Distribution Network Electric Vehicle Hosting Capacity Enhancement using an Optimal Power Flow Formulation

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by

Andres Enrique Avila Rojas

Advisor: Prof. Paulo Manuel De Oliveira De Jesus

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Thesis committee:

- **Advisor:** Paulo Manuel De Oliveira De Jesus, Associate Professor, Universidad de los Andes
- **Juror:** Mario Alberto Rios Mesias, Full Professor, Universidad de los Andes
- **Juror:** Manuel Alejandro Alvarez Perez, PhD Student position, Luleå University of Technology
To my parents...
Acknowledgments

“GOD Thank you for giving me the strength and encouragement during all the challenging moments in the process of completing this thesis. I am deeply grateful for your exceptional love and grace in my life”.

I would like to express my extreme gratitude to my advisor Paulo De Oliveira for all his encouragement and patience throughout this project. To my loved parents Edinson and Yully, and also to my dear sister Daniela, for getting up and pushing me to achieve all the goals in my mind.
I would like to extend my sincere thanks to all my fellow partners Daniel Restrepo, Fernando De La Rosa, Juan Bohorquez, Paula Osorio and Daniel Santos, thank you all for your daily support. To Universidad de los Andes and its staff for providing me with the tools and software necessary for the development of this work.

Don’t be pushed around by the fears in your mind. Be led by the dreams in your heart.

Roy T. Bennett, The Light in the Heart
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Abstract

This thesis presents a method based on an optimal power flow (OPF) procedure to determine the maximum Hosting Capacity (HC) of Electric Vehicles (EV) that can be supported by a distribution network. With a focus on the injection control of reactive power, it is possible to maximize the penetration of EV. The presented method is based on linearized power flow equations, allowing a significant reduction in the computational processing times. Two comparisons are presented. The first one is between a non-linear and a linear optimal power flow (OPF) method. Second one, it is comparative analysis between legacy iterative (non-optimized) method of HC and the proposed method. It is applied in the IEEE 13 node test feeder circuit showing its effectiveness and acceptable performance. Results demonstrate that the implemented method enhance the HC measured against a legacy HC method, and decrease the computational time measures against non-linear optimization methods.

Keywords: Hosting capacity, electric vehicle integration, radial distribution network, optimal power flow, linear power flow, overvoltage, undervoltage
1. Introduction

Electric vehicles (EV) provide a promising future for the next generation of transportation means. The market of this type of vehicles has grown in the last years, and an exponential increase is expected in the near future [21]. In many of the EV connection scenarios, demand is expected to be supplied by the residential electrical distribution system. Therefore, without proper handling in the time charging and discharging of the storage systems in the EV, the high penetration ranges of EV increase the complexity of the operation and control of the power systems, introducing negative impacts on the stability, load balance, voltage levels, etc. [33, 40]; and therefore, influencing negatively the network reliability [39].

The hosting capacity (HC) concept has been proposed as an important tool for quantify the impact of distributed generation [7]. With the introduction of new technologies, such as EV, the HC is defined as the amount of new production or consumption connected to the grid where the first performance index reach its limit impacting negatively the network reliability [5].

In [17] the analysis of several EV penetration scenarios is presented, examining the effect on the power quality, specifically on the total harmonic distortion (THD), and the amount of additional power that the network needs to supply the new requirements. In order to improve the power quality and efficiency of the distribution systems, coordination and cooperation strategies between these distributed power electronics devices have been proposed. Strategies based on the theory of evolutionary dynamics have been developed in order to propose a flexible approach, where all the EV connected cooperate with each other in a scheme that allocates resources and actions fairly to balance the active power load and, partially, supply the reactive power demand of each phase of a distribution transformer [30]. Other strategies like load scheduling [18] or schemas of vehicle-to-grid (V2G) [38] are proposed as an idea to the control and management of EV loads by the power utility or by aggregators with communication between EV and power network.

These strategies are based on the EV technology direct participation, however, it has been developed methods to enhance the HC focused on the Distributed System Operator (DSO) participation. Some different techniques have been used to HC enhancement, such as network reconfiguration, active power curtailment or, optimal location and sizing of battery storage. However, these techniques could be only implemented in a planning framework due to the high economic cost that involves them. Furthermore, optimization tools have been introduced to obtain a maximum HC in distribution networks and to use the fullest of the network. Nonetheless, many of the optimization tools used are non-linear models which take a high computational cost. In that way, optimization tools with linear models have been performed to decrease computational cost (See Section 2).

