Planning and operation of LV distribution networks: a comprehensive review

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Abstract: The low-voltage (LV) distribution network is the last stage of the power network, which is connected directly to the end-user customers and supplies many dispersed small-scale loads. To achieve environmental targets and to address the energy shortage issue, governments worldwide increase the renewable energy sources (RESs) into the electricity grid. In addition, different types of low carbon technologies (LCTs) such as electric vehicles are becoming widely used. A significant portion of RES and LCTs is penetrated into the LV distribution network, which poses a wide range of challenges. To address these challenges, there is a persistent need to develop traditional planning and operation frameworks to cope with these new technologies. In this context, this study provides a comprehensive review of planning, operation, and management of LV distribution networks. The characteristics, types, and topologies of LV distribution networks plus different aspects of operation and planning are investigated. An insightful investigation of the reasons impacts and mitigation of voltage and current unbalanced in LV networks is provided. Moreover, the main three-phase power flow techniques used to analyse the LV networks are analysed.

1 Introduction

Around the globe, the development of electric power industry is experiencing essential changes and challenges in recent years [1]. A significant part of the energy demand is generated by fossil fuel resources (e.g. natural gas and crude oil) leads to significant increase in carbon emission to the atmosphere which is resulting in the environmental concerns, namely global warming [2, 3]. The development of economics, and the rapid increase of population, resulting in the exponential rise in the energy demand, which implies energy shortage issue and even more greenhouse gas emission in the atmosphere [4]. During the period 1990–2007, the annual world energy demand increased by 1.3% and is expected to increase by 48% from 2012 to 2040 [5]. For instance, the energy demand in the UK is projected to increase by 4% by 2035 [6]. Therefore, many countries are in the process of implementing programmes to address climate change and energy shortage issues. To proceed with these programmes successfully, several corresponding policies are established [7]. On the basis of the Paris agreement, various developed countries committed to reduce emissions of greenhouse gases [e.g. carbon dioxide (CO₂)] [8]. The European Union agreed a 20% reduction of greenhouse gas emission by 2020 in comparison with 1990 baseline [9]. Also, many countries obliged under the Kyoto protocol to reduce their greenhouse emission on average 50% by 2050 [10]. For instance, the UK government committed an 80% reduction in their emission under this protocol [11].

On the basis of obligations made by governments worldwide to achieve environmental targets and to address the energy shortage issue, the energy generation system experiencing a shift toward a more sustainable system [3]. These issues addressed by increasing the generation from renewable energy sources (RESs) such as photovoltaic (PV) systems and wind in the form of distributed generations (DGs). A significant amount of RES integrated and installed low-voltage (LV) level [12]. In addition, the end-user consuming pattern is shifting toward low carbon technologies (LCTs) such as electric vehicles (EVs) and electro heating systems [13]. This adds more challenges to the LV network, where the scope of these challenges depends on the ability of an LV network to handle these changes. For instance, the LV networks have been traditionally designed assuming unidirectional power flow (from source to the consumer) with no consideration of the bi-directional power flow in the presence of renewable energy generation. This poses several technical challenges such as voltage rise and thermally overloaded assets [14].

To overcome and address these challenges, and to improve the ability of LV networks to host more of RES, there was a persistent need to develop the conventional planning and operation schemas of the LV network to be adapted with the new technologies [4]. Moreover, various planning and operational schemes have been proposed by different researchers and research organisations around the world. In this context, this paper provides a comprehensive literature review about the planning and operation of the LV distribution network. Starting with highlighting the main challenges facing the LV networks, which are posed by the high penetration of distributed RES. An insight, background on the main character and topologies of the LV networks with highlighting the key differences between LV networks and both high-voltage (HV) and medium-voltage (MV) networks is provided. Moreover, the main LV networks planning and reinforcement frameworks that have been discussed in the literature including both conventional and active network system schemas are investigated. Afterwards, the operational and management of LV networks is discussed, which provides an insightful overview of the methods that have been used to analyse the unbalanced three-phase LV distribution networks.

2 LV distribution networks

2.1 Introduction to transmission and distribution networks

This section presents an overview of LV distribution networks. A power system consists of a set of interconnected parts to generate, transmit, and distribute the electricity to end-user customers [7]. These parts are interfaced by a set of transformers to step up and step down the voltage level to the appropriate level which is suitable for the system operation to reduce the network line losses. The generation in the conventional system was only based on fossil fuel and located in a central location away from the load centres [14]. However, with the adoption of DGs, the electricity will be generated locally by both RES and other sources such as small diesel engine and fuel cells, and this has reshaped the conventional system topology toward decentralised generation [4]. In the centralised power system, the power generated by the centralised
The distribution network delivers the power to the end-user consumer through lower-voltage networks. First, the voltage is stepped down to MV level, e.g. 33 kV, at bulk supply point (BSP) and then to lower MV level, e.g. 11 kV, at primary substation. Finally, secondary distribution substation steps down the voltage into the LV level required to supply the single-phase and three-phase end users (230 V single phase and 0.4 kV three phase). In other words, the MV networks start after the BSP and terminate at a secondary distribution substation, where the voltage level stepped down to 0.4 kV between two lines of the three-phase networks. Thus, the electricity is distributed to the single-phase end user through the LV networks (230 V line to neutral) [15–17]. Fig. 1 summarises the power system structure in the UK [16].

