Controlled electric vehicle charging for reverse power flow correction in the distribution network with high photovoltaic penetration: case of an expanded IEEE 13 node test network

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ABSTRACT

Over the past years, the penetration of photovoltaic (PV) systems into the distribution network has experienced significant augmentation as the pressure to reduce greenhouse gas emissions into the atmosphere keeps increasing while the prices of the solar components keep reducing. Despite the benefits PV systems bring to the distribution network, the high penetration of this technology into the distribution network could lead to reverse power flow (RPF) when the PV systems produce more than the local loads require. This RPF could result in the malfunctioning of protective devices and their coordination. This research addresses this problem by utilizing electric vehicles (EVs) that are currently revolutionizing the transport sector. Here, the charging of EVs during the day is intelligently controlled to mitigate RPF as a result of the excess power produced by the PV systems. Resolving RPF is achieved through a control system that measures the power flow on each phase of the main grid substation. If at any instance negative power is detected (reverse power), quantified EVs needing recharge are instantly incorporated into the network for charging through the automatic closure of the power switches of the required number of charging points with EVs whose total power demand equals the amount of reverse power detected. The excess power is hence absorbed and stored by the EVs. The proposed method is tested on an expanded IEEE 13 node test feeder and simulated using ETAP software. Simulation results show the effectiveness of the proposed method in eliminating RPF which occurs from 10:00 am to 12:00 noon by connecting the required number of EVs during that timeframe. The proposed method involves the distribution network operators working in synergy with the transport sector to effectively solve the problem of RPF in the distribution network.

1. Introduction

The penetration of photovoltaic (PV) systems into today's power system is fast increasing, owing to the abundant nature of the solar resources as well as the increasing pressure to reduce greenhouse gas (GHG) emissions into the atmosphere as much as possible [1]. The top of the earth's atmosphere is exposed to solar energy in the range of 174 Petawatt of power, which is about 10000 times the power obtained from all conventional sources like nuclear, hydro, coal, oil, and natural gas put together [2]. This energy is so huge that if solar systems covering only 0.16% of the earth's surface and having an efficiency of just 10% were installed, the power produced from that will be 20 Terawatt and this is about twice the power the entire world consumes from fossil fuels [3]. The integration of PV systems into today's power system is fast increasing due to the continuous decrease in the prices of solar panels and the associated components [4]. Also, PV systems and other distributed generation (DG) technologies are gaining grounds in today's distribution network because DGs are being sorted as a solution to solving the problem of high power losses, high distribution transformer R/X ratios, poor voltage profile, and inadequate reliability of the distribution network due to the long length of the network. The increase in PV penetration in the distribution network is helpful to the network in solving the abovementioned problems as they can assist in voltage support, peak shaving, and power loss reduction [5]. Policies such as feed-in tariff have also been the driving force towards the increasing penetration of PV systems into the distribution network as electricity consumers can benefit from it by generating small power and selling to the grid. The consumer whose PV system feeds the grid benefits from reduced...
electricity bills paid as he/she pays only the extra power gotten from the utility company [6]. The word prosumer is used to describe a concurrent electricity producer and consumer [7]. It is usually used in the case of electricity consumers who produce electricity locally, use some and sell the excess to the grid [8]. However, the conventional power system was not built to harbor generation at the distribution level as it was designed for centralized generating stations, making use of transmission lines to carry the bulk power generated over long distances to loads centers connected to the distribution network. This topology gave a unidirectional flow of power from generation to distribution. With the massive introduction of PV systems in the distribution network, the problem of reverse power flow (RPF) upstream at certain times of the day when the PV systems produce more power than the load demand, leading to excess power losses, feeders overload and malfunctioning of tap changing transformers and voltage regulators surfaces [9].

On the other hand, the adoption of electric vehicles (EVs) in our communities is on the rise as there is a need to cut down GHG emissions from the transport sector and its dependence on fossil fuels. It is a viable way to render the transport sector free from carbon air pollution. Scientist and researchers have shown that EVs powered by renewables and other noncarbon emission power sources is the way forward to cut down global warming pollution to 80% lower than that of 1990 (22.4 billion metric tons of carbon dioxide) by the year 2050 [10, 11]. Even though EVs today may sound like a new technology to many, this technology began way back in 1820 with the first experimental cars and saw a breakthrough in 1870 thanks to the invention of powerful motors and the rechargeable battery [12]. Since then, electric cars continued to be used in competition with internal combustion engine (ICE) cars. It was up to around the 1920s that EVs began to be overtaken by ICE cars and this was due to the pavement of highways linking American cities and the discovery of oil reserves in California, Oklahoma, and Texas [13]. The interest in EVs was again renewed due to the energy crisis of the 1970s and 1980s and this led to the takeoff of the development of the technology. EVs are a promising technology as they are environmentally friendly since they are free from emissions, noiseless, and fuel-saving [14]. That notwithstanding, the rapid adoption of EVs heavily depends on the rapid construction of charging infrastructures where people live, play, and work. EVs can be extremely beneficial to the distribution network as they can be used as spinning reserves to solve distribution network problems like voltage unbalance, frequency fluctuations, peak shaving, amongst others [15]. The strategic charging and discharging of EVs can enable EVs to be used as a flexible resource to ensure a match between power demand and supply through grid-to-vehicle (G2V) and vehicle-to-grid (V2G) and in so doing mitigate the effects of the variability of the solar resource and potentially correct reverse power flow in the distribution network with high PV penetration.