Although linear model have been proposed, the controls implemented in these solutions take a long time framework for his action (Table 2.1) which is a drawback taking into account a real-time scale control. Moreover, the principal aim of linear model to optimization tools (faster solutions) is getting lost with the control actions implemented. In this way, this article presents the HC enhancement using the OPF approach by reactive power control in the EV connection nodes, assuming system full information by means of detection systems, such as micro-PMUs [25]. Further, the developed work implements a linearized model for the OPF problem which allows reducing computational times respect with non-linearized methods.

This paper is structured as follows. First, Section 2 is devoted to present a brief historical review of the application on HC. A theoretical framework for traditional iterative HC methods and AC-OPF non-linear is shown in Section 3. Section 4 presents the proposed methodology for HC maximization. The case study, results and analysis are shown in Section 5. Finally, conclusions and future work are drawn in Section 7.
2. State of Art or Thesis background

The concept of “hosting capacity”, in the context of electrical systems, was proposed by André Even in March 2004 during discussions for the integrated European EU-DEEP project [8, 13]. The idea of HC was later developed by Math Bollen in [4], in progress of the same project. However, the term was used in other contexts previously, such as in computer science, specifically in web servers allowing to define the ability to store many incoming access requests [9]. In [20,35] a first approach is given to the development of the HC concept in 2005. Nonetheless, the first officially definition found in literature was shown until 2008 [6]. The author defines HC as “the highest amount of distributed generation that can be integrated without the performance limit being violated”, a definition that would be supported and developed in [7].

To date, many studies have been developed with the calculation of HC, especially in distribution systems and focused on the new production of power that can be introduced to the network, for example, [24]. Recently the HC has been commonly used to evaluate the impact of EV chargers on the network [11,34]. Thus, the carrying capacity of the network has taken on greater importance in the definition of HC; therefore, the HC is defined as the amount of new production or consumption that can be connected to the network without damaging the reliability or power quality for other users [5]. The HC approach has been extended to present solutions to obtain a greater penetration capacity in the network. The introduction of a stochastic approach to HC concept, has allowed the development of impact analysis of distributed generation, especially because they allow to specify the possible locations of the future penetration that is expected to be added to the system [15,36]. In Figure 2.1 the concept of HC is illustrated and it is shown that enhancing the system allows a higher penetration capacity without exceeding the performance limits of the system.

![Figure 2.1: Hosting Capacity approach and the effect of its enhancement](image)

The methods mentioned above do not use control mechanisms that allow maximizing the use of network capacity for the inclusion of EV [15,31,31]. Therefore, the use of control tools without optimization methods for HC enhancement have been proposed [37]. The problem with this approach is the high economic cost [16], which makes this type of solutions unviable. In this sense, optimization tools have been implemented in order to fully use the available capacity of the network and reduce the economic costs. However, in studies such as [29,32] non-linear optimization models have been developed that slow down the computation times due to the inefficiency of non-linear solution methods. For this reason, linear optimization models have been proposed [41]. However, the linear optimization methods developed base their control actions on mechanisms that take an important time to activate [2], thus losing the time gained in the linearization of the model. Taking into account the approach of smart
Table 2.1: Executive resume for some HC studies

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Does any HC enhancement?</th>
<th>Does any optimization?</th>
<th>Optimization technique</th>
<th>HC enhancement technique</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>yes</td>
<td>no</td>
<td>Genetic algorithm</td>
<td>Network reconfiguration</td>
</tr>
<tr>
<td>[15]</td>
<td>yes</td>
<td>no</td>
<td>(non-linear)</td>
<td></td>
</tr>
<tr>
<td>[12]</td>
<td>x</td>
<td>x</td>
<td>-</td>
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<td>[10]</td>
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<td>x</td>
<td>-</td>
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<td>x</td>
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<td>x</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>[32]</td>
<td>x</td>
<td>x</td>
<td>Non-linear OPF</td>
<td>Optimal location</td>
</tr>
<tr>
<td>[29]</td>
<td>x</td>
<td>x</td>
<td>Linear OPF</td>
<td>Voltage control</td>
</tr>
<tr>
<td>This paper</td>
<td>x</td>
<td>x</td>
<td>Linear OPF</td>
<td>Reactive power control</td>
</tr>
</tbody>
</table>

networks, it seeks to achieve controls in the network in the real-time scale, for which, models such as those mentioned above become obsolete. Table 2.1 shows a resume of some HC techniques in the literature.

