Exploring Prospective Benefits of Electric Vehicles for Optimal Energy Conditioning in Distribution Networks

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Abstract— A potentially beneficial new opportunity is emerging around the exchange of energy between electric vehicles and the electrical energy grid, particularly as more low-carbon energy sources are connecting to the grid. Accordingly, this paper presents an optimization framework to activate the potential capabilities of electric vehicles equipped with bidirectional chargers for energy conditioning (including energy management and power quality improvement) of the future distribution networks. The proposed nonlinear optimization seeks to concurrently enhance the operation performance (using the network voltage deviation index) as well as power quality of the grid (using total harmonic distortion index). The proposed model is tested on a 33-bus distribution network to demonstrate its efficiency and performance.

Index Terms— Electric Vehicles, Energy Conditioning Management, Power Quality, Harmonic Load Flow, Non-linear Programming.

Nomenclature

Acronyms

AC	Alternating Current
AER	All-Electrical-Range
BC	Battery Capacity
BD	Benders Decomposition
CLF	Conventional Load Flow
CR	Charge Rate
DC	Direct Current
DG	Distributed Generation
ECR	Energy Consumption Requirement
EV	Electric Vehicle
FACTS	Flexible Alternating Current Transmission System
FQ	Four-Quadrant
HLF	Harmonic Load Flow
MILP	Mixed Integer Linear Programming
NLP	Non-Linear Programming
OLTC	On-Load Tap-Changers
PFC	Power Factor Correction
PHEV	Plug-in Hybrid Electric Vehicle
SOC	State of Charge
THD	Total Harmonic Distortion
UPQC	Unified Power Quality Conditioner

Sets and indices

b, t, l, h	Indices of bus, time, line and harmonic number
$\varphi_b, \varphi_t, \varphi_l, \varphi_h$	Sets of bus, time, line and harmonic number

Variables: All variables are in per unit (pu)

ID^p, ID^q	Active and reactive load current
IE^p, IE^q	Active and reactive current of a parking lot
IG^p, IG^q	Active and reactive current of a generation
IL^p, IL^q	Active and reactive current of a line
PB, QC	Active power of total batteries and reactive power of chargers in a parking lot
PE, QE	Active and reactive power of a parking lot
PLC, QLC	Active and reactive power loss of chargers in a parking lot
THD^v	Voltage THD [without unit]
V^r, V^i	Real and imaginary parts of voltage, respectively
V, I, S	Voltage, injecting current and apparent power, respectively

Parameters

A	Incidence matrix of lines and buses
a^p, a^q	Coefficients of active power loss of a charger
b^p, b^q	Coefficients of reactive power loss of a charger
EC	Total required energy in a parking lot in pu
GL, BL	The line conductance and susceptance in pu
HF^p, HF^q	Active and reactive harmonic factor current
IE^{max}	Charger capacity of all EVs in parking lot in pu
IG^{max}	Station or generation capacity in pu
IL^{max}	Line capacity in pu
NE_t	Number of EVs at hour t
PB^{max}	Charge rate of all batteries in a parking lot in pu
PD, QD	Active and reactive load in pu
T_{step}	Time step in hour
THD^{max}	Maximum voltage THD

V^{max}, V^{min}	Maximum and minimum voltage in pu
V_{ref}	The voltage magnitude for the reference bus in pu

Subindexes

V, I, S	Voltage, injecting current and apparent power, respectively, in pu
Y	The network admittance matrix in pu
f_s	The fundamental frequency in hertz
W	The sub-problem objective function term
M , π	slack and dual variables in sub-problem, respectively

1. Introduction

Diesel and gasoline vehicles are one of main causes of environmental pollution and emissions. Hence, Electric vehicles (EVs) are the suitable alternatives to reduce emissions. There are different types EVs that can be categorized into two major categories: hybrid EVs and plug-in EVs. Hybrid EVs utilize internal mechanisms to generate and store electricity, and the second type of EVs stores electricity by connection to the grid. The combinations of these categories are as plug-in hybrid EVs (PHEVs) which take advantage of both technologies. Commonly, PHEVs' batteries are connected to the distribution network using unidirectional chargers that control active power in one direction, i.e., grid-to-vehicle (G2V) [1]. Also, the unidirectional chargers use power electronic devices in their structure wherein a diode full bridge is used in the first part of this charger. As a result, these chargers inject harmonic current to the distribution network. In addition, EVs commonly are connected to the distribution network in the peak load periods as stated in [2] and [3]. Therefore, there are two major problems due to charger structure and connection time of EVs as follows: (i) increasing the energy demand while EVs are connected to the network at the peak load periods [4]; (ii) injection of the harmonic current to the grid during the connection of EVs to the grid [5]. According to the first problem, the network power loss, buses' voltage drop, congestion of lines and energy cost will be increased in the distribution network [6]. It is also possible that the bus voltage would be less than its standard mimimum limit, and line power would be more than its maximum standard value in the high penetration rates of EVs. In this case, system operation constraints do not allow that all EVs on the network to be connected to the distribution network [7]. In other words, the penetration rate of EVs should be decreased [7]. Moreover, due to the second issue, the electrical equipments of distribution network would be degraded or some of the equipment would be failed [8]. For instance, injection of the harmonic current to the network causes that the life time of the distribution transformer is decreased as shown in [9].

It is noted that the energy management [10], operation planning [11] and demand side mangement [12] are important alternatives to improve the power system indexes. In this regard, the enargy management of storage systems has been presented in [13]. Also, [14] and [15] express the enargy management of distributed generation and electrical sources, respectively. According to these researches, the enargy management cuases improvment in network indexes such as voltage, power loss, overloading of lines and network power factor. In some researches, the EVs energy management refers to the charging management of EVs' batteries using an optimization framework for minimization the energy cost [16], network load variation [17] and voltage deviation [18]. However, in these works, it is assumed that EVs' batteries are charged in the low load period. Accordingly, the penetration of EVs could be increased, but, the network indices such as the network voltage profile would not be improved at the peak load period. Because, these indices are in the critical condition due to other network loads that are modeled as a constant value. In this regard, [19] has used charging/discharging management of EVs batteries as the EVs' energy management strategy. Based on the results of this strategy, the charging management causes that EVs' batteries are charged at the low load period [20], and the network indices can be improved using EVs' discharging management strategy at the critical conditions [21]. Besides, [22] and [23] have presented energy management of EVs wherein the charging/discharging management of EVs' batteries, and distributed generations (DGs) such as solar and wind systems have been considered concurrently. Therefore, EVs' batteries can store the energy of DGs when the produced energy of the DGs is more than demanded energy in the network such as low load period [22]. Also, the EVs' batteries can contribute in the energy shifting programs to inject their stored energy into the network in the critical conditions, e.g., peak load hours [23]. This capability can improve the network operation indices at whole scheduling periods, increase the penetration rate of EVs [24], and decrease EVs' energy cost [25]. Additionally, there are other applications of EVs in the network while EVs implemnt the energy management strategy. For instance, in [26], EVs are considered as storages in the network to be coordinated with DGs.