2. Reverse power flow (RPF)

Reverse power flow (RPF) is a phenomenon that has been introduced in power systems due to the increased adoption of distributed generation (DG). It is the backward flow of power upstream (from the low voltage side to the high voltage side) at certain times of the day when the DGs produce more power than the local load demand [16, 17]. On the other hand, RPF could also be a result of the drastic reduction in the local load demand to the point of excess power in the network which then flows backward [18]. RPF is dangerous in the distribution network as it leads to voltage peaks above acceptable margins [19], and also critically affects the sensitivity and parameters of protective device coordination, hence negatively affecting power quality [20].

A lot of researches have proposed solutions to eliminate reverse power flow in the distribution network. In [21], the authors proposed an online method that uses the dynamic Thevenin equivalent for prevention control of overvoltage in microgrids with PV systems since the over-voltage was caused by RPF and this limited the output of PV systems. The authors in [22] investigated the use of distributed Static Synchronous Compensators (STATCOM) for reactive power control and hence voltage control in the distribution network to mitigate voltage violation during excessive PV systems generation during peak solar irradiance periods. In [23], the authors evaluated the usage of an EV battery as a storage device for a home PV system with the aim of RPF reduction as well as reducing the dependency of the EV on the grid for charging power. The study took into consideration the electricity demand forecast in addition to solar irradiance and it was demonstrated that electricity bills could be reduced by controlling RPF into the grid. The authors in [24] proposed the use of reverse power relays to mitigate reverse power flow in the distribution network as a results of DGs. The reverse power relay monitored the power flow from the centralised generating units and disconnected the DGs in the distribution network when reverse power was detected. In [25] is proposed a technique based on impedance to monitor and detect RPF in a distribution network with high penetration of PV systems. Testing the technique on the IEEE 34 node test feeder showed its ability to detect slight variation in PV penetration levels as well as the fast transient effect of cloud movement on PV production.

This research proposes a novel method to mitigate RPF in the distribution network with high penetration of PV systems during the day when the PV systems produce more power than the loads need. The novel method makes use of EVs that are speedily gaining their integration into the transport sector to mitigate RPF in the distribution network due to the saturation of the network with PV systems. EVs and PVs are two technologies that are being embraced by all and using EVs to solve the challenge of RPF brought in by PV systems without further network modifications is a plus for today’s power systems. In this paper, mitigation of RPF is achieved by controlling the charging of EVs connected to the distribution network. The method is based on a control system that measures the amount of reverse power on each phase of the utility main substation and automatically connects quantified EVs into the network to absorb and store the reverse power. In so doing protecting the distribution network against the harmful effects of RPF. The proposed method is tested on an expanded IEEE 13 node test distribution network to ascertain its effectiveness. The contributions of this paper to the body of knowledge are;

- An expanded IEEE 13 node test distribution network whose main node voltages match closely with published results of the original network.
- A control scheme for the charging of electric vehicles during the day to correct reverse power flow in a distribution network with high penetration of photovoltaic systems.

The remaining parts of this paper are organized as follows; the next section is the methodology, and it is followed by the results and discussions, and then a conclusion.

3. Methodology

3.1. Test network

An expanded IEEE 13 node test feeder is used as the test network in this research. IEEE test distribution networks are famous distribution networks that were introduced in the first instance in 1991 by W. H Kersting with the aim of providing an ordinary set of data for program developers and other users to validate the efficacy of their solutions [26]. Since then, these networks have undergone modifications in addition to the development of other benchmarked networks. The IEEE 13 node test feeder is chosen for this study because it is an unbalanced network that is very short, at a nominal voltage of 4.16kV, comprising of a mixture of underground and overhead lines, with a variety of phasing [27]. Despite this network being very short, it is heavily loaded with a 4.16/0.48kV inline transformer as shown in Figure 1 below.

The expansion of the IEEE 13 node test feeder is done in this research so as to include the low voltage side of the network. The expansion is
done by adding step-down transformers and cables that feed the three-phase loads of the network at a voltage of 0.48kV and the single-phase loads at a voltage of 0.277kV. The various load nodes of the network are expanded and named as shown in Table 1. The expansion of the network is executed such that the voltage and angle at the original nodes after load flow analysis agrees closely with published IEEE results as shown in Table 2.

### 3.2. Photovoltaic penetration into the test network

The PV systems are installed on the three-phase nodes of the test network at 10%, 20%, 40%, and 60% penetration levels. From the literature, various methods are used to estimate the percentage of PV penetration into the distribution network. The percentage PV penetration into the distribution network could be estimated as [28];

- The ratio of the rated power of the PV systems to the active power demand of the loads
- The ratio of the peak capacity of the PV systems to the peak apparent power demand of the loads
- The ratio of the PV systems' total production to the total generation of the network

In this work, the percentage of PV penetration is calculated as the ratio of the total rated power of installed PV systems to the total active power demanded by the loads in the network as shown in Eq. (1).

\[
\% PV = \frac{PV \text{ Capacity}}{Total \text{ active power of the Loads}} \times 100
\]  

#### Table 1. IEEE 13 Test System Load node expansions.

| Node | Expansion |
|------|-----------|
| 611  | 611,1     |
| 612  | 611,2     |
| 613  | 611,3     |
| 614  | 611,4     |
| 632  | 612,1     |
| 633  | 612,2     |
| 634  | 612,3     |
| 635  | 612,4     |
| 636  | 612,5     |
| 645  | 612,6     |
| 646  | 612,7     |
| 652  | 612,8     |
| 671  | 612,9     |
| 672  | 612,10    |
| 673  | 612,11    |
| 674  | 612,12    |
| 675  | 612,13    |
| 692  | 612,14    |