In [2] a linearized formulation of the OPF problem is presented, however, the paper is based on a network reconfiguration which is a shortcoming for the computational time reached with the linearization. Additionally, this only makes an analysis taking into account the nodes adjacent to the insertion of the EV, which is a drawback because the whole distribution system can be affected and must be taken into account for the analysis.

Many of the developments and analysis of hosting capacity in distribution systems are based on iterative processes. Incrementally, in each iteration, the penetration level in the network is changed until the selected performance measure leaves the acceptable region of operation. This methodology solves in each iteration the problem of power flow for the system, in order to evaluate the selected performance levels, which results in a high computational cost, making an immediate control action difficult to reach to the enhancement of the HC of the system. In this sense, the work developed have two principal contributions:

1. The HC enhancement is proposed using the OPF concept by reactive power control in the EV connection points. The aim of this contribution is improve the legacy HC calculation and obtain a higher EV penetration level. Integrating the spacial dependency of HC studies with OPF, it seeks to know the maximum HC for the greatest number of scenarios.

2. It is proposed the application of a linearized power flow method to the optimization process. Contrasting traditional non-linear power flow formulations, the linearized power flow does not require iterations to find a feasible solution which is an advantage to the computational efficiency.
3. Theoretical Framework

3.0.1 Legacy iterative Hosting Capacity Assessment

The location of the distributed generation and EV penetrations is a very influential factor to estimate the HC ranges of a distribution system. The impact of this type of elements connected near to the main feeders is significantly different (in terms of voltages and thermal conditions) than when they are connected downstream of the substation [28]. The method based on an iterative stochastic approach is one of the methods most recently used to study HC which give importance to the location of distributed generation. This approach starts with a base development of the power flow, which allows knowing the initial state of the network, and the impact of increasing the penetration of distributed generation. A general algorithm adapted from [15] for HC analysis is shown in Figure 3.1.

![Figure 3.1: Legacy method: Iterative stochastic algorithm](image)

To determine the EV penetration scenarios in the system, Monte Carlo simulations are used. This type of simulations is a stochastic numerical method used to approximate computationally complex mathematical expressions. Through a sequence of states that evolve due to random events, this method delivers calculations with a structure of a stochastic process. The stop criterion of this computational process will be given taking into account the coefficient of variation in each random iteration [22], determining the penetration power of each scenario. In this sense, it is expected to obtain a coefficient of variation of the nodes voltages in each iteration less than 1%. The coefficient of variation will be defined with the Bessel correction for the variance (See equation 3.1), which allows the correction of the statistical bias in this dispersion measure [27]. Figure 3.2 shown an example of convergence with this criterion.

\[
C_v = \frac{\sigma}{\bar{x}} = \frac{\sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (x_i - \bar{x})^2}}{|\bar{x}|} < 0.01
\] (3.1)
3.0.2 non-linearized AC optimal power flow

The general OPF problem is raised to minimizing the objective function $F(x,u)$, satisfying the constraints $g(x,u) = 0$ and $h(x,u) \leq 0$. Where $g(x,u)$ and $h(x,u)$ represent the non-linear equality constraints and non-linear inequality constraints, respectively. The vector $x$ contains the dependent variables and vector $u$ contains the control variables [26]. In this sense, the non-linear OPF problem for HC maximization is following showed:

$$\begin{align*}
\max_{i \in B_i} \sum_i |P_i^p| \\
s.t. \quad & P_{G_0}^p + \sum_{j \in L_i} P_{L_{ij}}^p + \sum_{i \in B_i} P_i^p = 0 \\
& Q_{G_0}^p + \sum_{j \in L_i} Q_{L_{ij}}^p + \sum_{i \in B_i} Q_i^p = 0 \\
& -S_{L_{ij}}^{p,Max} \leq S_{L_{ij}}^p \leq S_{L_{ij}}^{p,Max} \\
& S_{L_{ij}}^p = \sqrt{(P_{L_{ij}}^p)^2 + (Q_{L_{ij}}^p)^2} \\
& v_i^{Min} \leq v_i \leq v_i^{Max}
\end{align*}$$

(3.2)

Where $p=1,2,3$ corresponds to the phases.
4. Proposed Methodology

This section presents the formulation of the linearization method used, the OPF approach problem and the proposed method considering the EV location. For the study carried out on this paper, the voltage in p.u. is used as an evaluation criterion to the impact of the network. Taking into account the ANSI C84.1 standard, it will be said that the voltage in the system nodes must not be greater than 1.05 Vpu and must not be less than 0.95 Vpu. Additionally, it is worth mentioning that for this occasion two studies will be carried out (given the principle of EV) in the HC evaluation: (i) including additional generation to the system; (ii) including additional consumption to the system.

