (veh/hr) on the shortest path between OD pair q, x_q is 1 if flow f_q is refueled otherwise 0, b_{qh} is 1 if combination h could refuel flow f_q otherwise 0, h is index of combination, H is a set of all combinations, v_h is 1 if all facilities in combination h are selected to get assigned otherwise 0, p is index of candidate location, p_n is index of of candidate location which is a node, p_r is index of candidate location which is a candidate path, P is a set of all candidate locations, a_{hp} is 1 if a refueling facility is assigned to candidate location p in combination h otherwise 0. y_p is 1 if a refueling facility is assigned to candidate location p, c is fixed number of refueling facilities to locate on the network, p_n is index of of candidate location which is a node, p_r is index of candidate location which is a candidate path.

The objective is to maximize the refueled flow volume as described by Equation (1). Constraint (2) specifies that a flow f_q is considered refueled only when at least one of its eligible combination is selected. Constraint (3) specifies

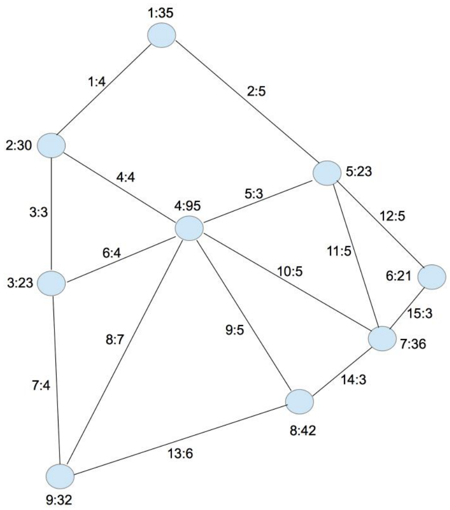

Fig. 2. A sample network with 9 nodes where A:B indicates that node (link) A has weight (length) B.

that an eligible combination is considered selected only when all of the facilities required by the combination are actually being assigned with refueling facilities. Constraint (4) fixes the total number of refueling facilities to locate on the network. Constraint (5) means that no overlapping of charging station and charging pad is allowed. Constraint (6) specifies that x_q, y_p and v_h are all binary variables. By restricting x_q to be either zero or one, it makes sure each refueled flow is counted at maximum one time.

V. EVALUATION

In this section, we evaluate the extended FRLM on a network, shown in Figure 2. We use A:B in which A represents the index of corresponding link or node and B denotes the weight of the node or length of the link.

The feature of this network is that node four is the center node which has the most weight while rest of the nodes share similar weights and the weights are apparently lower than node four.

Weights of nodes can be interpreted as their popularity. In other words, node four attracts most of the traffic flows traveling to the center. One real life example of this type of network is the city Berlin of Germany. Berlin is typically grouped into six districts with district Mitte in the center and the other five surrounding it. The center district Mitte attracts and generates large volumes of traffic flows into the center. Therefore, studying the network in Figure 2 helps us to have a better understanding on how the charging facilities should be located for such center-formed networks and later apply the model to similar cities.

This network has 36 flows, i.e., OD pairs, with the top five flows listed in Table I. As we can see from Table I, flows traveling from the center node 4 to other surrounding nodes have the top flow volumes which corresponds to the fact that center node 4 attracts and generates most of the flows.

TABLE I

TOP FLOWS OF THE 9-NODE NETWORK

Flow ID	O	D	Distance	Path	Volume (veh/hr)
25	4	8	5	4 → 8	1197
22	4	5	3	4 → 5	1092.5
10	2	4	4	2 → 4	1068.8
24	4	7	5	4 → 7	1026
34	7	8	3	7 → 8	756

TABLE II

REFUELED FLOWS WITH LINK 4, LINK 5, AND LINK 10 ASSIGNED WITH CHARGING PADS.

Flow ID	O	D	Distance	Path	Volume (veh/hr)
10	2	4	4	2 → 4	1068.8
11	2	5	7	2 → 4 → 5	147.86
13	2	7	9	2 → 4 → 7	180
22	4	5	3	4 → 5	1092.5
24	4	7	5	4 → 7	1026

When testing the extended FRLM model, we set the two variables as follows: 1) Number of facilities equals three. 2) Number of candidate paths equals five.

