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Impact of Electric Vehicle Charging on the Nairobi Aerial Distribution Network

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***Abstract*—** Kenya has a strong interest in electric vehicles (EVs), which are quickly being deployed in key cities such as Nairobi. The problem with the increasing number of EVs in the country is that they will lead to an increase in electrical power demand and excessive power losses. This paper seeks to analyze the impact of the large adoption of electric vehicles on the Nairobi aerial distribution network, with a focus on the Juja section. The methodology in this work assumes that 50% of the households in the study area own EVs. Two types of chargers to service the EVs are considered; Level 1 chargers and Level 2 chargers. Levels 1 chargers are installed at homes and are used to charge the EVs at night when the owners are back home, while Level 2 chargers are installed at commercial parking lots and are used to charge the EVs during the day when the EV owners are at work. A 24 hours Time Domain Analysis is performed using ETAP software considering two scenarios; the first being that all the EVs are charged at night from 9 pm to 6 am the next day using Level 1 chargers, and the second being that all the EVs are charged during the day from 10 am to 2 pm using Level 2 chargers. Simulation results show that charging all the EVs at night leads to an increase in the total daily active power loss in the study network from 0.57MW with no EVs to 190.36MW, while charging the EVs during the day using Level 2 chargers leads to an active power loss of 271.616MW. From this study, it is recommended that appropriate charging schemes must be put in place as the number of EVs keeps growing in Nairobi, and other parts of Kenya.

***Keywords*—**Electric vehicles, Charging stations, Nairobi, Power losses

I. INTRODUCTION

TOday's transport sector is undergoing a rapid mutation as a result of the increasing integration of electric vehicles (EVs). Though EVs today may seem like new technology, they began way back in the late middle of the 19^{th} century, with the first electric cars being developed by England and France in the late 1800s [1]. EVs are proving to be a promising way to reduce the amount of greenhouse gas (GHG) emissions from the transport sector [2]. In Kenya for example, as of 2019, the country's domestic transport emissions stood at 12.343 $MtCO_2e$ (excluding emissions from waterborne navigations) and of this, 12.09 $MtCO_2e$ came from the roads [3]. The world is fast embracing EVs which are fuel-efficient, noise-free, and emissions-free because of the urgent need to cut down emissions from this sector as the fight against climate change intensifies [4][5]. The fast adoption of EVs by all heavily depends on the swift expansion of charging infrastructures in the communities and work environments [6].

Kenya has a very great interest in EVs which are progressively being deployed in major cities like Nairobi with electric vehicle charging stations (EVCSs) already at Thika Road Mall, Two Rivers Mall, and the Hub Karen [7]. Also, the unfolding of EVs in Kenya is a result of strategies put in place at gearing up the population to acquire EVs. The electric vehicle standards adopted in 2019 by the Kenya Bureau of Standards (KEBS) aiming at reducing excise duty from 20% to 10% on EVs has been an excellent way to promote the ratification of EVs in the country [7]. In addition, Kenya Power and Lighting Company (KPLC), which is the electricity distribution operator of the country, in March 2021, expressed its plan of building EVCSs in Malls, parking lots, and along major highways as a way of stimulating electric car demand as well as boosting the revenue stream of the company . With these strategies put in place, the number of EVs in the country will keep increasing and it is important to be able to assess the impact of these EVs on the electrical distribution network to be able to know how to strategically install the EVCSs and also adopt a beneficial charging scheme to minimize the impact of the EVs on the distribution network. This is because EVs in addition to benefiting the transport sector could endanger the electrical distribution network in terms of excessive power losses, distribution feeder imbalance, and an increase in the bidirectional flow of current and fault current levels [8]. Variations in the network voltage beyond acceptable could also be experienced [9].

This paper seeks to analyze the impact of EVs on the Nairobi aerial distribution network, with a focus on the Juja network section. Two charging scenarios are considered, the first being that all the EVs in the chosen area are charged only at night using Level 1 chargers at homes, and the second being that all the EVs are charged during the day using Level 2 chargers in parking lots, and commercial areas.