4.0.1 Power Flow Linearization

\[ V_0 = 1 \text{ Vpu} \]
\[ \theta_0 = 0^\circ \]

To determine the changes in the magnitudes and phases of the voltages, and the power flows in lines, the power flow must be solved. Most power flow methods at the distribution level are non-linear and must be solved iteratively. In order to reduce computation times in the analysis, linearization models of the power flow have been proposed [1, 23]. However, many of them are models based on ZIP loads, which is useless for modeling EV [14]. The model presented in this work is based on [3], where is present a linearization model for radial distribution systems (See Figure 4.1). It starts from the following equations of the non-linear model. The flow of active and reactive power in the line \( i,j \), respectively is,

\[ P_{L_{ij}} = g_{ij} v_i^2 - g_{ij} v_i v_j \cos(\theta_i - \theta_j) - b_{ij} v_i v_j \sin(\theta_i - \theta_j) \]  
\[ Q_{L_{ij}} = -b_{ij} v_i^2 + b_{ij} v_i v_j \cos(\theta_i - \theta_j) - g_{ij} v_i v_j \sin(\theta_i - \theta_j) \]  

Conductance \( g_{ij} \) and susceptance \( b_{ij} \) are obtained from the system’s admittance matrix. In steady state analysis of the system, it can be assumed that the magnitude and phase of the voltage at the interconnection point of the distribution system with the sub-transmission system are fixed and known. As shown in Figure 4.1 the voltage of this interconnection point or bus 0 is assumed as \( 1 \angle 0^\circ \). From there, all the magnitudes and phases of the downstream buses can be represented as a voltage deviation at the interconnection point.

\[ v_i = 1 + \Delta v_i \]  
\[ \theta_i = 0 + \Delta \theta_i \]  

Moreover, two assumptions are given in the linearization of the problem:

- The phase differences in the voltages are small, so the trigonometric functions can be approximated as follows:

\[ \sin(\theta_i - \theta_j) \approx \Delta \theta_i - \Delta \theta_j \]  
\[ \cos(\theta_i - \theta_j) \approx 1 \]  

Figure 4.1: Diagram of a general radial system
• Terms that include the product between $\Delta v$ and $\Delta \theta$ tend to zero, so they can be ignored. Therefore, $\Delta v_i \Delta \theta_i = \Delta v_j \Delta \theta_i = \Delta v_i \Delta \theta_j = \Delta v_j \Delta \theta_j \approx 0$.

Given the above assumptions, the following expressions for the flow of active and reactive power are obtained,

$$PL_{ij} = g_{ij}(1 + \Delta v_i)(\Delta v_i - \Delta v_j) - b_{ij}(\Delta \theta_i - \Delta \theta_j) \quad (4.7)$$

$$QL_{ij} = -b_{ij}(1 + \Delta v_i)(\Delta v_i - \Delta v_j) - g_{ij}(\Delta \theta_i - \Delta \theta_j) \quad (4.8)$$

![Figure 4.2: Removing non-linear term for the final approximation](image)

As can be noted, the expressions 4.7 and 4.8 are still non-linear. To eliminate the non-linearity present in these, proceed to follow the steps shown in Figure 4.2. First, the system is resolved without losses, i.e. $PL_{ij} + PL_{ji} = 0$ and $QL_{ij} + QL_{ji} = 0$. Which is an approximation to the expression $\Delta v_i$, which can be replaced in the non-linear term of the expressions 4.7 and 4.8. Obtaining a linearized system of the form:

$$PL_{ij} = g_{ij}(1 + \hat{\Delta} v_i)(\Delta v_i - \Delta v_j) - b_{ij}(\Delta \theta_i - \Delta \theta_j) \quad (4.9)$$

$$QL_{ij} = -b_{ij}(1 + \hat{\Delta} v_i)(\Delta v_i - \Delta v_j) - g_{ij}(\Delta \theta_i - \Delta \theta_j) \quad (4.10)$$