The reason of picking the above values for these two variables is to generate a sufficient amount of distinct combinations to choose from. We will later compare the affect of different numbers of charging facilities may have on the network.

We pick candidate paths based on flow volumes in decreasing order. Therefore, Flow 25, Flow 22, Flow 10, Flow 24, and Flow 34 are candidate paths to assign charging pads which are listed in Table I.

The optimal solution is to locate charging pads and charging pads only on the network. The configuration is assigning charging pads to Flow 10, Flow 22, and Flow 24. The corresponding links are Link 4, Link 5, and Link 10. The total amount of flow being refueled is 3515.1 (veh/hr). Details of refueled flows by this combination are listed in Table II.

Since we are locating three charging facilities on the network, the possible situations of charging pads and charging stations are:

- locate 3 charging pads,
- locate 2 charging pads and 1 charging station,
- locate 1 charging pad and 2 charging stations,
- locate 3 charging stations.

Next, we compare the performance of the optimal solutions each from the above situations in Table III:

As we can see from Table III, locating 3 charging pads on the network is doubling the amount of flows being refueled

TABLE III

MAXIMUM FLOW REFUELED UNDER VARIOUS SITUATIONS

# pad	# station	Configuration	Volume (veh/hr)
3	0	Link 4, Link 5, Link 10	3515.1
2	1	Link 4, Link 5, Node 1	2309.1
1	2	Node 1, Node 2, Link 5	2726.9
0	3	Node 1, Node 2, Node 4	1692.2

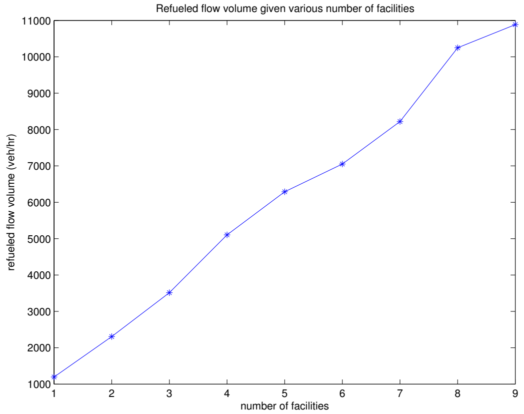

Fig. 3. Refueled flow volume given various number of facilities.

by locating charging stations only.

Next, we compare the charging time, i.e. contact time, when placing charging stations and charging pads. Suppose we study EV model of Nissan Leaf driving between OD pair node 2 and node 7. The battery capacity of Nissan Leaf is $24kWh$ and its driving range is about 70 miles [7] which corresponds to the 5 unit of full fuel range we assumed previously. Scale the distance accordingly, then the distance of the round trip between this OD pair is 252 miles. Therefore, driving from this OD pair $2, 7$ requires at least 4 times of charging. Also, assume the speed limit is $70mile/hr$ meaning without stops, it takes 3.6 hours to complete the trip.

Given the fact that on-board charger on the Nissan Leaf is around 3kW [7], [13], so the time it takes to fully charge Nissan Leaf is about 8 hours. Further more, to complete the round trip between OD pair $2, 7$, it requires 32 hours of charging. Comparing with its pure driving time, 3.6 hours, this is a significant amount of time.

However, if locating charging pads between OD pair $2, 7$ which has the power level of $5kW$ with efficiency from AC to DC battery of 86% [17], as long as the vehicle drives on the path it does not need to stop for charging. This results in a huge saving in terms of time. Therefore, assigning charging pads to roads could be considered for those who have high traffic volumes or those who are required to have shorter travel time and higher efficiency.

Next, we show the effect of locating different number of facilities on the refueled traffic flow volumes.

As shown in Figure 3, the total amount of traffic flows being refueled increased with the number of charging facilities to locate. This meets our expectation since increasing accessibility of charging facilities by EVs enables EVs to travel longer distances. However, increasing the number of facilities on a network raises the building and management cost which is normally a limitation.

Also, discussions on comparison between the costs on building and managing charging stations and charging pads are not available. For now, the constraint which sets a fixed number of facilities to locate only helps us to roughly control the total cost but it is not precise. As long as these numbers are available, we could modify the optimization problem so that it suits better in practice.