As above mentioned, the second problem refers to the injection of harmonic current into the network due to nonlinear characteristics of the EVs' chargers. Different researchers such as [27], [28] and [29] in the area, propose changing the structure of EVs' charger. In [27], an interleaved boost topology is used in AC/DC converter or power factor correction (PFC) converter. Based on [27], the total harmonic distortion (THD) of current for the new EVs' charger has been reduced. [28] and [29] propose using the full bridge AC/DC converter in the charger which is called a four-quadrant (FQ) bidirectional charger. This charger can be operated in four areas of the PQ power plane [28], and also it can control its harmonic current [29]. Hence, the THD of the current can be reduced in this type of EVs' charger. In addition, as proposed in [30], if EVs charged by group instead of individual, accordingly the current THD for the group of EVs is less than the current THD for the individual EVs. It is noted that in [27]-[30], the charger structure of EVs is investigated. That is, these research works have not presented the optimization problem as proposed here. All in all, the taxonomy of recent works in the area is expressed in Table 1. According to Table 1, three main research gaps of the available literature about the presence of EVs in the smart distribution systems are as follows:

- As seen in Table 1, many works in the area, consider only active power management in the operation of the distribution networks [19]-[21] while considering charging and discharging simultaneously. It is noted that the continuous charging/discharging of EVs' batteries will reduce their lifetime.
- As seen in Table 1, there are limited works [27]-[30] in the area that considers the harmonic compensation of EVs in the distribution networks using suitable structure of EV charger, and they do not consider the harmonic compensation of other non-linear loads.
- Finally, in the large scale networks, the calculation time is still a challenge despite using linear formulations.

It should be noted that some researchers have used bidirectional chargers in EVs. Based on [31], the bidirectional chargers include two converters that are called AC-DC bidirectional converter and DC-DC bidirectional (buck and boost) converter. In the active power control mode, the AC-DC and DC-DC converters are used to control the charging/discharging power of EV's battery [32]. But, AC-DC converter is only needed for EVs' reactive power control [33], and EVs' harmonic current control for decreasing the output current THD [34]. In these works, the metering point is the charger output point. Hence, energy conditioning (power and harmonic control) should be implemented in the charger output to change power and harmonic currents at this point, and the EVs' chargers do not control the network power and harmonic current of the non-linear loads. In addition, references [35] and [36] have introduced different kinds of custom power and FACTS devices, respectively. These devices commonly use AC-DC bidirectional converter that AC side is connected to the network and DC side is connected to the energy storage device such as capacitor. These devices with AC-DC bidirectional converter can control the network reactive power such as D-STATCOM and UPQC, and it is capable of controlling the harmonic current of non-linear loads such as active filters and D-STATCOM. Therefore, it is noted that the AC-DC bidirectional converter structure of the bidirectional chargers is similar to the AC-DC converter structure of FACTS or custom power devices such as D-STATCOM and active filters. Accordingly, EVs with bidirectional charger can control active and reactive power of the network and compensate the harmonic current of non-linear loads. Consequently, the connection point of non-linear load to the network should be considered as a metering point of the charger control to decrease the current THD of the non-linear load.

Finally, to cope with the above three issues, an optimization approach is presented in this paper for energy conditioning of the smart distribution networks and energy quality enhancement, i.e., harmonic compensation of non-linear loads using EVs equipped by the bidirectional charger. At the first step, this paper presents that EVs can concurrently control active (charging) and reactive power, as well as harmonic current of their chargers or the distribution network. However, the active power discharging mode of battery is not considered in this paper, because, it is assumed that the profit of concurrent charging and discharging active power management is less than the profit of only charging management. The reason is that increasing the discharging mode of EVs for injecting active power will increase charging/discharging cycles that results in decreasing battery life time as well as decreasing reactive power control limit. Then, the non-linear deterministic problem model is presented with the objective of minimizing the voltage deviation at the fundamental frequency and the voltage THD. This objective is subject to the harmonic load flow (HLF) equation, system operation limits and EVs' constraints. Finally, the Benders decomposition (BD) is used to solve the non-linear deterministic problem for increasing the calculation speed. Accordingly, to the best of authors' knowledge, the contributions of this paper with respect to the previous ones are threefold:

— Energy conditioning (simultaneous control of reactive power and harmonic current) in the smart distribution network using EVs equipped by bidirectional chargers.
— Presenting an optimization problem that models energy conditioning (including energy management and power quality improvement) of the smart distribution; the objective function of this is non-linear optimization problem is the minimization of the voltage deviation at the fundamental frequency and the voltage THD, and constraints include HLF equation, system operation limit and EVs' constraints with bidirectional chargers.
— Using the Benders Decomposition (BD) approach to accelerate the solution process of the non-linear deterministic optimization problem.

The rest of the paper is organized as follows: Section 2 describes the HLF and case study. The assumptions, NLP model of the deterministic problem and solution method have been presented in Section 3. Sections 4 and 5 demonstrate numerical simulations and conclusions, respectively.

2. Case study description

In this paper, the proposed problem model has been tested on the radial 33-bus distribution system [37]. The loads' data are taken from [37] for the peak time, and their values have been obtained using the load percent curve, i.e., the percentage of the peak load at different times, as shown in Fig. 1 for the non-peak times. The maximum and minimum voltages for all buses are considered as 1.05 and 0.9 per unit, respectively. In addition, the non-linear load used in this paper is a 6-pulse converter that plugged into the network in buses 4, 7, 10, 13, 18, 21, 25, 27, 30 and 33 of the test case. The active and reactive harmonic factor current (HF^p, HF^q) are considered as the same, and these parameters are presented in Table 2. In addition, it is noted that the conventional load flow (CLF) is expressed for steady state conditions and linear loads. But, the waveforms of the network quantities such as bus voltage and line current are not sinusoidal if non-linear loads are connected to the network. Accordingly, the non-sinusoidal waveform should be expressed as a summation of the multi sinusoidal waveforms with different magnitudes and frequencies. It should be noted that the frequency of h^{th} waveform is as $h \times f_s$ wherein the f_s is the fundamental frequency of the network, and h is the harmonic order. Therefore, the harmonic load flow (HLF) is needed for implementation of the load flow in all harmonic order conditions [38] and [39]. In the HLF, the apparent power for each bus is represented as follows:

$$S_b = \sum_{h \in \varphi_h} V_b^h \left(I_b^h\right)^* \tag{1}$$

Based on (1), there are two different presentation forms of HLP formulations as follows [38],[39]:

— In the HLP, the power components are presented only at the fundamental frequency.