#### Table 2. Load flow analysis of Mod13 node compared with published IEEE results.

| Node | Phase | Simulation Results | IEEE Results |
|------|-------|--------------------|--------------|
|      |       | Voltage | Angle | Voltage | Angle |
| 611  | C     | 0.9715  | 115.8 | 0.9738  | 115.78|
| 632  | A     | 1.0211  | -2.5  | 1.021   | -2.49 |
|      | B     | 1.0425  | -12.17| 1.042   | -12.72|
|      | C     | 1.0166  | 117.8 | 1.0174  | 117.83|
| 633  | A     | 1.018   | -2.6  | 1.018   | -2.56 |
|      | B     | 1.0406  | -12.18| 1.0401  | -12.77|
|      | C     | 1.0139  | 117.8 | 1.0148  | 117.82|
| 634  | A     | 0.9941  | -3.2  | 0.994   | -3.23 |
|      | B     | 1.0223  | -12.22| 1.0218  | -12.22|
|      | C     | 0.9951  | 117.4 | 0.996   | 117.34|
| 645  | B     | 1.0333  | -12.19| 1.0329  | -12.19|
|      | C     | 1.0146  | 117.9 | 1.0155  | 117.86|
| 646  | B     | 1.0316  | -12.21| 1.0311  | -12.19|
|      | C     | 1.0126  | 117.9 | 1.0134  | 117.9 |
| 652  | A     | 0.9756  | -5.2  | 0.9825  | -5.25 |
|      | B     | 1.0537  | -12.3 | 1.0529  | -12.34|
|      | C     | 0.9758  | 116.1 | 0.9778  | 116.02|
| 671  | A     | 0.9899  | -5.3  | 0.99    | -5.3  |
|      | B     | 1.0537  | -12.3 | 1.0529  | -12.34|
|      | C     | 0.9758  | 116.1 | 0.9778  | 116.02|
| 675  | A     | 0.9833  | -5.6  | 0.9835  | -5.56 |
|      | B     | 1.0562  | -12.25| 1.0553  | -12.52|
|      | C     | 0.9739  | 116.1 | 0.9758  | 116.03|
| 680  | A     | 0.9899  | -5.3  | 0.99    | -5.3  |
|      | B     | 1.0537  | -12.3 | 1.0529  | -12.34|
|      | C     | 0.9758  | 116.1 | 0.9778  | 116.02|
| 684  | A     | 0.9877  | -5.4  | 0.9881  | -5.32 |
|      | B     | 1.0537  | -12.3 | 1.0529  | -12.34|
|      | C     | 0.9732  | 116   | 0.9758  | 115.92|
| 692  | A     | 0.9899  | -5.3  | 0.99    | -5.3  |
|      | B     | 1.0537  | -12.3 | 1.0529  | -12.34|
|      | C     | 0.9758  | 116.1 | 0.9777  | 116.02|

The total active power demanded by the IEEE 13 node test feeder is shown in Table 3.

With the information in Table 3, the total required PV capacity at the various study levels of PV penetration is calculated using Eq. (1) and shown in Table 4.

#### Table 3. Load active power demand of test network.

| Phase | Active Power (kW) |
|-------|------------------|
| A     | 1175             |
| B     | 1039             |
| C     | 1252             |

#### Table 4. Random sizing and siting of PV system

In this study, three-phase PV systems are randomly sized and installed on three-phase nodes of the test network. Single-phase loads are left without PV systems. The random sizing and siting of the PV systems are done using Microsoft Excel, and the results are imported into ETAP software. To randomly size the PV systems at a particular level of PV penetration, random numbers are generated using the `rand()` function and assigned to the target nodes. These randomly generated numbers are then utilized to determine the number of PV modules of a chosen rating to be placed on the various target nodes in the network such that the total PV capacity all over the network equals the required PV capacity at a given PV penetration level. ETAP software has a vast library of PV panels of various ratings. From that library, the Yingli YL 280-35 b PV panel is...
chosen. It is chosen because it is the PV panel with the highest rating in the ETAP library hence will require the least number of modules to achieve the PV systems of desired ratings. Also, Yingli YL 280-35 b PV panels are suitable for residential and commercial applications as shown in Figure 2, and this study is focused on distributed PV systems.

At a said level of penetration, the number of PV modules placed on a particular node $k$ is given by Eq. (2)

$$n_k = \frac{\text{rand}(k)}{\sum_{k=632}^{675} \text{rand}(k)} + b$$  \hspace{1cm} (2)

where:

- $n_k$ is the number of PV modules installed on node $k$
- $k$ is the node number
- rand($k$) is the random generation function that generates random numbers between 0 and 1 and assigned to node, $k$

- $b$ is a number carefully chosen such that the total PV capacity equals the expected PV capacity at a particular penetration level.