2.2 Transmission and distribution networks topologies

There are three main configurations of electrical power networks as shown in Fig. 2 [16, 17]:

- **Interconnected network topology** is adopted in HV transmission networks to provide a secure power supply in the event of an outage, as there are multiple paths to transmit electrical power.
- **Ring topology** includes both link arrangement and open loop which is mostly used in MV and 33 kV MV networks to provide more secure supply as well. The open point is located between two interconnected radial feeders to ensure the radial operation for each feeder to isolate a faulty section.
- **The radial network topology** is widely used in LV distribution networks, where faults occur infrequently and the fatality level of the fault (the number of consumers affected by the fault) is not high. The radial network can be reconfigured to weakly meshed interconnect two buses in the network.

2.3 Definition of LV distribution networks

On the basis of the British standards, the LV networks are defined as a network with a maximum limit of voltage level 1 kV [18]. Moreover, around the world, the most common voltage levels of local LV networks are within the range 120–240 V single phase (i.e. phase to neutral), or 208–415 three-phase's four wires (3-phase 4 wire) [19]. On the basis of the international standard recommendation [International electricity commission (IEC) 60038], the voltage level of three-phase-four wire is 230/400 V [19]. The LV network is the last stage of the power network, which connected directly to the end-user customers and supplies many dispersed small-scale loads [20]. Thus, it has the characteristics of small individual capacity, but a massive number of nodes. Owing to the LV level, installation and development of LV feeders require lower finance compared with higher-voltage feeders such as MV and HV [21]. However, the massive number of LV feeders requires a significant amount of work that might consume most of a utility's capital [22].

2.4 LV networks layouts in different regions

Around the world the LV network system has structured into various forms, among them, the ‘European’ and ‘American’ layouts are the most widely used layouts in European countries and Central and North of America [22, 23].

2.4.1 European LV networks layout: ‘European’ layout of LV networks is used by most countries in Europe. For example, the LV network in the UK is three-phase's four wire system supplied from a three-phase MV/230/400 V distribution transformer [19], where 230/400 refer to a secondary voltage level, 400 V line to line, and 230 V line to neutral (nominal voltage or root mean square) [18]. The circuit diagram of a distribution network in the UK is illustrated in Fig. 3. In this schema, each MV/LV distribution substation can supply various numbers of three-phase's four wire LV feeders. Moreover, the LV feeder can carry the power efficiently up to 300 m approximately [22]. In other words, at LV levels (400 V), each substation can supply an area corresponding to a radius of 300 m from the substation, which makes it suitable for high load densities areas [24]. On the basis of the practical application, the LV feeders can be underground cables or overhead lines extended from the secondary distribution substation. Most LV feeders in the UK are designed as multi-phase feeders, which consist of four wires (three phase and neutral) [22]. Table I summarises the characteristic of LV feeders in the UK in both urban and rural areas [25].
The MV network system through many single-phase's primary laterals is practically non-existent. Moreover, the system has significantly from the European layout, where the three-phase LV supplies numerous single-phase transformers which connected effectively carries the power through three-phase's four wire system (Figs. 6\&7). Table 2, Fig. 5, and Fig. 6 provide a summary of the voltage distribution system layout is a mixture of European and American topologies in different countries around the world [19]. From Table 2, Figs. 5, and 6, it is illustrated that the European system (Figs. 5a and b) is the most adopted system around the world. However, the American system (Figs. 6c–f) is adopted in North America, Latin America, and few countries in Asia and the Middle East such as Saudi Arabia. Moreover, some countries mixed between the European layouts and American layouts such as Iran and South Korea [19].