II. METHODOLOGY

A. Classification of electric vehicles

According to [10], EVs can be classified as follow;

i. Battery Electric Vehicle (BEV): This type of EV is powered 100% by batteries. They are commonly called

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Battery-only Electric vehicles (BOEV) [11]. BEVs suffer from a short range of up to 250km when their batteries are fully charged [12]. That notwithstanding, the new models of BEVs developed such as the Nissan Leaf e+ can go up to 325km before necessitating recharging. BEV can be charged by plugging the EV into a socket outlet or through battery swapping.

ii. Plug-in hybrid electric vehicle (PHEV): This type of EV makes use of a combination of an electric engine and an internal combustion engine (ICE) for propulsion. The batteries in PHEV are charged by plugging the vehicle into a utility outlet. The problem of the short-range of BEV is overcome significantly by PHEVs which can go up to 500km due to the use of ICE as well [12].
iii. Hybrid electric vehicles (HEVs): They use a combination of an electric engine and an ICE for their propulsion like the PHEV. Nonetheless, HEV differs from PHEV in the sense that HEV's batteries are charged by the power that is generated by the ICE, hence the vehicle does not require to be plugged into a utility for charging. Advanced HEVs also make use of regenerated braking to charge the batteries.
iv. Extended range EVs (ER-EVs): This type of EV is similar to BEV, but is equipped with a supplementary ICE whose main function is to charge the vehicle's batteries when needed, thereby giving the vehicle an extended range. The ICE in ER-EVs is not used for propulsion as is the case in PHEV and HEV.

Fig. 1 shows a summary of the classification of EVs.

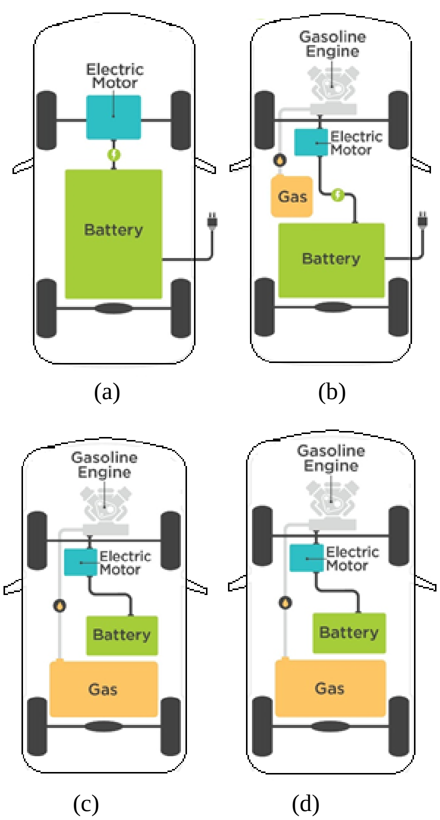


Fig. 1. Classification of EVs, (a) BEV, (b) PHEV, (c) HEV (d) ER-EV [10]

Among the various classifications of EVs discussed above, BEV and PHEV are plug-in electric vehicles (PEVs) because they can be plugged into the grid socket outlet for battery recharge while HEV and ER-EV are not. Only BEVs are considered in this research work.

B. *Electric vehicle charging stations*

An Electric vehicle charging station (EVCS) can be defined as a secured, monitored, and controlled channel that connects the EV to the grid as shown in Fig. 2 [13]. The EV charger is the power electronic equipment that converts the AC power from the grid into DC power to charge the EV batteries.

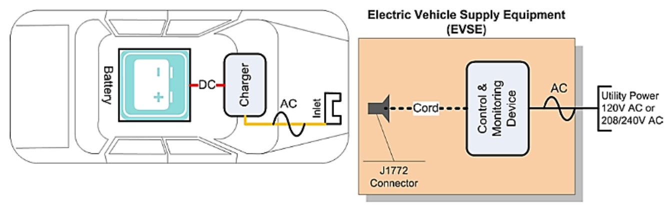


Fig. 2. Electric vehicle charging station with an EV [13]