— In the HLP, the power components are presented at both the fundamental frequency and harmonic frequency.

In the first type, the product of voltage and injecting current of a bus at the fundamental frequency is equal to the injected apparent power of the bus. In this type, the load flow at the harmonic frequency considers the relation between voltage and injected current of buses. Therefore, the HLP equations are written as follows:

$$S_b = V_b^1 \left(I_b^1\right)^* \tag{2}$$

$$I_b^h = \sum_{j \in \varphi_b} Y_{b,j}^h V_j^h \tag{3}$$

Based on (2), the conventional load flow (CLF) is performed at the fundamental frequency for the first presentation form. Hence, the HLP includes CLF and (3) [38]. Moreover, in the second type, voltage and injected current of a bus at both fundamental frequency and harmonic frequency make the apparent power of the bus. Hence, the HLP formulation includes (1) and (3) [39]. Also, it should be noted that some of network parameters such as line reactances are changed at the harmonic frequency. Thus, the network admittance matrix would change, hence, Y^h is used in (3).

This paper considers three groups for EVs' number in the parking lot, and a parking lot has been assigned to each bus. The EVs' numbers are 21, 30, and 60 for the range of active load in per unit as (0, 0.1), (0.1, 0.2) and (0.2, >0.2), respectively. Also, the EV's characteristics are presented in Table 3. The coefficients of active power loss (a^p, a^q) and reactive power loss (b^p, b^q) of the charger, are equal to 0.09, 0.0475, 0.02 and 0.02, respectively. Also, the time interval is one hour. Moreover, in this paper, two charge strategies are used as follows:

Strategy I [3], [40], [41]: The EV is connected to the network, and the EV battery is fully charged after especial charging time which is equal to *BC/CR*, wherein BC and CR are battery capacity and charge rate of EV, respectively. Also, the active power of total batteries in the parking lot (*PB*) at time *t* is equal to the charge rate of all batteries in parking lot (PB^{max}) at time *t* ($PB_{b,t} = PB_{b,t}^{\max}$), where $PB_{b,t}^{\max}$ is equal to $\sum_{i=1}^{NE_t} CR_i$, and NE_t is the number of EVs at hour t. Moreover, the number of EVs at each hour has been shown in the Fig. 2 (a) that is obtained based on the assumption that "EVs are connected into the distribution network when they arrive at home after their last trip" [3].

Strategy II [41]-[43]: the EV battery is not charged after its connection to the network. But, it is charged based on objective function which is introduced in the main problem. Also, the inequality of $PB_{b,t} \le PB_{b,t}^{\max}$ is used in this strategy. Moreover, the number of EVs at each hour has been shown in Fig. 2 (b) that is obtained based on assumption that "EVs are connected into the distribution network when they arrive at home after their last trip" [3].

3. Mathematical formulation

3.1. *Assumptions*

In this section, the assumptions of the proposed problem model have been presented as follows:

1- The first type of HLP equation is used in the proposed model.

2- This paper investigates EVs' capability for energy conditioning of smart distribution networks (including network energy management and harmonic compensation of non-linear loads). Hence, the other power controlling equipment such as capacitor bank, distributed generations, OLTC are not considered.

3- According to [34], increasing the number of charging/discharging cycles of the EV's battery causes decreasing its lifetime. Therefore, the active power discharging mode of EV's battery is not considered. It is noted that usually the active power discharging of EVs is used in peak load times. Accordingly, it is expected that EVs would be charged in two periods, i.e., before and after peak load times. Indeed, EVs will be charged in the period of before peak load times to be discharged in the peak load times, and they are charged in the period of after peak load times to provide EVs' energy consumption requirements. According to this mechanism, the number of charging/discharging cycles of the EVs' batteries will be increased; accordingly, it will decrease their lifetime as mentioned in [34] and will decrease the charging cost. Also, the injected active power to the grid during the high price hours causes that the injection/absorption of reactive power into/from the grid to be decreased. Indeed, the discharging mode of active power will limit the reactive power control by EVs. Finally, it would be shown in simulation results that the profit of concurrent charging and discharging modes of active power management is less than the profit of just charging management.

4- The battery of EVs are recharged in the parking lot or parking of an apartment.

5- EVs are connected into the distribution network when they arrive at home after their last trip.

3.2. *Problem formulation*

In this section, the NLP deterministic optimization model of the energy conditioning (energy management of smart distribution network and energy quality enhancement, i.e., harmonic compensation of non-linear loads using EVs with bidirectional charger) is presented. The objective function of the proposed optimization problem includes the minimization of both the voltage deviation at the fundamental frequency and voltage THD subject to the HLP equations, system operation limits and EVs constraints.

Objective function: the objective function of the proposed problem is represented in (4). The first term of this equation refers to the minimization of voltage deviation at the fundamental frequency. Also, the minimization of the voltage THD is presented in second term of (4). It should be noted that these terms are included in the objective function to investigate EVs capability to regulate voltage of buses and harmonic compensation of non-linear loads and motivate EVs for energy conditioning (energy management and harmonic current control).

$$\min_{v^r, v^i, THD^v} \sum_{b \in \varphi_b} \sum_{t \in \varphi_t} \{ \frac{\left| \sqrt{\left(V^r_{b,t,1}\right)^2 + \left(V^i_{b,t,1}\right)^2} - V_{ref} \right|}{V_{ref}} + THD^v_{b,t} \} \tag{4}$$

It should be noted that voltage is defined as $\sqrt{\sum_{h \in \varphi_h} \left(V^r_{b,t,h}\right)^2 + \left(V^i_{b,t,h}\right)^2}$ in the harmonic space. But, based on this term, the voltage at harmonic frequency may be increased, and the voltage at fundamental frequency is reduced. Accordingly, in addition to the first term, the voltage THD is augmented in the objective function. Because, based on (3), the harmonic of current is decreased if voltage harmonic is reduced. Thus, this is the main reason that the term of current THD is not considered in this formulation.