The total number of PV modules $N_{PV_m}$ all over the network is obtained by summing up all the PV modules at various nodes using Eq. (3)

$$N_{PV_m} = \sum_{k=632}^{675} n_k$$ \hspace{1cm} (3)

The installed PV capacity at node $k$ is obtained using Eq. (4) and from that, the total PV capacity installed in the network is obtained using Eq. (5).

$$P_{PV_k} = n_k \times P_{PV_m}$$ \hspace{1cm} (4)

| PV penetration (%) | Expected PV Power (kW) |
|--------------------|------------------------|
| 10                 | 346.6                  |
| 20                 | 693.2                  |
| 40                 | 1386.4                 |
| 60                 | 2079.6                 |

| Nodes | Rand () | Panel rating (W) | $n_k$ | PV (kW) |
|-------|---------|------------------|-------|---------|
| 632   | 0.294   | 280              | 1361  | 380.98  |
| 634   | 0.519   | 280              | 2407  | 673.82  |
| 671   | 0.016   | 280              | 72    | 20.20   |
| 692   | 0.546   | 280              | 2530  | 708.52  |
| 675   | 0.231   | 280              | 1070  | 299.67  |
| TOTAL |         |                  | 7440  | 2083.2  |

Table 4. Percentage PV penetration.

Table 5. Random sizing/siting of PV systems at 60% penetration.

Figure 2. Yingli YL 280P-35 b PV panel in ETAP library.
\[ P_{\text{tot}} = \sum_{k=675}^{675} P_{\text{PV}} \]

where:
- \( P_{\text{PV}} \) is the PV power installed on node \( k \)
- \( P_{\text{PVm}} \) is the rating of a single PV module
- \( P_{\text{tot}} \) is the total PV capacity installed in the network.

The random sizing and placement of PV systems at 60% PV penetration are shown in Table 5.

### 3.4. Time domain analysis parameters

ETAP's time-domain analysis tool is used in this research work and for that to be accomplished, the daily profile of the various components should be clearly defined.

#### 3.4.1. Network loads

The network loads are categorized into residential loads and commercial loads, with each having its daily load profile.

##### a. Residential Loads

Some of the loads in the network are considered to be residential and hence, it is possible to estimate the number of households in the network. All single-phase loads are considered to be residential loads with each household having an estimated power demand of 5.8 kVA. From the IEEE 13 node dataset, all single-phase loads total to a power rating of 712.96 kVA and this is used to estimate the number of single-phase households as shown in Table 6. A few three-phase loads are considered residential when the buildings considered are more than three floors. These are loads connected on nodes 634, 671_1, 671_2, 671_3, and 675_1. To estimate the number of three-phase households, it is assumed that three-phase households have a power demand of 17.3 kVA each and this enables the estimation of the number of three-phase households as elaborated in Table 7.

From Tables 6 and 7, the total rating of residential loads and the total number of households is obtained and presented in Table 8.

All residential households are assumed to have the same daily load curve shown in Figure 3. This is the load curve on a Wednesday of a typical household in Nairobi, Kenya obtained from [29].

##### b. Commercial loads

All other loads other than residential loads are considered commercial loads. The load profile of commercial loads is obtained from [30] and shown in Figure 4. Commercial loads are assumed to be small retail shops and offices.

##### c. Estimation of the EV population of the study area

It is important to estimate the EV population of the area to ascertain the efficient useability of the proposed scheme for reverse power flow correction. The number of EVs in the study area is obtained from Eq. (6) which is an equation used to estimate the percentage EV penetration of a given locality expressed as the ratio of the number of households with EVs to the total number of households in the area.

\[ \%\text{EV} = \frac{\text{Households with EV}}{\text{Total number of households}} \times 100 \]  

Assuming a percentage EV integration of 15%, and also assuming that a household can have a maximum of one EV, the number of EVs in the study area made up of 176 households is obtained to be approximately 27 EVs.

#### 3.4.2. Solar irradiance and temperature

For time-domain analysis of PV systems, solar irradiance and temperature are necessary. The peak solar irradiance of Machakos, a county next to Nairobi, Kenya obtained from [31], and the temperature in the hot season (month of March) of Nairobi obtained from [32] are used as shown in Figure 5 and Figure 6 respectively. Peak solar irradiance is used.
because it is more likely to experience reverse power flow at high solar irradiance.

3.5. Electric vehicle integration

There are various manufacturers of electric vehicles such as Nissan, Hyundai, Chevrolet, Mitsubishi, among others. In this study, the focus is on the 2018 Nissan Leading which is environmentally friendly, affordable, and a Family Car (LEAF). It is commonly known as the 2018 Nissan Leaf. It is a battery electric vehicle. This EV has a battery pack energy rating of 40 kWh, of which 37 kWh is useable for a driving range of up to 225km before necessitating charging [33]. The 2018 Nissan Leaf model has a Lithium-ion battery pack with the specifications as shown in Table 9. The vehicle’s charger characteristics are shown in Table 10.

3.5.1. Nissan Leaf modeling in ETAP

ETAP has a vast library of batteries with various specifications. The chosen 2018 Nissan Leaf EV is modeled in ETAP using a battery with characteristics that closely agree with the EV battery characteristics shown in Table 9. Since there is no 56.3 Ah battery in ETAP, a 50 Ah battery is used to represent the EV as shown in Figure 7.

Various options exist to charge the 2018 Nissan Leaf using the 3.6kW onboard charger as shown in Table 11 [33]. The third charging option from Table 11 wherein the Nissan Leaf draws 32A from the mains through a single-phase charging point is used in this work. According to the international standard IEC 61851, there are various modes of charging EVs, and charging an EV with 32A from the mains is categorized as mode 2 charging [35]. This type of charging mode is also referred to as level 2 charging and according to research conducted by [36], level 2 chargers have an average efficiency of 89.4%.