### 4.0.2 HC calculation with OPF

The aim of calculating HC in an OPF problem is to maximize EV penetration. Taking into account that one EV has the approach to inject and consume active power, the objective function will change depending on the type of analysis that is desired to obtain. In the case of analyzing the power injection to the system by EV, the objective function will be to maximize the active power injected in each node; while if its desire to analyze the consumption by the EV, the objective function will be to minimize the power injected into the nodes. In this way, it can know the case in which the distributed generation in each node is greater than the consumption and vice versa. In this way, the objective function is,

$$\max_{i \in B} \sum_i |P_{pi}^{p}| \quad (4.11)$$

Where $P_{pi}^{p} = P_{Gi}^{p} - P_{Di}^{p}$. Operating constraints of the system are:
\[ P^p_{G_0} + \sum_{j \in L_i} P^p_{ij} + \sum_{i \in B_i} P^p_i = 0 \]
\[ Q^p_{G_0} + \sum_{j \in L_i} Q^p_{ij} + \sum_{i \in B_i} Q^p_i = 0 \]
\[ -SL_{ij}^{p,Max} \leq SL_{ij}^p \leq SL_{ij}^{p,Max} \]
\[ SL_{ij}^p = \sqrt{(P^p_{ij})^2 + (Q^p_{ij})^2} \]
\[ \Delta V_i^{Min} \leq \Delta V_i \leq \Delta V_i^{Max} \]
\[ \Delta V_i^{Min} = V_i^{Min} - 1 \]
\[ \Delta V_i^{Max} = V_i^{Max} - 1 \]

(4.12)

Where the power flow in the line is given by the expressions 4.9 and 4.10 for each phase \( p \).

### 4.0.3 Method considering the EV location

Due to the scenarios are created taking into account only the variation of new penetration location, the simulation scenarios decrease considerably. In this way, making use of Monte Carlo simulations is useless in small-scale systems, such as the case under study on this occasion. However, in a large-scale system, where the possible locations are billions, simulations in a Monte Carlo approach must be considered. Figure 4.3 shows the algorithm followed for the maximization of the HC, where the EV location changes taking into account the matrix generated with the possible locations. With this procedure, it is possible to obtain a maximum HC for each EV penetration location scenario.

![Figure 4.3: HC process with OPF](image)

- **Start**
- **Read system data**
- **Location of EVs**
- **Run optimal power flow**
- **Show maximum HC and reactive control**
- **Stop**
5. Case Study

The distribution system used for this work is the IEEE 13 node test feeder circuit [19], an MV-LV system. In this, it will be assumed that the switch between buses ‘671’ and ‘692’ is closed during the instant time of simulation in a steady state. The system is shown in its detailed form in Figure 5.2. This highlights the candidate buses for the EV location. The system is simulated in OpenDSS, where the voltage profile obtained is shown in Figure 5.1. Table 5.1 shows the order and information of the buses in Figure 5.1. Considering that the regulator voltage ‘RG60’ is outside the operating voltage limits, it will be assumed that the voltage of the first three buses shown in Figure 5.1 are not modified, i.e. fixed. It should be mentioned that in OpenDSS the bus ‘670’ is the concentrated point load of the distributed load on the line joining the bus ‘632’ and ‘671’ located at 1/3 of the distance of the same line.

<table>
<thead>
<tr>
<th>Number</th>
<th>Name</th>
<th># Phases</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>SOURCEBUS</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>650</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>RG60</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>633</td>
<td>3</td>
</tr>
<tr>
<td>5</td>
<td>634</td>
<td>3</td>
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<tr>
<td>6</td>
<td>671</td>
<td>3</td>
</tr>
<tr>
<td>7</td>
<td>645</td>
<td>2</td>
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<tr>
<td>8</td>
<td>646</td>
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<tr>
<td>9</td>
<td>692</td>
<td>3</td>
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<tr>
<td>10</td>
<td>675</td>
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<td>15</td>
<td>680</td>
<td>3</td>
</tr>
<tr>
<td>16</td>
<td>684</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 5.1: Names and phases of buses according to OpenDSS

Figure 5.1: Initial voltage of the IEEE 13 nodes system

Figure 5.2: IEEE 13 nodes distribution system
6. Results

6.0.1 Validation of Power Flow Linearization

In order to validate the results of the linear model proposed for the power flow, the voltage magnitude and phase resulting from the linear method and the OpenDSS power flow method were compared for the case study. The results are shown in Figure 6.3, where the low error percentage between both methods is observed. The highest error percentage reported in the voltage magnitude and phase respectively are 0.0305% and 0.2028%.