The HLP constraints: these constraints are presented as follows based on assumption 1:

$$IG^p_{b,t,h} - ID^p_{b,t,h} - IE^p_{b,t,h} = \sum_{l \in \varphi_l} A_{l,b} IL^p_{l,t,h} \quad \forall b,t,h \tag{5}$$

$$IG^q_{b,t,h} - ID^q_{b,t,h} - IE^q_{b,t,h} = \sum_{l \in \varphi_l} A_{l,b} IL^q_{l,t,h} \quad \forall b,t,h \tag{6}$$

$$IL^p_{b,t,h} = \sum_{j \in \varphi_b} A_{l,j} \left\{ GL_{l,h} V^r_{b,t,h} - BL_{l,h} V^i_{b,t,h} \right\} \quad \forall l,t,h \tag{7}$$

$$IL^q_{b,t,h} = \sum_{j \in \varphi_b} A_{l,j} \left\{ GL_{l,h} V^i_{b,t,h} + BL_{l,h} V^r_{b,t,h} \right\} \quad \forall l,t,h \tag{8}$$

Equations (5) and (6) represent active and reactive current balance, respectively. Also, the active and reactive current flow of lines are defined in (7) and (8), respectively. These equations are expressed for each bus and each harmonic order at hour t. In these constraints, the value of IG^p and IG^q in all buses except the substation bus of the network is equal to zero based on assumption 2. In addition, $A_{l,b}$ is equal to 1, if the current of line l exits from bus b, and $A_{l,b}$ is equal to -1 if the current of line l enters to bus b, otherwise, it is zero.

Load constraints: generally, the active and reactive power of load are pre-specified, and the harmonic current of load is defined as the percent of load current at the fundamental frequency. Hence, load constraints can be written as follows based on assumption 1:

$$PD_{b,t} = V^{r}_{b,t,h} ID^{p}_{b,t,h} + V^{i}_{b,t,h} ID^{q}_{b,t,h} \quad \forall b,t,h=1 \tag{9}$$

$$QD_{b,t} = V^{i}_{b,t,h} ID^{p}_{b,t,h} - V^{r}_{b,t,h} ID^{q}_{b,t,h} \quad \forall b,t,h=1 \tag{10}$$

$$ID^{p}_{b,t,h} = HF^{p}_{b,h} ID^{p}_{b,t,1} \quad \forall b,t,h \neq 1 \tag{11}$$

$$ID^{q}_{b,t,h} = HF^{q}_{b,h} ID^{q}_{b,t,1} \quad \forall b,t,h \neq 1 \tag{12}$$

Equations (9) and (10) are expressed based on the first type of HLP presentation. In other words, the voltage and current of the load at the fundamental frequency perform active and reactive power of the load. The relations of active and reactive load currents have been introduced in (11) and (12), respectively.

Constraints of EVs/parking lots: In this paper it is considered that there is a parking lot in each bus, and also, the active and reactive power of parking lot have been denoted by *PE* and *QE*, respectively. Accordingly, we have: $PE_b + jQE_b = V_b\left(IE_b\right)^*$, $V_b = V_b^r + jV_b^i$ and $\left(IE_b\right)^* = IE_b^p - jIE_b^q$. Therefore, according to the above formulations, the equations (13) and (14) are obtained.

$$PE_{b,t} = V^{r}_{b,t,h} IE^{p}_{b,t,h} + V^{i}_{b,t,h} IE^{q}_{b,t,h} \quad \forall b,t,h=1 \tag{13}$$

$$QE_{b,t} = V^{i}_{b,t,h} IE^{p}_{b,t,h} - V^{r}_{b,t,h} IE^{q}_{b,t,h} \quad \forall b,t,h=1 \tag{14}$$

Moreover, the active power source in the parking lot is the total batteries of EVs which is denoted by *PB.* Also, this source is connected to the network though the chargers of EVs. Therefore, the *PE* is equal to the summation of *PB* and active power loss of EVs' chargers, i.e., $PLC_{b,t}$, as shown in (15).

$$PE_{b,t} = PB_{b,t} + PLC_{b,t} \quad \forall\, b,t \tag{15}$$

Also, there is an inductance in the output of the charger and it consumes reactive power that is called reactive power loss. Besides, the reactive power source in the parking lot is EVs' chargers. In the proposed problem, *QC* represents the reactive power of this source. Therefore, *QE* is equal to the summation of *QC* and reactive power loss of EVs' chargers, i.e., $PLC_{b,t}$, as formulated in (16).

$$QE_{b,t} = QC_{b,t} + QLC_{b,t} \quad \forall b,t \tag{16}$$

The active and reactive power losses of EVs' chargers depend on *PE* and *QE* as shown in equations (17) and (18) [41].

$$PLC_{b,t} = a^p \left(PE_{b,t}\right)^2 + a^q \left(QE_{b,t}\right)^2 \quad \forall b,t \tag{17}$$

$$QLC_{b,t} = b^p \left(PE_{b,t}\right)^2 + b^q \left(QE_{b,t}\right)^2 \quad \forall b,t \tag{18}$$

In this paper, the discharging mode of the active power for EV's battery is not considered, hence, the lower limit of *PB* is equal to zero based on the assumption 3.

$$0 \le PB_{b,t} \le PB_{b,t}^{\max} \quad \forall b,t \tag{19}$$

Where this equation is used for Strategy II, and also, it is expressed by $PB_{b,t} = PB_{b,t}^{\max}$ in Strategy I.