From the distribution network points of view, an EV can be seen as

- A simple and straightforward load that draws a stable power from the utility when charging. This is called grid-to-vehicle (G2V).
- A complex load whose charging period can be adjusted.
An energy storage device that is charged and discharged as per the conditions of the network. The discharging of the EV into the network is known as vehicle-to-grid (V2G).

In this paper, the EVs are considered as per the third option with the exception that the V2G is not considered, but is future scope of this work. Modeling the EV charger in ETAP software is done such that the charger draws 32A from the mains to charge the Nissan Leaf battery. The charger has an efficiency of 89.4% and operates at a power factor of 0.98. The modeled charger characteristics are shown in Figure 8.

A test simulation is conducted wherein the modeled 2018 Nissan Leaf is charged using the modeled charger and the charger draws 32A from the single-phase mains as a practical level 2 charger as shown in Figure 9.

### 3.5.2. Algorithm for EV insertion into the network for RPF correction

The process of RPF monitoring and correction begins in the morning with EV owners arriving at work at 8 am–9 am, and plugging in their EVs into available charging points in parking lots. The state of charge (SoC) of the batteries of the plugged EVs are measured and recorded. Nevertheless, the charging points are kept powered off despite the EVs being plugged into them. This is achieved by a control system that keeps the individual power switches of all the EV charging points opened. The direction of power flow on each phase of the utility main substation supplying the entire network begins to be monitored and this process continues throughout the day. When the direction of power flow in any of the phases is reversed due to the PV systems producing more power than what the loads in the network require at that moment, the reverse power flow is immediately detected and the amount of reverse power instantly measured. The measured reverse power, \( P_{rev} \), is used to determine the number of EVs whose batteries require charging, to be connected to the network using Eq. (7).

\[
N_{EV} = \frac{P_{rev}}{P_{EV,ch}} \tag{7}
\]

where \( N_{EV} \) is the number of EVs whose batteries require charging, \( P_{rev} \) is the magnitude of the reverse power (kW) and \( P_{EV,ch} \) is the rated power of the EV charger (kW).

With the appropriate number of EVs whose battery require charging connected to the network, the direction of utility power and the amount of power absorbed by the connected EVs keeps being monitored by the control system to avoid the EVs serving as extra loads to the network when the PV systems no longer produce in excess. During the process of reverse power being stored in the EV batteries, the SoC of the EVs is being monitored to avoid overcharging. Once the system detects an EV is fully charged and that the PV systems are still producing more than the loads demand, the control system automatically disconnects the fully charged
EV while simultaneously connecting a replacement EV connected on a charging point whose battery requires charging. In so doing, the possibility of overcharging an EV during periods of RPF is minimized. When the control system detects that the PV systems no longer produce excess power, and that power begins to be drawn from the utility main substation to power the loads, the EVs are instantly disconnected through the automatic opening of the power switches of the charging points on which the EVs are connected. The complete process of reverse power monitoring and correction is shown in Figure 10.

3.5.3. Simulation scenario

The method for the utilization of EVs to revolve reverse power flow in the distribution network with high penetration of PV systems is tested on an expanded IEEE 13 node test feeder and implemented using ETAP. The time-domain analysis is carried out for a single day (Wednesday) in the dry season in March. This day of the year is chosen because, during the dry season, there is sufficient sunlight for maximum PV production and in so doing it is most probable that the network experiences RPF. It is therefore on this basis that this single day is chosen to test and evaluate the proposed method for RPF correction in this paper as it considered that other times of the year with less sunlight will be least likely to experience reverse power due to the PV systems.

4. Results and discussions

The simulation of the expanded IEEE 13 node test feeder with high penetration of PV systems and EV charging points is shown in Figure 11.

4.1. Instances of reverse power flow (RPF)

From the time domain load flow analysis simulation of the expanded IEEE 13 node feeder test network at various levels of PV penetration, RPF is noticed at 60% PV penetration and this happens from 10:00 am to 12:00 noon. As shown in Table 12, RPF is experienced only on phase B of the network. From Table 12 above, the number of EV charging points with EV plugged in whose batteries require charging required to be connected into the network at various times to absorb and store the reverse power is calculated using Eq. (6) and shown in Table 13.

4.2. Reverse power flow correction at 60% PV

The time-domain analysis simulation results show that reverse power flow occurs at 60% PV penetration and this reverse power flow is observed from 10:00 am to 12:00 noon when most people are at work as shown in Figure 12. In this time interval, the PV systems are at peak production and the net load demand of the distribution network is lower than the combined power injected by the grid and the PV systems. This,
Therefore, results in surplus power flowing upstream into the distribution network substation (RPF). It is noted that the RPF is only experienced on phase B (below the red line) as can be seen in Figure 12. This is because phase B is the least loaded phase of the test network having a total active power demand of 1039kW compared to phase A that has a total active power demand of 1175kW and phase C an active power demand of 1252kW. Therefore, also due to the PV systems being haphazardly placed in the distribution network to mimic real-life consumer-based penetration of PV systems into the distribution network, it falls that this phase B has an excess share of PV power and hence experiences reverse power flow during high PV production.