**2.5 LV network topologies**

The investigation in the main topologies used to configure the LV distribution networks shows that most LV networks are configured as radial networks due to the simplicity of analysis and protection system design [22]. However, due to the advantages of the loop or ring, or mesh configuration to mitigate some of the technical issues such as voltage variations and reverse power flow; the use of mesh configuration is becoming more common [26, 27]. As mentioned in the previous section, most LV networks are following the European layout. So, the three-phase 400 LV secondary circuit is designed based on the circuit diagram as shown in Fig. 5a, which is three-phase-four wire circuit underground cables or overhead lines.
suspected from, concrete, metal, or wooden poles \[19, 28\]. Owing to high load and housing density in urban areas, the underground cable is utilised usually in LV network construction \[24\]. Using the underground cable improves the possibility for the LV cables from the neighbouring substation to terminate close to each other, which permits simplicity and low cost joining them together (interconnected) using the underground link box \[22\]. Therefore, interconnected the surrounding substations to each other called looped or meshed or ring network arrangement as shown in Fig. 7a \[28, 29\]. The chief advantages such arrangement is improving the reliability and the security of supply, as well as improve the system flexibility, for example, in case of shutting down or suddenly losing the connection of one substation, the power can be supplied normally to the load by the surrounding substation via the link box \[30\]. Also, loop topology has proven its ability to improve the system hosting capacity for DGs such as PV systems, which helps to mitigate the technical issues such as voltage rise and reverse power flow \[27\]. However, in rural areas, where the load density with highly separated uncritical loads, the radial arrangement found to be the most economical and with a low level of faults and simple protection schema as shown in Fig. 7b \[24, 25\]. Despite the fact that the radial topology is widely used in 400 V three-phase-four wire LV networks, it has the lowest level of supply security and reliability, with the absence of flexibility \[22\]. To increase the level of reliability of two adjacent radial systems which they served from the same substation \[19, 22\]. These feeders can be interconnected via a normally open point to supply to ensure the radial operation of each feeder, where the location of the normally open point can be moved following the occurrence of the fault to isolate the faulty section with maintaining the supply for the rest of the faulty feeder \[22\]. Such an arrangement is also called a ring open-loop topology as shown in Fig. 7c \[30\]. Moreover, parallel interconnected configuration or spot topology can be used by interconnected two adjacent LV radial feeder supplied from two different substations as shown in Fig. 7d \[22, 31\]. Such configuration improves the system reliability and flexibility in case of a maintenance event, where the loads may still supply by the other transformer \[19\].

2.6 Main characteristics of the LV distribution network

On the basis of the above investigation, the main characteristic of the LV distribution network is listed as follows:

i. Consists of a large number of nodes: The LV network is to supply many consumers. For example, in the Dutch power system, the network has more than 99.6% of the whole system connections as that illustrated in Fig. 8 \[32\].

ii. Usually, the network is not monitored: A significant part of the metering system, particularly the household metre still without communication possibility. The advanced metering infrastructure (AMI) is still in the early stage of the installation. Moreover, this leads to the lack of understanding of the real state of the LV network, which resulted in a wide range of uncertainties.

iii. Operated in radial or weakly meshed topology: The majority of LV is radial in nature, and this simplifies the power flow analysis.

iv. High R/X ratios compared with HV and MV networks: especially in the case of underground cable. Moreover, that makes the resistance a very important factor in determining the voltage, where the voltage angle is approximately constant at the LV network.

v. Highly violated load pattern: The load pattern is unbalanced with a high level of uncertainty.

vi. Untransposed feeders: The spacing between conductors is non-symmetrical and the transposition principle does not apply compared with HV and MV networks.

vii. Bi-directional power flow: The distribution generator injected the excess generated power into the LV network, which resulted in reverse power flow from the load side, and this raises the voltage level in the load side.

3 Unbalanced voltages and currents in three-phase LV networks: reasons, impacts, and mitigation

3.1 Introduction to voltage and current imbalance in LV networks

In the power system, a three-phase system, or networks considered as balanced or symmetrical if two conditions are verified. The first condition is: the voltages and currents in the three phases have the same magnitudes. The second condition is: the phase shift angle
with respect to each other or between consecutive phases must equal to 120° [33]. However, for different reasons related to the operation and planning of the LV networks, practically LV networks are considered as unbalanced or asymmetrical [25]. The unbalance describes the LV network conditions, in which the voltages and current magnitudes in the three phases are not equal. Also, the phase shift angle between two adjacent phases is not precisely 120°. Fig. 9 provides a phasor diagram to compare the balanced three-phase system (ideal condition) and various unbalanced conditions [34], where $U_a$, $U_b$, and $U_c$ refer to the voltage or current phasors in the system. The chief reasons for voltage and current unbalance in LV networks are an uneven distribution of single-phase customers among the three phases and the load variations, which might happen normally or because of the high penetration of LCTs, either DGs such as residential PV systems or new smart loads such as EVs [21].