VI. CONCLUSION

In this paper, we proposed an extended FRLM to find optimal location for both charging pads and charging stations. Our evaluation on a sample 9-node network suggests that allocating charging pads helps to charge significantly more EV traffic flows compared to allocating charging stations only. Also, by comparing the charging time required by charging stations and charging pads, it showed that charging pads performs better in terms of saving travel time.

REFERENCES

[1] Baha M. Al-Alawi and Thomas H. Bradley. Review of hybrid, plug-in hybrid, and electric vehicle market modeling studies. *Renewable and Sustainable Energy Reviews*, 21(0):190 – 203, 2013.

[2] A. Ayob, W.M.F.W. Mahmood, A. Mohamed, M.Z.C. Wanik, M.M. Siam, S. Sulaiman, A.H. Azit, and M.A. Mohamed Ali. Review on electric vehicle, battery charger, charging station and standards. *Research Journal of Applied Sciences, Engineering and Technology*, 7(2):364–373, 2014. cited By (since 1996)0.

[3] Ismail Capar and Michael Kuby. An efficient formulation of the flow refueling location model for alternative-fuel stations. *IIE Transactions*, 44(8):622 – 636, 2012.

[4] C.C. Chan. The state of the art of electric, hybrid, and fuel cell vehicles. *Proceedings of the IEEE*, 95(4):704–718, 2007. cited By (since 1996)428.

[5] M. Cruz-Zambrano, C. Corchero, L. Igualada-Gonzalez, and V. Bernardo. Optimal location of fast charging stations in barcelona: A flow-capturing approach. 2013. cited By (since 1996)0.

[6] Xiaohui Cui, Cheng Liu, Hoe Kyoung Kim, Shih-Chieh Kao, Mark A Tuttle, and Budhendra L Bhaduri. A multi agent-based framework for simulating household phev distribution and electric distribution network impact. *TRB Comittee on Transportation Energy (ADC70)*, 2010.

[7] J.G. Hayes, R.P.R. De Oliveira, S. Vaughan, and M.G. Egan. Simplified electric vehicle power train models and range estimation. 2011. cited By (since 1996)1.

[8] A. Ip, S. Fong, and E. Liu. Optimization for allocating bev recharging stations in urban areas by using hierarchical clustering. pages 460–465, 2010. cited By (since 1996)4.

[9] Michael Kuby and Seow Lim. The flow-refueling location problem for alternative-fuel vehicles. *Socio-Economic Planning Sciences*, 39(2):125 – 145, 2005.

[10] Michael Kuby, Lee Lines, Ronald Schultz, Zhixiao Xie, Jong-Geun Kim, and Seow Lim. Optimization of hydrogen stations in florida using the flow-refueling location model. *International Journal of Hydrogen Energy*, 34(15):6045 – 6064, 2009.

[11] A.Y.S. Lam, Y.-W. Leung, and X. Chu. Electric vehicle charging station placement. pages 510–515, 2013. cited By (since 1996)0.

[12] Karen Sikes, Thomas Gross, Zhenhong Lin, John Sullivan, Timothy Cleary, and Jake Ward. Plug-in hybrid electric vehicle market introduction study: final report. Technical report, Oak Ridge National Laboratory (ORNL), 2010.

[13] E. Sortomme and K.W. Cheung. Intelligent dispatch of electric vehicles performing vehicle-to-grid regulation. 2012. cited By (since 1996)3.

[14] John L Sullivan, IT Salmeen, and CP Simon. Phev marketplace penetration: An agent based simulation. 2009.

[15] T. Sweda and D. Klabjan. An agent-based decision support system for electric vehicle charging infrastructure deployment. 2011. cited By (since 1996)2.

[16] G. Wang, Z. Xu, F. Wen, and K.P. Wong. Traffic-constrained multiobjective planning of electric-vehicle charging stations. *IEEE Transactions on Power Delivery*, 28(4):2363–2372, 2013. cited By (since 1996)1.

[17] H.H. Wu, A. Gilchrist, K. Sealy, P. Israelsen, and J. Muhs. A review on inductive charging for electric vehicles. In *Electric Machines Drives Conference (IEMDC), 2011 IEEE International*, pages 143–147, May 2011.