With the automatic and instantaneous introduction of the appropriate number of EVs at the instances of reverse power flow detection and quantification, that is -45.68 kW at 10 am, -40.25 kW at 11 am, and -46.11 kW at 12 noon, the power flow on phase B is leveled automatically by powering up the required number of EV charging points with EVs whose total power roughly equals the reverse power at that time as shown in Figure 13. Based on the magnitudes of the reverse power at the various time intervals, the number of EVs required to cater for the reverse power are different. At 10 am, 8 EV charging points amounting to a total power of 46.32kW are connected to absorb the -45.68kW that was supposed to flow back upstream. At 11 am, one of the EVs are disconnected leaving 7 EVs in the network with a total power demand of 40.53kW to absorb the -40.25 kW at that time, and at 12 noon, the disconnected EV is reconnected back into the network to absorb the -46.11kW destined to flow back upstream in case of no EVs. With this strategic EV charging scheme, all the power that was to go back upstream and certainly affect the functioning of protective devices is diverted and stored in the EV

![Flowchart for EV insertion into the network.](image)

**Figure 10.** Flowchart for EV insertion into the network.
batteries connected to the EV charging points. The stored energy could then be used by EV owners to drive their EVs or the stored power could be sent back into the distribution network using the vehicle to grid (V2G) technology to support the grid during net peak load hours that starts from the 7:00 pm when the EV owners are back home and the PV systems are no longer generating any power.

4.3. Magnitude of the utility current

During the time of reverse power flow, the automatic insertion of the EVs into the network reduces the magnitude of the grid current significantly as shown in Figure 14. At 10 am, the grid current is reduced from 83.91A to 66.15A. At 11 am, it is reduced from 82.27A to 66.91A, while at 12 noon it is reduced from 81.20A to 63.17A. This reduction in the magnitude of the utility current means a significant reduction in the active and reactive power loss by the utility as power loss is a function of the current magnitude. This, therefore, means that utilizing EVs for reverse power flow is a solution that relieves the utility substation from excess stress and power losses.

### Table 12. Reverse power flow.

| Time | Phase A (kW) | Phase B (kW) | Phase C (kW) |
|------|--------------|--------------|--------------|
| 10:00| 0.00         | -45.68       | 72.31        |
| 11:00| 90.70        | -40.25       | 156.16       |
| 12:00| 139.47       | -46.11       | 196.35       |

### Table 13. Number of EVs Require to level reverse power flow at various time instances.

| Time | Number of EVs | Power rating of each EV charging points (kW) | Total power of inserted EV charging points (kW) |
|------|---------------|---------------------------------------------|-----------------------------------------------|
| 10:00| 8             | 5.79                                        | 46.32                                         |
| 11:00| 7             | 5.79                                        | 40.53                                         |
| 12:00| 8             | 5.79                                        | 46.32                                         |

4.4. Comparison of the proposed method for RPF correction with other methods and validation of the proposed method

The proposed method of using controlled EV charging for reverse power flow correction in the distribution network with high penetration of PV systems is compared with other methods of reverse power flow mitigation techniques to validate the superiority of the proposed method as shown in Table 14 below. From the table, it is seen that all the drawbacks presented by other methods are not encountered by the proposed method in this paper. This validated the superiority of the proposed method over the other methods. Nevertheless, The potential drawback of the proposed method is that it can’t be fully and efficiently used in a network with an inadequate EV population and also, it can be faced with the situation whereby, the number of EVs requiring charging during reverse power is not enough to absorb all the reverse power. That notwithstanding, for a study area with an adequate EV population, the proposed method will work efficiently.
5. Conclusion

The effect of reverse power flow in the distribution network has been examined and the various ways to take care of this phenomenon looked into. Electric vehicles that are revolutionizing today’s transport sector have been proposed in this research as a potential solution to correct reverse power flow in the distribution network with high PV penetration. The proposed method was tested on an expanded IEEE 13 node test feeder. The expansion of the IEEE 13 node test network was done such that the main node voltages and angles of the network matched closely the published results. The aim of expanding the IEEE 13 node test network was to ensure that the EVs and PVs are integrated into the network on the low voltage side of the network. Simulation results show that reverse power flow occurred at 60% PV penetration and this occurred from 10:00 am to 12:00 noon. This corresponded to the time of peak PV production and low load consumption. The RPF was detected on phase B of the network and quantified EVs were inserted into the network to absorb and store the reverse power.

Figure 12. Power flow at 60% PV with No EVs.

Figure 13. Reverse Power Flow correction using EV charging stations.
thereby leveling the power on phase B. The proposed method of controlled EV charging for RPF correction was compared with other methods of reverse power mitigation and the comparison demonstrated the superiority of the proposed method over the existing method for RPF correction. The proposed method requires the distribution network operators to operate in synergy with the transport sector to effectively install the EV charging points in public and private parking lots to solve the problem of reverse power flow in the distribution network and hence greatly improve power quality. The proposed method is an effective method given the fact that the excess energy stored in the EVs is used by the EV owners in driving the EVs or could be sent back to the grid using V2G technology to support the grid during peak power demand in the evening when the EV owners are back home and the PV systems are no longer producing any power. At that time, the loads sorely rely on the utility for power since the PV systems have stopped production due to no sunlight. The success of this novel method for RPF correction depends on an adequate EV population and the availability of EVs connected to charging points in parking lots and also on whether their batteries need to be charged.