3.2 Relationship between current and voltage unbalance conditions

On the basis of Ohm’s law, the network impedance is the connection between current and voltage. In three-phase networks, the network impedances might be either symmetrical or asymmetrical [35]. However, in both cases, the network impedance connects voltage unbalanced and current unbalanced. The symmetrical network is defined as networks with equal self and/or mutual impedance [35]. In three-phase LV networks, the impedance of the system component in each phase is rarely the same [22]. The overhead LV networks lines impedances values are always not equal due to the dependence of phase impedance on the distance to the ground and the distance from the line to line which are normally not equal [22]. For instance, the central line in three-phase's four wire LV overhead networks, the impedance of the central line is ~6-7% lower than the two outer phases impedance [25]. Moreover, in underground LV networks, many of LV feeders comprise of a mix of cables types, which resulted in unequal impedance among the three phases. Also, using a four-core cable design led to unequal impedances and between phases and neutral [34]. In addition, the asymmetrical transformer winding impedances cause impedance imbalance in LV network [36]. Fig. 10 illustrated the network impedance and the relationship between current and voltage unbalances.

3.3 Reasons for voltage and current unbalanced

3.3.1 Uneven distribution of single-phase loads: Usually in MV and HV networks, the three-phase-connected loads are balanced. However, most loads supplied by LV networks are single phase [22]. Thus, the load balance between the three phase is not an easy task to be implemented. At the planning stage of LV networks, the network planner paid much effort to connect an equal number of customers in each of the phases aimed at making the load level balanced among the three phases [24]. However, in practical life, phase load balancing cannot be granted due to human behaviour. To connect the single-phase consumers’ three-phase's four wire LV network, each customer needs to be connected to two wires: phase (one of the three-phase lines) and neutral. In practise, the electricity technicians tend to use one of the two lines closest to the neutral wire in LV underground cable, while ignoring the wire diagonally opposite to the neutral [34]. Also, in the three-phase vertical formation overhead lines, the worker technicians tend to use one of the two lines closest to the neutral wire. Fig. 11 provides an example for three-phase-four wire LV feeder with uneven distribution for single-phase loads [34].
3.3.2 Variations in load demands: Normally the load demand of single-phase customer is changed with time depending on the type of appliances used at that time. The impact of load variations on the accumulated demand per phase, becoming more notable when the numbers of customers connected to the feeder are low. Most likely that happens in rural LV feeders. On the other hand, in urban LV feeders with a high number of consumers, the variation of individual customer load demand generally has a low impact on the accumulated demand per phase [22]. However, applying energy saving schemas such as adjustable speed drive might increase the level of load variation, which can lead to non-balance between phases [37].

3.3.3 Propagation from the MV network: Generally, the unbalance voltage is not significant at the MV networks. However, the unbalanced voltages at MV networks interpreted through the windings of the MV/LV distribution transformer to the LV networks. Moreover, that might lead to changes in phase to neutral voltage at the secondary side of the transformer (LV side), which reflects the phase current on LV feeder [22].

3.3.4 Asymmetrical network impedances: As discussed before, the voltage and current unbalances are related to each other through the network impedances. If the network impedances (cable impedance and MV/LV transformer impedance) are non-systematical, voltage unbalance might occur even though the currents are balanced [35].

3.3.5 High penetration of LCTs in LV networks: The word LCTs is associated with any kind of technologies installed in the electric networks and used by the end-user customer aimed at cutting the level of carbon emission into the atmosphere [20]. LCTs include renewable DGs such as PVs and end-user smart technologies such as EVs, heat pumps, and combined heat and power [36]. As discussed before, to achieve carbon emission reduction targets, the use of LCTs has become more popular [38]. Installing these technologies at the LV network feeder will increase the current and voltage imbalanced levels because of:

Increase in the level of load demands variations: As discussed above, the demand variation of the individual customer can influence the accumulated demand at each phase. So, using similar LCTs by a group of single-phase customers in parallel will add greater impact on the accumulated load profile of the phase to which they are connected [39]. Generally, the LCTs have a high-current rating and longer operating time compared with the traditional appliance. Single-phase high-current rating appliance will take the highest share of the total current seen in the phase at which they are connected [38]. Therefore, the use of these technologies at a specific time can lead to highly violated load demand at a given phase of LV feeder, which resulted in the influence of the current unbalance. Moreover, using LCTs for a long time increases the probability of coincident usage. Therefore, the insufficient group usage of these technologies influences the load profile. For example, the customer tends to charge their EVs at night to use them in the morning [38].

Uneven distribution of single-phase LCTs: The uneven placement of single-phase LCTs will lead to current and voltage unbalance. For instance, the uneven distribution of single-phase DGs resulted in a high fluctuation of load profile each phase (unbalanced). Moreover, due to the stochastic nature of renewable DGs, high penetration of this technology in a specific phase will lead to highly fluctuated demand profile. In addition, using a mix of LCTs along the LV feeders might result in unpredicted increasing and decreasing the demand, consequently a significant increase in the current [40].