EV charging according to the international standard IEC 61851 is divided into four types or modes and these modes vary according to the current the EV charger draws from the mains and hence the time it takes to charge the EV [14]. As per this standard, the various modes of EV charging are;

i. Mode 1 charging: This is referred to as plugging the EV charger into a single-phase AC mains of 250V maximum or a three-phase mains of 480V at a frequency of 50/60Hz and the current drawn by the charger, in either case, should not exceed 16A. This mode of charging is very slow and requires several hours to fully charge the EV batteries. It is usually used at home to charge the EV overnight or at offices since very low power is drawn from the grid and it also does not require additional infrastructures. Mode 1 EV charging despite being slow is advantageous to the distribution network in the sense that it has a low impact on peak electricity demands.
ii. Mode 2 charging: This is similar to mode 1 charging with the exception that the EV is allowed to draw up to 32A from the mains while not violating the operations of the protective equipment put in place. In addition to the current drawn from the mains, mode 2 charging also differs from mode 1 charging in the sense that it has a control pin at the vehicle's inlet and connector. Unlike mode 1, mode 2 charging is used in dedicated facilities.
iii. Mode 3 charging: This mode is an extension of mode 2 charging with the EV being able to pull up to 63A from the mains. A piece of control equipment is permanently connected to the AC mains to adequately manage the charging of the EV. This mode of charging is fast as it can fully charge an EV within a few hours when the EV owner is at work. Despite mode 2 and mode 3 charging being faster and more efficient than mode 1 charging, mode 2 and 3 charging are costlier and have a higher potential to impact peak electricity demand.

iv. Mode 4 charging: While modes 1, 2, and 3 are done using the EV's onboard charger, mode 4 uses an offboard charger. The AC power from the mains is converted into DC power by the off-board charger and supplied to the EV. In mode 4 charging, an EV battery can be fully charged within 30 minutes. This charging mode is very costly and can potentially soar peak electricity demand as the EV draws up to 400A from the grid.

A summary of the various modes of EV charging is shown in Fig. 3 below.

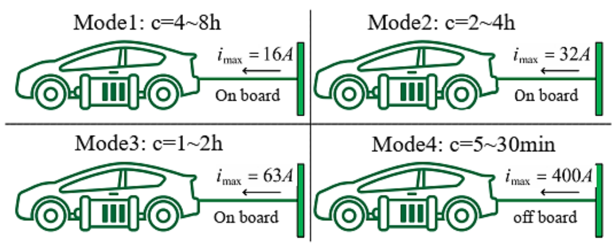


Fig. 3. EV charging modes according to IEC 61851-1 standard [14]

With these modes of EV charging, EV chargers have been categorized into 3 levels, that is; Level 1, Level 2, and Level 3 chargers. Level 1 chargers exhibit mode 1 charging, Level 2 chargers exhibit modes 2 and 3 charging, while Level 3 chargers exhibit mode 4 charging scheme [15]. A comparison of Level 1, 2, and 3 chargers is shown in Table 1.

Table 1: Comparison of Level 1, 2, and 3 EV Chargers

Charger	Charger Type	Current drawn from mains	Charging time	Range per charging hour
Level 1	AC	12-16A	6-10 hours	8 km
Level 2	AC	32-70A	1-3 hours	16-32 km
Level 3	DC	167A	30 mins	120+ km

Despite Level 3 chargers being able to fully charge an EV battery within minutes, this technology is not yet fully developed as there is a great need for a wide development of compatible EV batteries for this charger. Level 1 and Level 2 are the ones that are widely used so far. Therefore, making EV charging a long deal. In attempting to resolve this long charging time, EV battery swapping stations (EVBSS) are being introduced into the e-mobile industry. EVBSS offers the possibility for EV users to automatically and effortlessly replace their flat EV batteries with fully charged ones [16]. In this setting, an EV's battery can be replaced within a few minutes, a much shorter time than the one required to refuel a gasoline vehicle as already been utilized and demonstrated by some EV manufacturing companies like Tesla [17]. The first commercial usage of battery swapping was done in 2008 in China during the summer Olympics where the batteries of about 50 electric buses were swapped [18].