The future of this research will see the implementation of the V2G technology to utilize the energy stored in the EV batteries during the reverse power flow scenario. Also, the uncertainty on the availability of EVs at charging points will be examined critically and a potential solution proposed. In addition to that, it is envisaged to look into allocating benefit packages to EV owners whose EVs are used for RPF correction. This could be in the form of incentives. Also, another important aspect to be considered will be to analyse the effect of partially charging the EVs during the process of reverse power flow correction.

Table 14. Comparison of the Proposed Method for RPF Correction with other Methods.

| Method                                   | Mode of operation                                                                 | Drawbacks                                                                                   |
|------------------------------------------|------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------|
| Use of a Smart transformer [38]          | The smart transformer measures the voltage at the low voltage side of the distribution network and controls the droop controller of the DGs during reverse power, thereby reducing the production of the DGs at that moment. | - Leads to the instability of DG controllers  
- Limits the revenue of the DG owners feeding the grid  
- Risk of violating the upper limit of the voltage on the medium voltage side  
- Hinders the DGs from producing at their peak, especially PVs  
- Prohibits the distribution network from fully benefiting from the DGs |
| Use of the ANSI 59 overvoltage protective relay [18] | The ANSI 59 overvoltage relay detects and disconnects the DG that leads to reverse power flow in the network to minimize the impact of the DG | - Leads to loss of DGs  
- Limits the revenue stream of DG owners  
- Prohibits the distribution network from fully benefiting from the DGs |
| Use of reverse power relays [24]         | The reverse power relay monitors the power flow from the main substation operating in parallel with DGs. When reverse power flow is detected due to a fault, the faulted DG is disconnected and in so doing protecting the network | - Considers the reverse power flow to occur only because of a fault condition  
- Leads to loss of DG  
- Limits the revenue stream of DG owner  
- Prohibits the distribution network from fully benefiting from the DGs |
| Use of EV battery [23]                   | Considers a grid-connected home PV system with an EV. In times when the PV system produces excess power, the excess power is fed into the grid. In case this power exceeds a predetermined quantity, it is considered reverse power, and this reverse power is stored in the EV battery of the home if the EV is available. | - Limited to a single grid-connected home PV system  
- What is considered reverse power is excess power above the predetermined threshold  
- The EV may not be available during the period of excess power |
| Proposed method of controlled EV charging for reverse power flow correction | Makes use of EVs that are gradually flooding the transport sector to solve the problem of RPF by PV systems whose penetration into the distribution network is fast increasing. The proposed method makes use of parked EVs connected to charging points in parking lots to correct RPF. The reverse power stored by the EVs is later used to drive the EVs and can also be sent back into the grid (V2G) in the evening during peak load periods | - May be faced with the problem of insufficient number of EVs required to absorb and store the reverse power in the network |
Declarations

Author contribution statement

Willy Stephen Tounsi Fokui: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools, or data; Wrote the paper.

Michael Saulo, Livingstone Ngo: Contributed reagents, materials, analysis tools, or data.

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Data availability statement

Data associated with this study is available at IEEE Power and Energy Society, IEEE PES AMPS DSAS TestFeeder Working Group, Resources, https://site.ieee.org/ pes-testfeeder/resources/.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