3.4 Impacts of voltage and current unbalanced on LV networks

3.4.1 Ineffective utilisation of the network assets: In three-phase LV feeder, the total load demand of the feeder is unevenly distributed among the three phases. As a result of unevenly distributed of load demand among the three phases, some phases will be heavily loaded, especially with the future increasing of demand. On the other hand, the other phases are still not utilised efficiently. Hence, the heavily loaded phase conductors will need to be maintained or replaced, while the other phases are not [34]. Moreover, the three-phase equipment such as three-phase underground cables and the transformers are generally designed as one package. So, if one of the phases fails, the whole equipment must be replaced [22]. Indeed, the installed capacity of transformers or cables will never be fully utilised.

3.4.2 Increasing in neutral and ground currents: In the three-phase-four wire LV networks, the neutral conductor is the return path of any out of the balanced current. Therefore, in ideal conditions, the neutral current is zero, which means that the network is symmetrical or balanced. However, in practise, the amount of current in the neutral in the LV network cannot be zero. The neutral current increases when the out of balance level is increased. In other words, in the unbalanced LV networks, the neutral current will rise significantly [41]. As a result, the neutral conductor will thermally be overloaded especially if its rated capacity is lower than that for phase conductors. Moreover, if the level of the network out of balance is becoming larger, the ground current is becoming larger as well. The ground current depends on the neutral conductor, and Earth passes impedance. Such conditions will pose some safety issues [34].

3.4.3 Thermal overloading of the network's assets: The energy losses depend on the square of the currents that pass through the conductors. In a symmetrical or balanced network, the current flowing through the three phase is balanced and the neutral current is zero [42]. However, when the out of balance level among the three phase, becoming higher, the current passes through the neutral and some phases conductors increase. Therefore, the thermal overload in the transformer and cables or overhead lines become larger, resulted in reducing the useful life of these assets due to the additional thermal stress on insulations (e.g. transformer winding insulation, transformer oil, and underground cable insulation) [43].

3.4.4 Phase-neutral voltage displacement: In out of balance conditions, a considerable amount of current flow through the neutral conductors. In such a case, the neutral voltage is shifted (increased or decreased). If the neutral voltage becomes positive, the phase-neutral voltage of one phase decreases, while the phase-neutral voltage of the other two phases increases. However, if neutral voltage becomes negative, the phase-neutral voltage of one phase increases, whereas the phase-neutral voltage of the other two phases decreases [34]. If the single-phase voltage (e.g. 230) shifting outside the accepted limit (e.g. ±5%), this will add risk on single-phase consumer appliances. In addition, unbalanced conditions can result in a massive voltage drop on the heavily loaded phases, which resulted in a decreasing phase to neutral voltage. On the other hand, the phase-neutral voltage for the lightly loaded phase will increase.

3.5 Mitigation of the effects of voltage and current unbalanced

Different methods have been used to mitigate unbalance effects. Indeed, these methods are discussed as follows.

3.5.1 Phase and load balancing: The most basic mitigation method to reduce the out of balance level in the LV networks is to rearrange the loads (currents) to more evenly distributed conditions among the three phases. Phase balancing is associated with rearranging the single-phase transformer connection to the MV level. Load balancing is associated with rearranging the single-phase customer connections along the three-phase LV network. The conventional approach to achieve this is called manual trial and error approach. In this approach, a lot of field measurement and analysis are required to assess the network state to determine which phase is heavily loaded and which phase is lightly loaded in order to rearrange the customer connections. It was reported in [44,
3.5.4 On-load tap changer (OLTC) and automatic voltage studies using traditional reinforcement methods.

Load balancing transformer: It is a new version of a distribution transformer with a special winding configuration. The special winding configuration helps to achieve better current sharing on the primary side of MV/LV distribution transformer in the case of supervising unbalanced loads. As a result, it improves the utilisation of transformer capacity and mitigates the propagation of current unbalance from MV to LV side. A detailed description of the load balancing transformer is provided in [60–62].

3.5.8 Static balance: A detailed explanation of how this device can be used to mitigate the effects of current and voltage is provided in [34].

4 Planning of LV distribution networks

The planning for the distribution system comprises of three main areas, the long-term strategic planning, network planning, and construction design. The long-term deals with the future major investment such as (system reinforcement or expansion planning). While the network planning deals with individual investment in the future such as installing a new feeder or MV/LV substation. The construction design covers the structural design of each component in the network taking into account the available technologies and materials [17]. Power distribution planning includes both technical and economic objectives. Typically, the main objective of LV network planning is to find the most economical solution, size, and location of the newly installed equipment subjected to a set of technical constraint. For example, sitting and sizing of new feeders or substation to meet the future demand [63]. On the basis of the planning methods, there are two eras of the planning which is deterministic ‘Fit and Forget’ conventional approach and active distribution system (ADS) approach [64]. The main advantage of the ADS approach over conventional planning approaches is handling the high level of uncertainty posed by high renewable DG and the load varies. In the last decade, distribution networks planning is becoming more complicated with high penetration of renewable and non-renewable DGs technologies [63]. Planning function for such system includes three main factors: type of technology, the optimal size, and location to be installed in the network.