C. Study Area

In this study, the Juja section of the Nairobi aerial distribution network is used as a study network to analyze the impact of EV charging on the network. The Juja network section is a 14-bus distribution network comprising at a voltage of 66kV as shown in Fig. 4

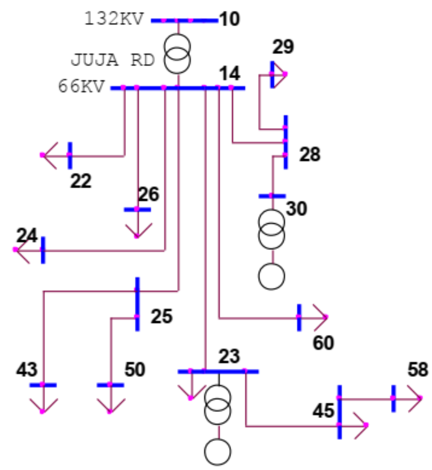


Fig. 4. Juja section of the Nairobi distribution network [19]

The study area is considered to be a mixture of commercial and residential loads, with the commercial loads clustered to form a commercial area. Loads on buses 22, 24, and 26 are commercial loads, while the loads on other buses are residential as shown in Fig. 5.

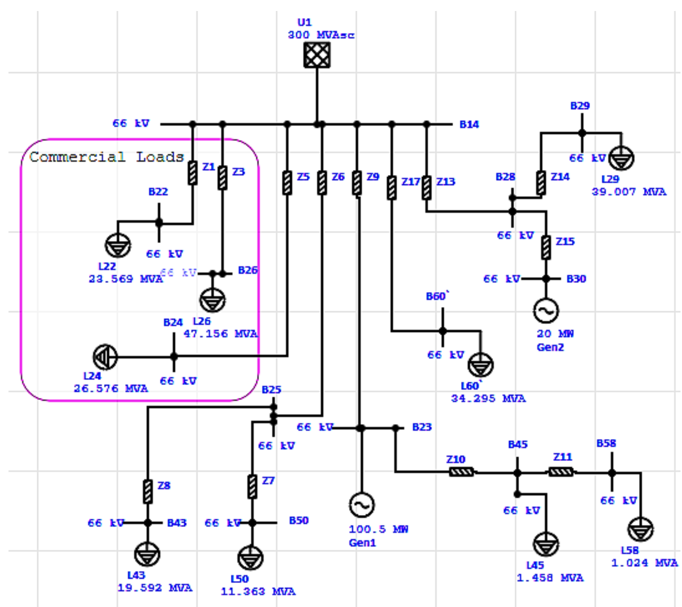


Fig. 5. Segregation of the study area into commercial and residential areas

The normalized daily load profile of the commercial loads, as well as the residential loads, are shown in Fig. 6 and 7 respectively. The normalized load curve of commercial loads is obtained from [20]. These commercial loads are offices and retail shops. The residential load profile is that of a typical household in Nairobi as obtained from [21]. The residential loads are small households.

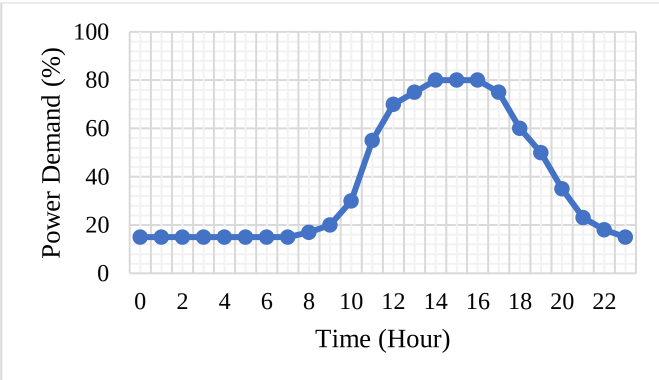


Fig. 6. Commercial daily load curve

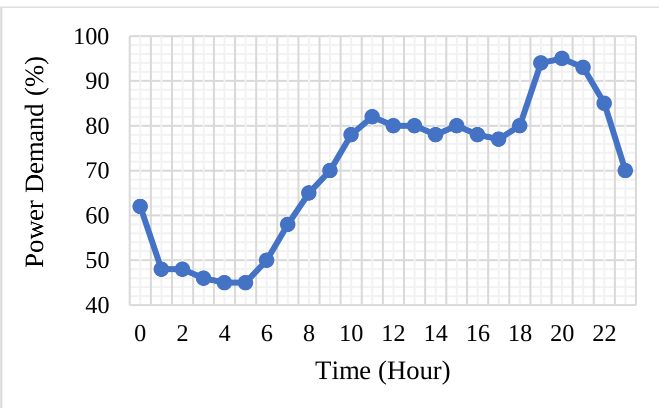


Fig. 7. Residential daily load curve

D. Estimation of the EV population

The EV population is obtained from the percentage of EV integration in the study area. This percentage of EV integration is calculated as the ratio of the number of households with EVs, N_{hhEV} to the total number of households in the study areas, N_{hh} as shown in equation (3.42).