In addition, this paper assumes that EVs are plugged into the network after their daily trip based on [3], hence, EVs are charged to provide their energy consumption requirements (ECRs) once per day after their last trip. Also, the ECR of an EV is equal to (1-*SOC*) × *BC*, which *SOC* and *BC* indicate the state of charge and battery capacity, respectively. The *SOC* is defined as the percentage of energy remaining in the EV's battery [3]. That is, the *SOC* is the percentage of remaining energy of EV's battery when EV arrives at the parking lot after its daily trips. Hence, the *SOC* depends on the distance that EV derives in the electric mode (*L*) and it is expressed as $(1 - L/AER)$, where, *AER*, i.e., all-electrical-range, presents the total distance that EV derives in the electric mode based on its battery capacity. Consequently, based on assumptions 4 and 5, in (20), the *EC* refers to the summation of the ECR of all EVs in the parking lot.

$$\sum_{t \in \varphi_t} T_{step} PB_{b,t} = EC_b \quad \forall b \tag{20}$$

Finally, the capacity of EVs' chargers is limited in equation (21).

$$\sum_{h \in \varphi_h} \left\{ (IE_{b,t,h}^{p})^2 + (IE_{b,t,h}^{q})^2 \right\} \le (IE_{b,t}^{\max})^2 \quad \forall b,t \tag{21}$$

Constraints of harmonic indices: there are different harmonic indices to investigate the harmonic impacts in the network [37]. One of the important harmonic indices is THD that can be calculated for voltage and current. But, this paper implements THD for voltage of all buses, because, the current depends to voltage. Thus, the calculation of current THD is not needed. These constraints are presented as follows:

$$THD_{b,t}^{v}=\sqrt{\frac{\sum_{h\in\varphi_h,h\neq 1}\left\{\left(V_{b,t,h}^{r}\right)^2+\left(V_{b,t,h}^{i}\right)^2\right\}}{\left(V_{b,t,1}^{r}\right)^2+\left(V_{b,t,1}^{i}\right)^2}}\quad\forall b,t \tag{22}$$

$$THD_{b,t}^{v}\leq THD_{b}^{\max}\quad\forall b,t \tag{23}$$

The voltage THD is calculated based on (22). Equation (23) limits the voltage's THD with a maximum value of THD^{max}, which is equal to 5% based on IEEE 519 standard [44].

System operation limits: these limits include voltage bus, line current and station (generation) current limits that are presented in (24), (25) and (26), respectively.

$$(V_b^{\min})^2\leq\sum_{h\in\varphi_h}\left\{(V_{b,t,h}^{r})^2+(V_{b,t,h}^{i})^2\right\}\leq(V_b^{\max})^2\quad\forall b,t \tag{24}$$

$$\sum_{h\in\varphi_h}\left\{(IL_{l,t,h}^{p})^2+(IL_{l,t,h}^{q})^2\right\}\leq(IL_l^{\max})^2\quad\forall l,t \tag{25}$$

$$\sum_{h\in\varphi_h}\left\{(IG_{b,t,h}^{p})^2+(IG_{b,t,h}^{q})^2\right\}\leq(IG_b^{\max})^2\quad\forall b,t \tag{26}$$

In this model, *PB*, *QC, IE^p* and IE^q are decision variables, and V^r, V^i and THD^v are the output variables of the problem.

3.3. *Solution method*

Constraints of system operation limits in the proposed deterministic model, i.e. (24)-(26), are the most complicated constraints. Hence, the calculation speed may be reduced. Consequently, based on [45], the BD algorithm is used to solve the proposed problem model. Generally, BD algorithm is deployed for solving the multi-stage MILP problems. But also, this algorithm can be applied to single or multi-stage NLP problems that have complicating constraints/variables in order to accelerate the calculation speed [45]. The BD algorithm includes two parts that are called master problem and sub-problem. The master problem refers to the main part of the fundamental problem, and sub-problem checks the complicating constraints using output results of the master problem. In other words, the master problem equations are (4)-(23), and the sub-problem equations can be written as follows:

$$\min_W \quad W=\sum M \tag{27}$$

Subject to:

$$\sum_{h\in\varphi_h}\left\{(V_{b,t,h}^r)^2+(V_{b,t,h}^i)^2\right\}-M_{b,t,1}\leq (V_b^{\max})^2:\pi_{b,t,1}\quad \forall\, b,t \tag{28}$$

$$\sum_{h\in\varphi_h}\left\{(V_{b,t,h}^r)^2+(V_{b,t,h}^i)^2\right\}+M_{b,t,2}\geq (V_b^{\min})^2:\pi_{b,t,2}\quad \forall\, b,t \tag{29}$$

$$\sum_{h\in\varphi_h}\left\{(IL_{l,t,h}^p)^2+(IL_{l,t,h}^q)^2\right\}-M_{l,t,3}\leq (IL_l^{\max})^2:\pi_{l,t,3}\quad \forall\, l,t \tag{30}$$

$$\sum_{h\in\varphi_h}\left\{(IG_{b,t,h}^p)^2+(IG_{b,t,h}^q)^2\right\}-M_{b,t,4}\leq (IG_b^{\max})^2:\pi_{b,t,4}\quad \forall\, b,t \tag{31}$$

$$M\geq 0 \tag{32}$$

Equations (28)-(32) refer to the sub-problem part of BD algorithm. It is noted that the constraints of the system operation limits part in the proposed deterministic model, i.e., (24)-(26), are the most complicated constraints. Hence, the problem of (4)-(26) can be solved hardly. For the sake of simplification, the BD algorithm is used at two parts. In the first part, the problem of (4)-(23) is solved that called master problem. The second part, called sub-problem, will check the satisfaction of equations (24)-(26) according to the solution of the master problem. To this end, the slack variable of M is added to equations (24)-(26) as equations (28)-(31). If $M > 0$, the equations (24)-(26) would not be satisfied. But, if $M = 0$, the equations (24)-(26) will be satisfied.

In the above formulations, M and π are slack and dual variables, respectively. Hence, the proposed problem (4)-(26) is converged if $|W|\leq\varepsilon$ (where ε is BD convergence tolerance level), otherwise ($|W|\geq\varepsilon$), the Benders cut is added to the master problem which is formulated as follows [45]:

$$\sum_{b\in\varphi_b}\left\{\begin{array}{l}\displaystyle\sum_{t\in\varphi_t}\pi_{b,t,1}\left((V_b^{\max})^2-\sum_{h\in\varphi_h}\left\{(V_{b,t,h}^r)^2+(V_{b,t,h}^i)^2\right\}\right)\\ \displaystyle+\pi_{b,t,2}\left(\sum_{h\in\varphi_h}\left\{(V_{b,t,h}^r)^2+(V_{b,t,h}^i)^2\right\}-(V_b^{\min})^2\right)\\ \displaystyle+\pi_{b,t,4}\left((IG_b^{\max})^2-\sum_{h\in\varphi_h}\left\{(IG_{b,t,h}^p)^2+(IG_{b,t,h}^q)^2\right\}\right)\end{array}\right\}+\sum_{l\in\varphi_l}\sum_{t\in\varphi_t}\pi_{l,t,3}\left((IL_l^{\max})^2-\sum_{h\in\varphi_h}\left\{(IL_{l,t,h}^p)^2+(IL_{l,t,h}^q)^2\right\}\right)\leq 0 \tag{33}$$

The flowchart of implementing BD for the proposed problem is shown in Fig. 3.