The challenges related to the high penetration of DGs into the LV networks have been studied and assessed by a variety of innovative methodologies which adopted the smart grid (SG) technologies aimed at reducing the impact of challenges. For instance, microgrid is becoming a proper solution for improving the networks DGs, however, a big effort has been paid toward improving the concept of microgrids [65–70].

The conventional power system structure is experiencing a significant change. Therefore, different approaches have been studied heavily in the current literature such as demand response (DR) [68, 71], virtual power plants [72, 73], improved optimisations methods for DGs planning and operations [7, 74–80], ADSs as an operation methodology for the SGs, which has been studied in [63, 81–83]. These papers established new methodologies which can handle the changes posed by moving toward SGs and/or smart cities. Also, the different requirement that needed to enable adoption of such technologies including information communication system (ICS), smart meters, Internet of things (IoT), big-data systems and control strategies as highlighted in [84–89].

In addition, the impacts of adoption of different technologies such as OLTC have been studied recently in [51, 52–54].

The planning of the distribution network has caught attention in the several published papers. In [63], Li et al. analyse the key features of ADS planning based on a different aspect such as DG sitting and sizing, coupling planning and operation, and the uncertainties aimed at developing appropriate models and methodology for the planning of ADS. To achieve that a comprehensive literature review analysed and categorised based on the objectives, system constraint, the methods, then providing critical analysis and discussion of the key issues and challenges faces the adoption of ADS scheme. Also, several important research areas for future research have been provided. In [81], Nijhuis et al. developed a probabilistic planning power flow approach for LV network by using a Gaussian mixture distribution in load modelling. The effectiveness of the method is evaluated by implementing a case study on the LV network with higher PV penetration. The results showed that the proposed method is highly accurate with low computational time. Moreover, a hybrid optimisation method based on genetic algorithm and sequential quadratic programming for sizing and sitting on a battery storage system (BSS) in unbalanced LV networks is proposed in [67].

In addition, a planning method for placement and sizing BSS in LV networks hosting high PV is proposed in [96]. The effectiveness of the proposed method is provided by carrying out a case study. The results showed that the improved method helps to reduce the overvoltage and energy losses by presenting the reverse power flow as well as a significant reduction in total investment costs. Rupolo et al. [97] developed a planning method for MV and LV radial distribution networks aimed at minimising the investment cost subjected to operational constraint and reliability index. The method is applied in a radial LV distribution network comprises of 410 buses, where the results indicated the importance of using an integrated planning technique for LV network planning rather than using sequential or hierarchical planning techniques.
5.1 Traditional approach of LV network reinforcement

The traditional reinforcement planning approach for the LV network is becoming essential when the LV network cannot handle the operational issues raised by the high penetration of renewable resource. The LV networks need to be reinforced when it starts operating beyond the allowable current and voltage limits.

5.2 Adoption of SG technologies for LV network reinforcement

5.2.1 Application of OLTC: High penetration of renewable DGs into LV distribution networks may result in the absolute magnitude of the voltage deviations (because of bi-directional power flow). To manage the voltage deviation, the active network management (ANN) scheme as a new SG technology can be utilised to control the bi-directional power flow. As a part of the ANN scheme, an OLTC can be installed on the MV/LV secondary substation [132]. OLTC enables the ratio between the corresponding primary and secondary voltages to be adjusted to achieve a certain voltage [93]. In fact, the majority of conventional MV/LV transformers is equipped only with off-load tap changer [93]. Therefore, the use of an OLTC in the LV network considered as an SG concept, which shows a promising advantage to reinforce the LV networks [94]. Indeed, a framework to evaluate the application of OLTC within the planning process is required.

5.2.2 Application of DR: DR is considered as a promising solution for the issues of the uncertain and fluctuating power supply, as the potentially significant flexibility of electrical demand can be utilised to provide the required power system services. Vianna et al. [71] have improved long-term planning method for LV networks based on the price-based DR and DGs. The results showed a significant reduction in technical losses.

6 Operation of LV distribution networks

The operation of the LV distribution networks is covered by power quality and network safety issues. These issues are usually resolved by applying a type of management or control on the network. For instance, many studies have been implemented to analyse the impact of DGs on LV operation. Also, the operational studies include the evaluation and addressing the issues related to voltage variations, thermal harmonics, network overload, load unbalanced, faults, and network energy losses.