$$\%EV = \frac{N_{hhEV}}{N_{hh}} * 100 \tag{1}$$

The number of households in a study area is obtained using equation (3.43)

$$N_{hh} = \frac{S_{Thh}}{S_{hh}} \tag{2}$$

Where N_{hh} is the number of households in the area, S_{Thh} is the total apparent power demand of the residential loads and S_{hh} is the apparent power demand of a single household.

The EV population of the study area is obtained from the total apparent power demand of the loads. As earlier mentioned, the study network is a mixture of residential and commercial loads. Considering each household to have an apparent power demand of 18kVA, using equation (2), the number of households is obtained to be 5930 households. The repartition of the network into residential and commercial loads is shown in Table 2. Furthermore, considering a percentage EV population of 50% and assuming that each household can have a maximum of only 1 EV, using equation (1), the number of EVs in the study area is calculated to be 2965EVs. A summary of the number of households and EVs in the study area is shown in Table 3.

Table 2. Repartition of the network into residential and commercial loads

Commercial load nodes	Residential load nodes	Total residential loads power demand (MVA)	Total commercial load power demand (MVA)	Total network power (MVA)
22, 24, 26	29, 43, 45, 50	106.739	97.301	204.04

Table 3. Estimation of the EV population of every network

Power demand per household (kVA)	18
Total number of Households	5930
% EV integration	50
Number of EVs	**2965**

E. EV modeling using ETAP

The EVs are modeled in ETAP using a battery whose capacity agrees closely to the chosen EV moel's battery pack capacity. For this study, the Nissan Leading, Environmentally Friendly, Affordable, Family Car (LEAF) commonly called Nissan Leaf is chosen to be the EV used by inhabitants of the study area, precisely the Nissan Leaf 2018. The Nissan Leaf 2018 has a battery pack capacity of 40.0kWh for a range of 220km. The battery characteristics of this EV model are shown in Table 4 [22],

Table 4: Nissan Leaf 2018 battery characteristics

	Characteristics
Number of cells	192
Cell configuration	2 parallel arrangements of 96 cells in series
Nominal voltage of a single cell	3.65 V
Nominal voltage of battery pack	364.8 V
Rated capacity of battery pack	56.3 Ah
Battery pack energy rating	40kWh
Battery Useable	36 kWh

ETAP has a vast library of batteries and the battery whose rating agreed closest to the Nissan Leaf 2018 battery pack is the CC model of the YUASA-EXIDE battery having a capacity of 50Ah as shown in Fig. 8. A total of 192 cells was selected giving a rated open circuit voltage of 395.5V

The Level 1 chargers used here are three-phase chargers that charge the modeled EV with a current of 16A from the mains, while Level 2 chargers used here are three-phase chargers that charge the modeled EV with a current of 32A from the mains as shown in Fig. 9