4. Numerical results and discussion

The proposed problem model is programmed in GAMS 23.5.2 and solved using the CONOPT 3.0 solver [46]. Also, it is noted that the start time for the simulation studies is 10:00 A.M due to constraints in (20).

1) *The impacts of EVs on the distribution network with reactive power management and harmonic compensation*: the results of this section are shown in Fig. 4. In this study, three cases have been performed as follows:

- *Case* I: Base load case that shows the results of the problem model without considering EVs in the network.
- *Case* II: Distribution network operation without using EVs active and reactive power as well as harmonic current control capability, and using Strategy I to charge 21% of EVs' batteries.
- *Case* III: Distribution network operation using only EVs reactive power and harmonic current control capability, and using Strategy I to charge 21% of EVs' batteries.

In the case II, 21% of EVs are connected to the network and the power management and harmonic compensation are not considered. In this case, EVs are plugged into the network after their last trip and charged fully after their special charging time. Thus, the EVs do not have any impacts on the distribution network after their especial charging time. Case III (21% EVs) implements the reactive power management and harmonic compensation when EVs charge their battery in the distribution network. The power variation between the cases I and II indicates that EVs are charged during 15:00 to 2:00 of the next day as shown in Fig. 4 (a). Based on this figure, the power demand of EVs from the distribution network is high in the peak load times. Hence, the voltage of all buses are leveled off with respect to the case I in this period, (see Fig. 4 (b)). In this condition, the system operation limits, i.e., (24)-(26), do not allow the large number of EVs to be plugged into the network. This matter has been shown in Fig. 4 (a). The voltage THD of the system has been shown in Fig. 4 (c). Based on this figure, the voltage's THD of all buses in the case II is larger than the voltage' THD of all buses in the case I, but, this difference is low. Case III adds the reactive power management and harmonic compensation to the case II. Based on Fig. 4, the power demand from the upstream network is reduced with respect to the case I. This reduction is due to the injection of the reactive power to the distribution network and non-linear harmonic compensation using EVs. This is because the active power demand of loads and EVs are the same as the case II. Also, the injection of the reactive power to the network causes to increase voltage of buses with respect to the case I. In addition, the voltage THD of 17 buses is more than 5% in cases I and II, but, the voltage THD of all buses is less than 5% in case III. Also, the voltage profile and voltage THD have been improved during the peak load periods for the case III, because the reactive power management and harmonic compensation have been implemented during hours 15:00 to 2:00 of the next day as can be inferred in Fig. 4 (a). As a last note, the apparent power of the upstream network at peak load period (hour 20) for the cases II and III are 4.84 per units and 5 per units, respectively. Thus, the reactive power management and harmonic compensation of EVs in the case III causes that the apparent power of the upstream network to be reduced with respect to the case II. This reduction is 0.16 per unit or 3.2% = 100*(5-4.84)/5. Hence, this reduction leads to more loads or EVs be able to demand power from the network.

2*) The impacts of EVs on the distribution network using power management and harmonic compensation*: In this study, three cases have been performed as follows:

- *Case* I: Base load case that shows the results of problem model without considering EVs in the network.
- *Case* II: Distribution network operation using only EVs' active power control capability, and using Strategy II to charge 100% of EVs' batteries.
- *Case* III: Distribution network operation using EVs concurrent active and reactive power as well as harmonic current control capability, and using Strategy II to charge 100% of EVs' battery.

Fig. 5 shows the daily pattern of the network apparent power, daily voltage profile and daily pattern of voltage THD for the bus 18. It is noted that based on Fig. 4 (b) and (c), the voltage of the bus 18 is less than all other buses' voltages, and voltage THD of the bus 18 is greater than all other buses' voltage THD; therefore, in this paper, the bus 18 is selected for the investigation of the network voltage and voltage THD for different cases. The results of the base load (no EVs) are expressed in case I, and active power management (charging management of EVs battery) only is implemented in case II (100% of EVs are connected to the network). The power management and harmonic compensation using EVs are studied in the case III with 100% of EVs plugged. Based on Fig. 5 (a), the power variations between cases I and II indicate charging of EVs' batteries in the period of 23:00 to 9:00 of the next day, and EVs do not demand power from the upstream network at the other times. Hence, the voltage and voltage THD of the bus 18 (or other buses) are changed in this period with respect to the case I, but, the changes of voltage THD are low. It should be noted that the penetration rate of EVs is increased to 100% in the case II, but, the network indices such as the voltage of buses, line power flow and voltage THD of buses are not improved at all times or peak load times. As stated, case III adds the reactive power management and harmonic compensation to the case II. Based on Fig. 5 (a), the apparent power of the upstream network is reduced in the period of 12:00 to 21:00 with respect to the case I, and it is increased in the period of 22:00 to 8:00 of the next day with respect to the case I. The reduction of network apparent power is due to the injection of reactive power into the network as well as non-linear harmonic compensation by EVs. Indeed, in this condition, the injection of the reactive power of EVs is greater than the network reactive load. Also, the reasons of the increment of the network apparent power are: (i) the charge of active power of EVs' batteries, (ii) the injection of the reactive power of EVs' charger which is more than the network reactive load (it is more than two times of network's reactive load), and (iii) the harmonic compensation by EVs such that the employed capacity of the harmonic compensation is less than other factors. Besides, the voltage deviation of bus 18 (and other buses) is low as shown in Fig. 5 (b). In other words, the minimum voltage of the bus 18 is 0.947 per unit that indicates EVs are capable to regulate voltage of buses. Also, the voltage THD has been improved at all times for case III based on Fig. 5 (c). Because, the maximum voltage THD of the bus 18 is equal to 4.43% that is less than 5%. This shows the EVs' capability for compensation of non-linear load harmonic at all times.