![Figure 6.1: Comparison between linear and non-linear power flow](image)

6.0.2 Comparison of HC with and without OPF

Considering the validation between the non linear and linear method presented previously, the following analysis will show only the HC found with the described method in Section 3.0.2 and the linear OPF method. The total scenarios simulated were 255 (combinatorial of all possible location), nonetheless only 15 were selected to show a comparison between both methods. Table 6.1 shown the scenarios selected to this analysis.

Figure 6.2(a) shows a comparison between the HC without enhancement and the HC with OPF when the EV injects active power to the network. It can note that in scenario 2 is obtained the greater HC (See Table 6.1), likewise that lowest HC is obtained in scenario 3. It is important to mention that these scenarios correspond to scenarios where only one bus is selected to the EV penetration and depending on the location in the network it can be obtained a highest or lowest HC. Taking into account the selected scenarios, the minimum improvement is given in the scenario 10 with an enhancement of 13.70%; while the maximum improvement is in the scenario 2 with an enhancement of 148.19%. However, the total average percentage of HC improvement in the 255 scenarios is 19.63%. On the other hand, the HC method with OPF required approximately 0.0143 seconds to arrive at the result (mentioned above), while the HC method mentioned in section 3.0.1 needed approximately 463 seconds. Showing again, the significant improvement in the speed of calculations of the presented method.
Table 6.1: Penetration scenarios of EV selected

<table>
<thead>
<tr>
<th>Number</th>
<th>Scenario (Buses with EV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>671</td>
</tr>
<tr>
<td>2</td>
<td>634</td>
</tr>
<tr>
<td>3</td>
<td>645</td>
</tr>
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<td>4</td>
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(a) Case of active power injection to the system
(b) Case of active power consumption to the system

Figure 6.2: Comparison between HC legacy and HC with linear OPF

Figure 6.2(b) shows the comparison between the calculated HC with the method presented in Section 3.0.1 and the HC calculated with linear OPF, in the case when EV is consuming active power from the network. It shows that the minimum improvement is in scenario 4 with a percentage of 3.92%, while the maximum improvement is in scenario 14 with a percentage of 38.33%. The total average percentage of HC improvement in this case is 10.03%.

6.0.3 Comparison between non-linearized and linearized OPF

To validate the formulation of the OPF problem with the linear and non-linear method (Section 3.0.2), scenarios were simulated with different EV location. Table 6.1 show the scenarios selected to the comparison, they were selected randomly. In this way, it is verified that the results of maximization of the HC are consistent with these two methods. The results of this validation are shown in Figure 6.3(a) and Figure 6.3(b). Figure 6.3(a) present the case where the EV injects active power to the system, while Figure 6.3(b) corresponds to the case in which the EV consumes active power from the system. Where it can be observed that in all the evaluated scenarios the result is consistent. Additionally, it is
important to mention that the average time that it took to find a feasible solution, for the case study, with the non-linear method (calculated with the \texttt{fmincon} function of MATLAB) was 2.2458 seconds; while the linear method (calculated with the function \texttt{linprog}) took 0.0143 seconds in average. Giving a time reduction that is significant in large-scale systems.

(a) Case of active power injection to the system

(b) Case of active power consumption to the system

Figure 6.3: Non linear and linear OPF comparison
7. Conclusions

This paper had proposed a HC enhancement method to maximize the EV integration at the distribution network. Employing OPF concept, reactive power control was proposed to reach maximum HC without exceeding voltage limits on the system. Results showed that the proposed methodology outperforms HC calculations presented by legacy iterative HC methods (without optimization), with an improving percentage of 19.63% for the case of injection and 10.03% for the case of consumption. Furthermore, a linearized OPF formulation was presented to obtain a faster solution and to mitigate performings iteration respect to other non-linear optimization, achieving to reduce the computation times in 99.36%. Two comparisons were given in order to validate the proposed method. First one, it was a comparison between the HC maximization with linear and non-linear optimization. The second one was a comparison between a legacy iterative HC and the proposed method. Both comparisons demonstrated the improvement of the method.

A Future extension to this work could be the economic approach inclusion by using a multi-objective optimization model. Additionally, a way to extend the proposed method could be introducing new operational constraints, as THD, fast voltage changes, protection limits, etc.
References


REFERENCES