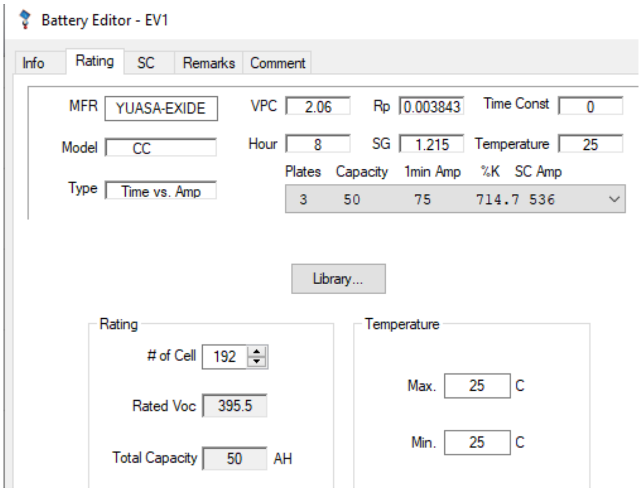


Fig. 8. Nissan Leaf 2018 model using ETAP

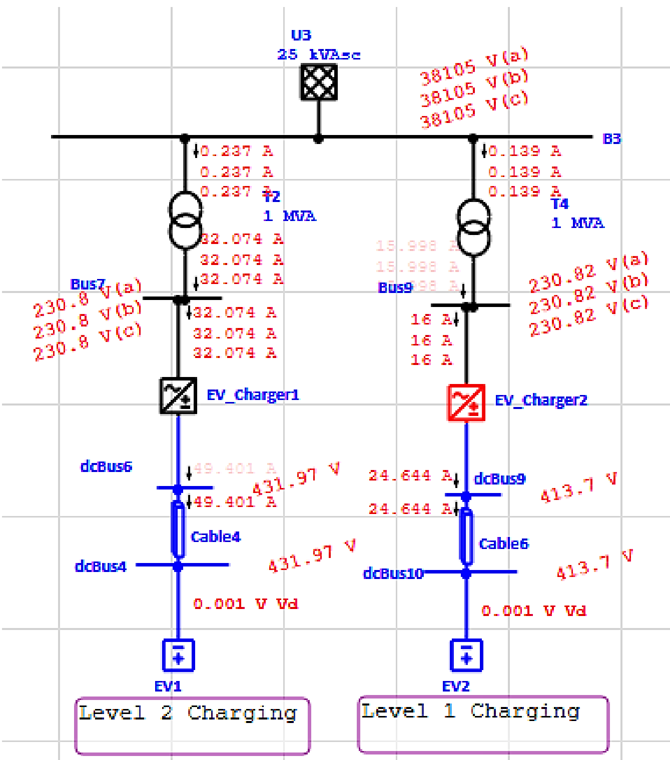


Fig. 9. Test charging of the modeled EV in ETAP

F. *Simulation Scenarios*

ETAP software time-domain analysis is used to analyze the impact of the EVs on the Juja distribution network. A 24 hours simulation is performed considering two scenarios bringing out the uniqueness of this study;

- All the EVs are charged at night using Level 1 chargers in homes as shown in Fig. 10; that is, the EVs are charged from the normal socket outlets in homes
- All the EVs are charged during the day using Level 2 chargers installed in parking lots and commercial areas as shown in Fig. 11.