6.1 Power quality and voltage control

In LV distribution networks, a pure sinusoidal waveform at the rated frequency (e.g. 50 Hz in the UK) is expected to be delivered to the end customers [136]. The power quality is referring to the measurements and analysis to maintain the sinusoidal voltage waveform at the rated frequency [137]. Hence, the concept of power quality has been defined by IEC as ‘characteristics of the electricity at a given point on an electrical system, evaluated against a set of reference technical parameters’.
These technical parameters are the voltage and/or currents [138]. Power quality issues include a number of individual power system disturbance such as voltage variation (i.e. transients, long, and short duration), voltage unbalance, frequency variation and waveform distortions [139]. The various indicators are used to describe the power quality issues among them: voltage dip, overvoltage, under-voltage, voltage unbalance (asymmetry), voltage swell (temporary overvoltage), voltage or current harmonic distortion, and frequency deviation. With the integration of the smart grid technologies, the power quality issues have become an increasing concern to utilities and customers [138]. For example, the presence of power electronic devices increases the distortion level in LV networks which might lead to voltage or current harmonics [136]. In addition, the high penetration of DGs might possess different power quality issues. Li et al. [138] and Sikorski and Rezzer [139] provided a detailed interpretation of the impact of DGs on power quality in LV networks. Also, Version [136] provides a detailed study of power quality in distribution networks which covers the voltage dip and harmonic distortion issues. Das et al. [137] provide an overview of the most common power quality issues based on the energy storage system as mitigation technology.

As discussed above, a big effort has been paid to mitigate the issues associated with the voltage in LV networks. Corresponding to the reason and the effects, many studies have been implemented in the area of voltage control. Among them, some of the most recent studies on the topic of voltage control and power quality in the three-phase LV network have been studied with [51, 79, 82, 126]. In [51], a new approach for unbalanced voltage control has been proposed. The method is based on OLTC and the DR with considering customer preferences. A three-phase voltage management method is proposed in [95]. The method focused on the design a model, which include OLTC and power electronic devices to control unbalance voltage among the three phases. A harmonic-based analysis is proposed in [140]. The analysis is applied to the LV network aimed at assessing power quality. In [141], a multi-function DGs unit was designed to improve the power quality in the LV network. The designed unit applied at three-phase’s four wire LV networks to mitigate the current unbalance and harmonics.

6.2 Power flow analysis of LV networks

6.2.1 Introduction: Power flow calculation is an essential tool for various types of power system analysis studies. On the basis of the network topology and the operation conditions, the power flow calculation can be implemented to evaluate all important networks elements such as voltage angle, voltage magnitude, line power transmission, and line power losses [142]. Therefore, the power flow analyses widely used in many studies that executed to evaluate and address various issues such as fault analysis, feeder reconfiguration, network load balancing, network losses reduction, DGs allocation and so on. Initially, researchers have paid big attention to develop powerful power flow approaches which are capable of analyses operation of the transmission networks. Indeed, the standard Newton–Raphson (NR) and Gauss seidel power flow techniques are widely used to evaluate the operation of power system networks. These approaches successfully converge the solutions by assuming the studied system is three phases balanced. The transmission and sub-transmission networks are structured symmetrically (tightly meshed networks) with a low R/X ratio and even allocation of load across the three phases. Thus, it is usually considered as a balanced three-phase network. Therefore, applying the standard version of these techniques on such types of networks (HV and MV) is inefficient [83]. Owing to the characteristic difference between the transmission and distribution networks, applying the standard techniques directly on the distribution networks has failed to converge the solution without assuming that the network is three phases balanced. Although various studies applied the conventional power flow (PF) techniques to analyse the LV distribution networks by assuming that the LV network is a three-phase balanced network; this assumption is unrealistic [143]. In practical, the LV distribution system is unbalanced due to load across the three-phase; (ii) unbalanced characteristic of the LV lines, e.g. high R/X ratio; (iii) the network structure is asymmetrical, e.g. single-phase and two-phase lateral; (iv) untransposed lines; and (v) uneven allocation of DGs on different phases. Therefore, using conventional PF methods fail to converge for unbalanced LV networks that resulted in unrealistic indications into an actual problem [144, 147]. While the energy system shifting toward a more sustainable system, a significant share LCTs are adopted in the LV network. Hence, LV networks become an essential part of the modern energy system. Consequently, to study the impacts of the DGs and to ensure a secure operation LV network, different research works developed a variety of power flow methods based on the standard techniques to be able to deal with the uniqueness of the LV networks. Also, many of the recently published research works have proposed different power flow techniques. These techniques cover a wide range of the LV networks operational challenges posed by the adoption of LCTs such as increasing the level of load demand variation. Meanwhile, an efficient power flow algorithm must be able to find the solution of the power flow problem for systems with a large number of nodes, asymmetrical line impedances highly violated load demands, and unbalanced voltage and current. Generally, the proposed methods can be classified into deterministic methods, probabilistic methods, and hybrid methods. In the following section, a brief definition and review of the main power flow algorithm for LV network are provided.