References

[1] M.Y. Wei, Impact of distributed generation on power distribution system, Appl. Mech. Mater. 543–547 (2014) 681–684.
[2] C.J. Rhodes, Solar energy: principles and possibilities, Sci. Prog. 93 (1) (2010) 7–112.
[3] H. Mosazadeh, A. Keyhani, A. Javadi, H. Mobli, K. Arefin, A. Sharifi, A review of principle and sun-tracking methods for maximizing solar systems output, Renew. Sustain. Energy Rev. 13 (2009) 2009 1800–1818.
[4] European Photovoltaic Industry Association, Solar Generation 6 Solar Photovoltaic Electricity Empowering the World, 2011.
[5] P. Chiradeja, Benefit of distributed generation: a line loss reduction analysis, in: IEEE/PES Transmission and Distribution Conference & Exhibition: Asia and Pacific, 2005, pp. 1–5.
[6] A.P. Reiman, A. Somani, M.J.E. Alam, P. Wang, D. Wu, K. Kalsi, Power factor correction in feeders with distributed photovoltaics using residential appliances as virtual batteries, IEEE Access 7 (2019) 99115–99122, c.
[7] M. Lotfi, C. Monteiro, M.S. Javadi, M. Shafee-Khab, J.P.S. Catalao, Optimal prosumer scheduling in transactive energy networks based on energy value signals, in: SEST 2019 - 2nd International Conference on Smart Energy Systems and Technologies, 2019, pp. 1–6.
[8] A.J.D. Rathnayaka, V.M. Potdar, T.S. Dillon, O.K. Hussain, E. Chang, A methodology to find influential prosumers in prosumer community groups, IEEE Trans. Ind. Inf. 10 (1) (2014) 706–713.
[9] M.S. Elnozahy, M.M.A. Salama, Technical impacts of grid-connected photovoltaic systems on electrical networks — a review, J. Renew. Sustain. Energy 5 (2013).
[10] T. Khokhar, Chart: Global CO2 Emissions Rose 60% between 1990 and 2013, World Bank Blogs, 2017, https://blogs.worldbank.org/opendata/chart-global-co2-emissions-rise-60-between-1990-and-2013 (accessed Mar. 14, 2020).
[11] M. Baumberner, R. Hwang, P. Bull, DRIVING OUT POLLUTION: How Utilities Can Accelerate the Market for Electric Vehicles, 2016.
[12] M. Guarnieri, Looking Back to Electric Cars, 2012.
[13] Vepachedu Education Foundation, The history of the electric car, Andhra J. Indust. News (2016) 1–8.
[14] W. Ejaz, M. Naeem, M.R. Ramzan, F. Iqbal, A. Anpalagan, Charging Infrastructure Placement for Electric Vehicles, An Optimization Prospective, 2017.
[15] S. Faddel, A.T. Al-Awami, O.A. Mohammed, Charge control and operation of electric vehicles in power grid: a review, Energies 11 (4) (2018).
[16] V. Salehi, R. Teodorescu, B. Hredzak, Index-based assessment of voltage rise and reverse power flow phenomena in a distribution feeder under high PV penetration, IEEE J. Photovol (2015) 1–11.
[17] G. Ramos, T. Quintero, Reverse Power Flow Analyzer (RPFA): a tool to assess the impact of PVs in distribution systems, 2019 IEEE Ind. Appl. Soc. Annu. Meet. (2019) 1–8.
[18] J.P. Holguin, D.C. Rodriguez, Reverse power flow (RPF) detection and impact on protection coordination of distribution systems, IEEE Trans. Ind. Appl. 56 (3) (2020) 2393–2401.
[19] J. Von Appen, M. Branz, T. Stets, K. Divold, D. Geibel, Time in the sun: the challenges of high PV penetration in the German electric grid, IEEE Power Energy Mag (2013) 55–65, no. april.
[20] T.P. Sari, A. Priyadi, M. Pujiantara, M.H. Furrano, Enhancing the coordination of reverse power overcurrent, under-frequency, and under-voltage relays using transient stability analysis in real plant applications, Ain Shams Eng. J. (2019) 1–9, 6.
[21] Y. Wang, P. Zhang, S. Member, W. Li, Online overvoltage prevention control of photovoltaic generators in microgrids, IEEE Trans. Smart Grid (2012) 1–8.
[22] C. Chen, C. Lin, W. Hsieh, C. Hsu, T. Ku, Enhancement of PV penetration with DSTATCOM in a power distribution system, IEEE Trans. Power Syst. 28 (2) (2013) 1560–1567.
[23] A. Mustapha, O. Takashi, Reduction of Reverse power flow through the use of EV’s battery with consideration of the demand and solar radiation forecast, in: IEEE International Electrical Vehicle Conference (IEVC), 2013, pp. 1–3.
[24] P. Sudhakar, S. Malaji, B. Sarvesh, Reducing the impact of DG on distribution networks protection with reverse power relay, Mater. Today Proc. 5 (1) (2018) 51–57.
[25] H. Mortazavi, H. Mehrjardi, M. Sand, S. Lefebvre, D. Asher, L. Lenoir, A monitoring technique for reversed power flow detection with high PV penetration level, IEEE Trans. sm (2015) 1–12.
[26] W.H. Kerting, Radial distribution test feeder tests, IEEE Trans. Power Syst. 6 (3) (1991) 975–985.
[27] W.H. Kerting, Radial Distribution Test Feeders, 2006.
[28] M. Wajahat, Hassan Abdullah Khalid, G.M. Bhutto, C.L. Bak, A comparative study into enhancing the PV penetration limit of a LV CIGRE residential network with distributed grid-tied single-phase PV systems, Energies 12 (2019) 1–17.
[29] C. Hart, J. Wright, Impact of Novel and Disruptive Approaches/Technologies on a Distribution Utility: A Kenyan Case Study, Energyexemplar, 2016, pp. 1–14.
[30] X. Luo, T. Hong, Y. Chen, M.A. Piette, Electric load shape benchmarking for small- and medium-sized commercial buildings, Appl. Energy 204 (1) (2017) 715–725.
[31] K. Muchiri, J.N. Kamau, D.W. Wekesa, C.O. Saoke, J.N. Mutuku, J.K. Gathua, Solar PV Potential and Energy Demand Assessment in Machakos County, 2019.
[32] Time and Day, Past Weather in Nairobi, Kenya, 2021 (accessed Mar. 23, 2021), https://www.timeanddate.com/weather/kenya/nairobi/historic.
[33] EV Specifications, 2018 Nissan Leaf SV Specifications, 2021 (accessed May 17, 2021), https://www.evspecifications.com/en/model/0da615.
[34] “2018 Nissan Leaf Battery Real Specs,” PUSHEVS (accessed Mar. 30, 2021), https://pushevs.com/2018/01/29/2018-nissan-leaf-battery-real-specs/.
[35] B. Faridpah, H.F. Ghareghel, M. Fereidunifar, D. Pozo, Two-step LP approach for optimal placement and operation of EV charging stations, in: IEEE PES Innovative Smart Grid Technologies Europe (ISGTEurope), 2019, pp. 1–5.
[36] J. Sears, D. Roberts, K. Giltman, A comparison of electric vehicle level 1 and level 2 charging efficiency, in: IEEE Conference on Technologies for Sustainability (SusTech) A, 2014, pp. 255–258.
[37] E. Hadian, H. Akbari, M. Farzinfar, S. Saeed, Optimal allocation of electric vehicle charging stations with adopted smart charging/discharging schedule, IEEE Access 8 (2020) 196908–196919.
[38] G. De Carne, G. Buticchi, Z. Zou, M. Lieber, Reverse power flow control in a ST-fed distribution grid, IEEE Trans. Smart Grid 9 (4) (2018) 3811–3819.