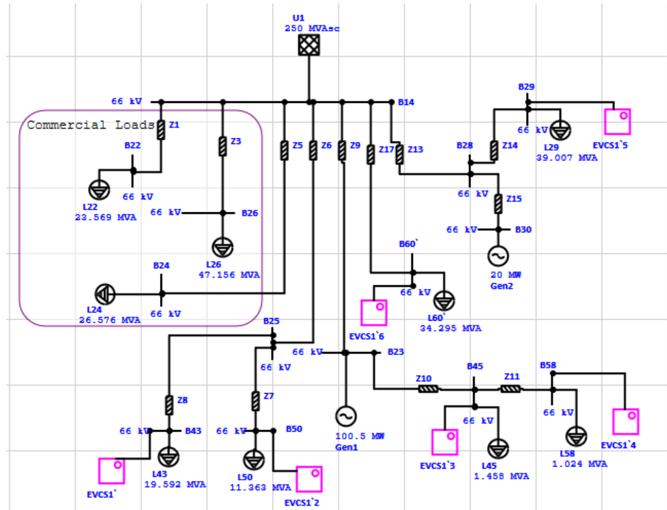


Fig. 10. All EVs charged using Level 1 chargers at homes

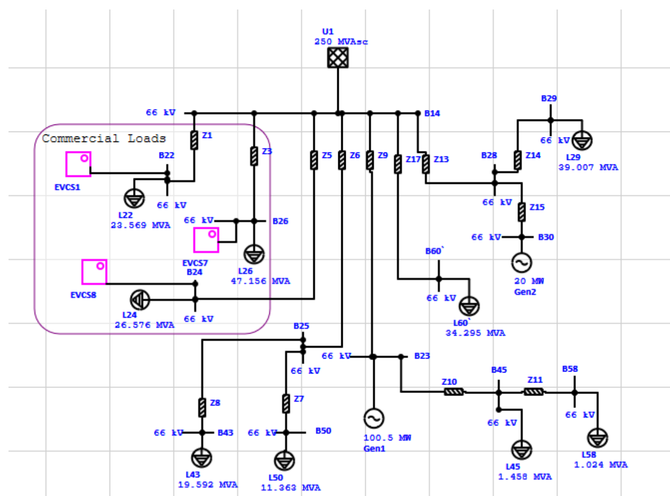


Fig. 11. All EVs charged using Level 2 chargers at the commercial district

III. RESULTS AND DISCUSSIONS

The impact of the two simulated EV charging scenarios on the Juja section of the Nairobi aerial distribution network is shown below.

A. *Impact of the EVs on the substation current*

As shown in Fig. 12, it is observed that for both charging scenarios, incorporating the EVs into the distribution network leads to an increase in the current supplied by the main substation. The increase in the current supply is a result of the EVs being an extra load to the distribution network and hence extra power needs to be supplied by the substation to be able to charge the EVs while servicing other loads. That notwithstanding, the increase in current due to the Level 1 charging scenario is lesser compared to that due to Level 2. Charging the EVs with Level 1 chargers at night increase the current by roughly 185.73A at each hour of charging. Meanwhile, charging the EVs with Level 2 chargers during the day leads to an increase in the substation current by roughly 475.18A at each hour of charging. The Level 1 scenario lead to a lower increase in the substation current compared to the Level 2 charging scenario because of the lower power demand of Level 1 chargers (11kW) compared to 22kW of Level 2 chargers. It can therefore be deduced that the distribution substation is more stressed with the Level 2 charging scenario compared to the Level 1 charging scenario.

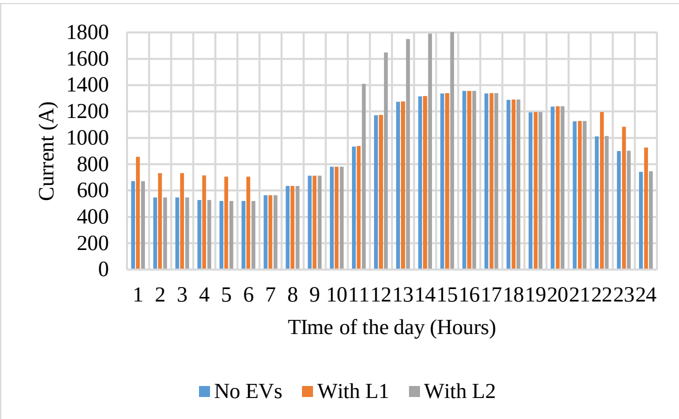
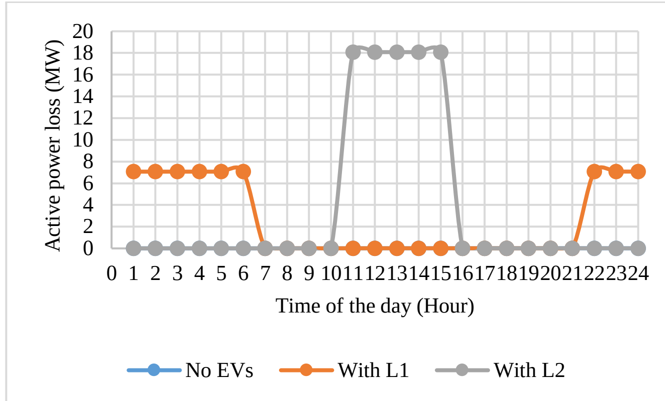


Fig. 12. Impact of Level 1 and Level 2 EV charging scenarios on the substation current supply