3) *Benefits of using BD algorithm to solve the proposed problem model*: in this section, the calculation time of solving the proposed problem model with and without BD algorithm has been presented. To better show the capability of BD, three distribution networks, i.e., 33-bus, 69-bus [47] and 123-bus [48], are used. The data of non-linear loads' (6-pulse converter) connection is presented in Table 4. The other data of the problem, i.e., voltage limit, HF^p and HF^q, and EVs' data, for 69-bus and 123-bus networks is the

same with the previous data in section 2. Table 5 shows the calculation time of solving the proposed problem model with and without BD algorithm. In this table, different solvers of GAMS software are used to solve the proposed problem without BD algorithm. As seen in the table, the results of GAMS solvers are the same. Based on this table, solving the proposed NLP deterministic problem model without BD algorithm can be performed on small size distribution network. In other words, solving problem without BD algorithm cannot find the optimal or locally optimal solutions in the large size distribution networks. Also, the calculation time still is high for the small size of the distribution networks. But, implementing BD algorithm would reduce the calculation time, and it can reach the global/local optimal solutions in the large size of the distribution networks. In addition, the BD convergence time for the proposed problem is low. In addition, table 6 shows the number of equations and variables for the problem with and without BD algorithm. Based on this table, the number of equations and variables in the problem without BD algorithm is less than the problem with BD algorithm. However, the calculation time of BD algorithm is less than the problem without BD algorithm.

5. Conclusions

This paper proposed the energy conditioning management of the smart distribution network and energy quality enhancement, i.e., harmonic compensation of non-linear loads using EVs equipped by bidirectional chargers. The proposed non-linear deterministic model considers the voltage deviation at the fundamental frequency and the voltage THD as the objective function, while harmonic load flow equations, system operation limit, harmonic index equations and EVs constraints have been modeled as optimization problem constraints. Finally, the BD algorithm is used for solving the proposed problem model. Using BD algorithm to solve the optimization problem causes reduction of the calculation time by 8. Based on the numerical results, the network and harmonic indices have been improved at the peak load conditions if only reactive power management and harmonic compensation are implemented. Also, the penetration rate of EVs would be increased to 100% if only the charging active power management is used. But, the voltage deviation at the fundamental frequency and voltage THD of all buses are reduced by about 48 and 51 percent, respectively, at all times of the study period in the case of the higher EVs penetration rates (when EVs control the charging of active power and reactive power and compensate the non-linear load harmonics). These points refer to advantages of using EVs with bidirectional chargers to enable active and reactive power control capability in distribution network and compensating the harmonic of non-linear loads. All in all, the main significance of the proposed energy quantity and quality management services for distribution networks in the presence of EVs is that not only it will remedy the challenge of increased demand due to charging EVs in the distribution network, but also, will add new capabilities to manage the operation of the distribution networks proactively. Finally, the research work is underway to utilize the EVs' capability in harmonic compensation of the network in addition to active and reactive power management while considering the cost and revenue of this strategy for EVs.

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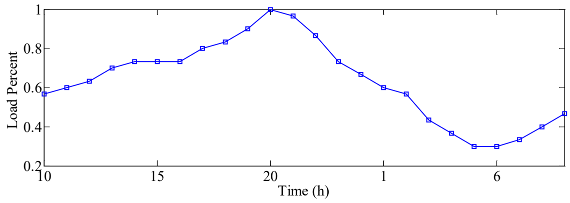
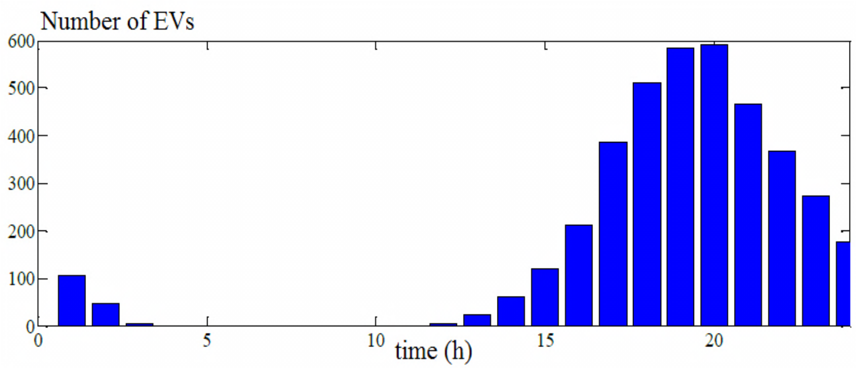
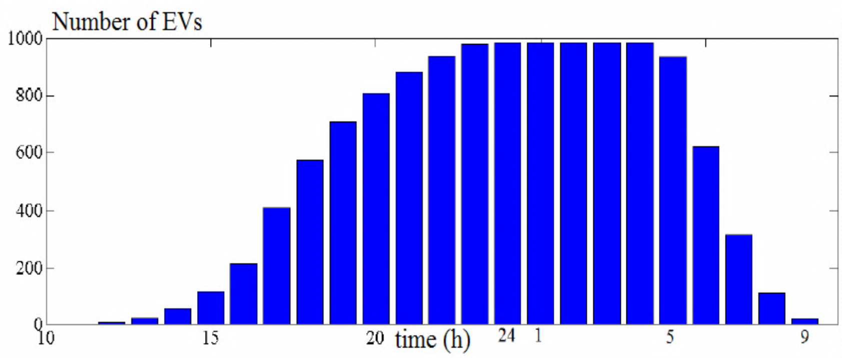


Fig. 1. Daily load percent curve [3].



(a)



(b)

Fig. 2. The number of EVs at each hour, (a) Strategy I, (b) Strategy II.

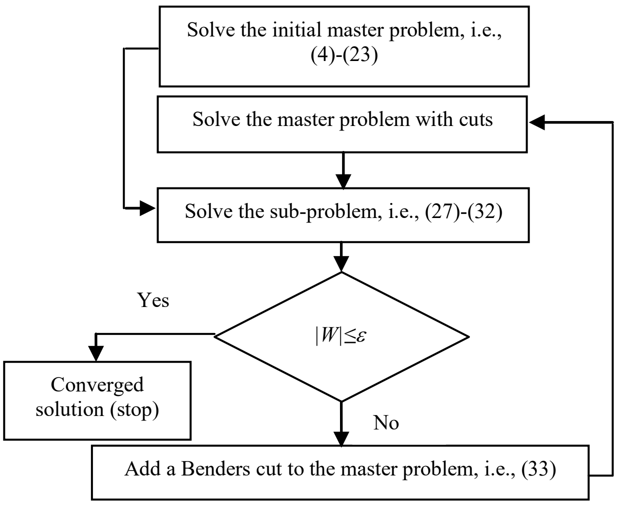
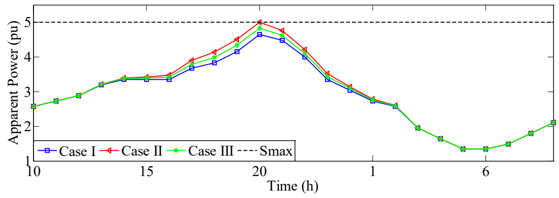
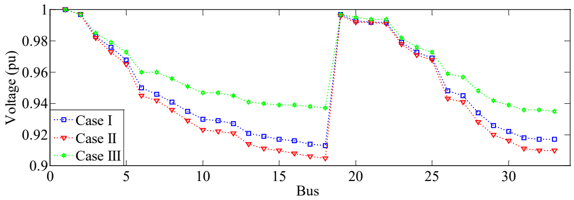