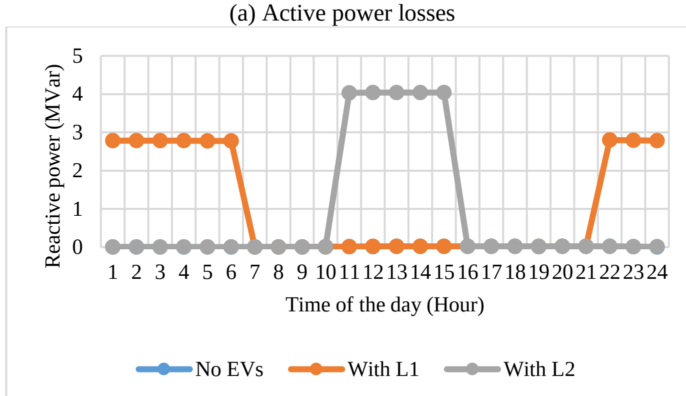
B. *Active and reactive power losses*

As can be observed in Fig. 13, the insertion of the EVs into the distribution network at any time of the 24 hours simulation time leads to an increase in the active and reactive power losses at that instance. Nevertheless, the increase in power losses due to the Level 2 charging scenario is more than that due to the Level 1 charging scenario. This is because as explained in the previous section, Level 2 charging leads to a higher current being drawn from the substation, and power loss is a function of the current flowing through the network feeders.

Looking at the overall daily total active power losses during the 24 hours simulation for both charging scenarios, the total active power loss with the adoption of the Level 1 charging scheme on each phase of the network is lower than that when the Level 2 charging scheme is utilized even though Level 1 charging takes a longer time (9 hours) compared to 5 hours of the Level 2 charging. The total active power loss on each phase of the network increases from 0.19MW giving a total of 0.58MW of power loss on all three phases to 63.79MW giving a total of 191.36MW on all three phases of the network. Meanwhile, for the Level 2 charging scenario, the total active power loss on each phase of the network increases to 90.34MW, giving a total of 271.62MW on all three phases of the network. Fig. 14 shows the total active power loss in the network for both EV charging scenarios. It, therefore, means that adopting the Level 1 charging scenario will be beneficial to the distribution network compared to adopting the Level 2 charging scenario.



(a) Active power losses



(b) Reactive power losses

Fig. 13. Daily active and reactive power losses as per the two charging scenarios

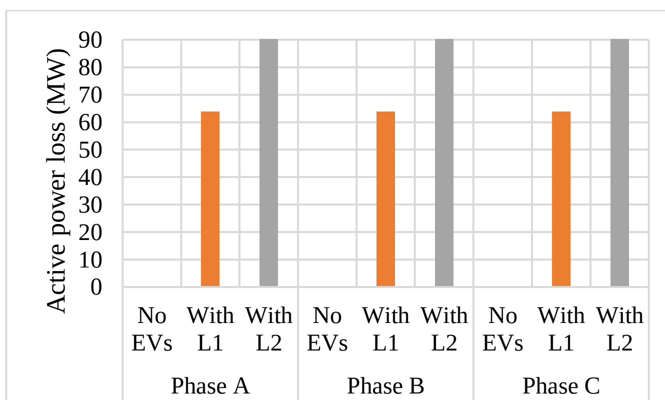


Fig. 14. Total daily active power loss

IV. CONCLUSION

In this paper, the aim was to analyze the impact electric vehicle adoption will have on the Nairobi aerial distribution network with the focus being on the Juja section of the network. A 24 hours simulation was done using ETAP software. Two charging scenarios of the EVs were considered; the first being that the EVs are charged at night using Level 1 chargers, and the second being that the EVs are charged during the day using

Level 2 chargers. From the simulation results obtained, it is observed that in both simulation scenarios, the charging of EVs leads to an increase in the network total power losses because of the EVs being extra loads to the electrical distribution network. Nonetheless, the increase in power losses in the Level 1 charging scenario is lower compared to that in the Level 2 charging scenario and the reason for that is that the lower power demand of Level 1 chargers is lower compared to that of Level 2 chargers. It can therefore be deduced that adopting the Level 1 charging scheme is better for the health of the electrical distribution network as it leads to lower power losses and hence less stress on the network compared to the Level 2 charging scenario.

The future scope of this research will see the simulation of both scenarios on the entire Nairobi aerial distribution network. Also, a combination of Level 1 and Level 2 charging will be considered as a third scenario.

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