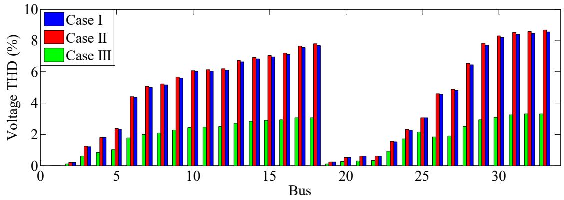
Fig. 3. BD algorithm to solve the proposed problem.



(a)

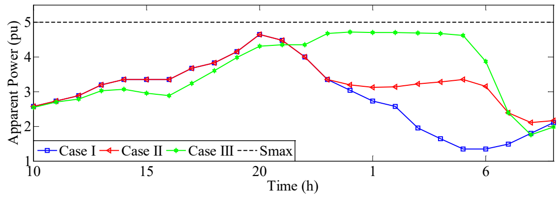


(b)

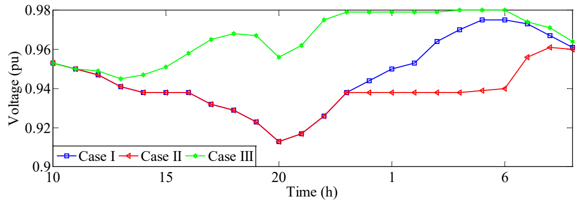


(c)

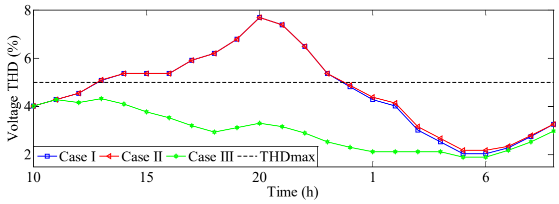
Fig. 4. Results of reactive power management and harmonic compensation using EVs based on Strategy I, (a), daily pattern of the network apparent power, (b) voltage profile at peak load time, and (c) voltage THD in each bus at peak load time.



(a)



(b)



(c)

Fig. 5. Results of power management and harmonic compensation using EVs based on Strategy II, (a), daily pattern of the network apparent power, (b) daily pattern of the voltage in the bus 18, (c) daily pattern of the voltage THD in the bus 18.

Table 1 Taxonomy of recent works

Ref	Power management			Harmonic compensation	Optimization problem	Solving with BD approach
	Active		Reactive			
	Charging	Discharging				
[16]-[18]	Yes	No	No	No	Yes	No
[19]-[21]	Yes	Yes	No	No	Yes	No
[22]-[26]	Yes	Yes	No	No	Yes	No
[27]	Yes	No	No	Yes	No	No
[28]	Yes	No	Yes	Yes	No	No
[29]-[30]	Yes	No	No	Yes	No	No
Proposed model	**Yes**	**No**	**Yes**	**Yes**	**Yes**	**Yes**

Table 2 The value of active harmonic factor current [37]

h	1	5	7	11	13	17	19
HF^p	1	0.2	0.143	0.091	0.077	0.059	0.053
h	23	25	29	35	37	41	43
HF^p	0.043	0.04	0.034	0.029	0.027	0.024	0.015

Table 3 Characteristics of EV

Battery capacity (KWh) [1]	BC≤8	8≤BC≤15	BC≥15
State of charge [3]	0	0.15	0.25
Charger capacity (kVA) [1]	3.3	4.6	6.6
Charging time (h) [1]	≤4	2-4	≥2.5
Charge rate (kW) [1]	2	4	6
EVs in each group (%) [3]	20	60	20

Table 4 Buses with non-linear loads

Network	Bus no.
33-bus	4, 7, 10, 13, 18, 21, 25, 27, 30, 33
69-bus	4, 10, 16, 22, 27, 30, 35, 40, 46, 50, 55, 60, 65
123-bus	4, 6, 11, 12, 16, 20, 24, 29, 33, 39, 46, 59, 83, 90, 104

Table 5 Calculation time of problem solution with and without BD algorithm

<table>
<tr><th colspan="3">Network (bus)</th><th>33-bus</th><th>69-bus</th><th>123-bus</th></tr>
<tr><td colspan="3">BD converged (|W| in pu)</td><td>0.03</td><td>0.10</td><td>0.15</td></tr>
<tr><td rowspan="7">Calculation time of (seconds)</td><td colspan="2">With BD algorithm</td><td>123</td><td>231</td><td>312</td></tr>
<tr><td rowspan="6">without BD algorithm (different solvers of GAMS software)</td><td>CONOPT</td><td>981</td><td>Out of memory</td><td>Infeasible</td></tr>
<tr><td>BARON</td><td>993</td><td>Out of memory</td><td>Infeasible</td></tr>
<tr><td>COUENNE</td><td>990</td><td>Out of memory</td><td>Infeasible</td></tr>
<tr><td>IPOPT</td><td>Infeasible</td><td>Infeasible</td><td>Infeasible</td></tr>
<tr><td>KNITRO</td><td>978</td><td>Out of memory</td><td>Infeasible</td></tr>
<tr><td>MINOS</td><td>994</td><td>Out of memory</td><td>Infeasible</td></tr>
</table>

Table 6 Number of variables and equations of problem with and without BD algorithm

<table>
<tr><th colspan="2">Number of</th><th>Equations</th><th>Variables</th></tr>
<tr><td colspan="2">without BD algorithm</td><td>58642</td><td>116424</td></tr>
<tr><td rowspan="2">With BD algorithm</td><td>Master problem</td><td>55474 with benders cut equation</td><td>116424</td></tr>
<tr><td>Sub-problem</td><td>6337</td><td>69697</td></tr>
</table>