6.2.2 Deterministic power flow techniques: The deterministic power flow techniques do not consider the uncertainties (stochastic nature) associated with renewable DGs and load demands [144]. In these techniques, the non-linear power flow equations are solved for a deterministic value of renewable DGs outputs and load demand [147]. Although a large number of these techniques have been proposed to date, the majority of them can come under three main groups. Forward–backward sweep-based (FBS) methods, NR-based methods, Gauss-Z-bus-based methods, and correction current injection-based (CCI) methods:

i. FBS-based methods: This technique is widely used in the distribution system analysis, because of its robustness and simplicity of implementation especially in case of the multi-phase circuit. The initial version of the FBS algorithm is developed for the radial system in [148]. Afterwards, the method has been applied in a wide range of research papers to solve weakly meshed, strong meshed, and multi-phase unbalanced networks. In [149], Wu and Zhang applied the FBS method to solve three-phase power flow problem for a loop network. The proposed method considers the loops as two branches with considering the unbalanced conditions for three-phase networks. The result showed the effectiveness of the proposed method for radial and weakly meshed three-phase unbalanced networks. Also, a three-phase PF technique to analyse unbalanced distribution network was proposed by Ghatak and Mukherjee [145]. The technique integrates the conventional FBS technique with employing the load impedance matrix to calculate the bus voltage in one step instead of two steps. The proposed method evaluated different three-phase balanced and unbalanced radial and weakly meshed networks and the results proved the effectiveness of the proposed method over the standard FBS technique. Alinejad et al. [150, 151] developed a three-phase power flow method for unbalanced LV networks aimed at minimising the network losses. The system element modelled in three-phase frameworks based on the FBS technique. Breadth-first search method used along with Backward-Forward sweep (BFS) to minimise the read element in each iteration resulted in minimising the computational time. The result showed that the three-phase proposed method is more accurate than the symmetrical model, which makes it more applicable in real-time analysis. In [152], Karagiannopoulos et al. employed the BFS method in optimal power flow optimisation formulation aimed at developing a centralised operation scheme to handle the LV network unbalance posed by high penetration of
NR-based methods: The standard NR is failing to converge the power flow solution of the unbalanced LV network. However, various approaches developed the standard NR method to study the operation of LV networks. For example, NR-based three-phase PF method is developed in [142] using graph theory, injected current, and matrix decomposition techniques. In [154], NR-based power flow method has been developed to study the effect of active and reactive power injections on the network voltage. The proposed method validated in real German 234-bus test system and it has been applied in the LV system. Moreover, a three-phase power flow method based on the NR and the voltage rectangle coordinates method has been proposed in [155]. The effectiveness of the proposed method is tested by implementing a case study and the results are compared with the BFS power flow software results. In [156], Sereeter et al. developed five new versions of NR power flow technique to solve three-phase power flow problem for unbalanced LV network. The formulation for three-phase power flow is described for both current and power. To validate the proposed methods, the development versions have been compared with the BFS method. Also, Husain et al. [157] developed a novel power flow technique for radial and weakly meshed distribution network. The proposed method is based on the NR algorithm. The developed method has been tested using 33 and 69 IEEE benchmarks, considering different load conditions and R/X ratio.

Gauss-Z-bus-based methods: Gauss Z-bus is one of the commonly used methods for solving power flow problem. It uses the Y-bus matrix to model the network structure and employing current injection technique to calculate the power flow solution. One of the first methods that applied Gauss-Z-bus algorithm to calculate the power flow solution for unbalanced three-phase LV networks has been presented in [158]. Also, a modified Gauss-Z-bus method for three-phase power flow was proposed by Teng [159]. The modified method considers the three-phase distribution network as three single-phase distribution networks, thus the power flow can be solved phase by phase. Chen and Yang [160] proposed a three-phase power unbalanced power flow technique based on Gauss-Z-bus algorithm and loop frame of references. Huang [161] developed a three-phase power flow programme based on the implicit Gauss-Z-bus method. The proposed method was developed to study the impact of multi DGs on three-phase 400 V microgrid. In addition, a Gauss-Z-bus approach has been employed to develop a multi-phase power flow simulation which could open as presented in [162]. Moreover, a similar approach has been used along with FBS to develop GridLa-D software by the US department of energy as presented in [163]. Recently, Verma and Sarkar [164] employed the concept Gauss-Z-bus technique to developed modified technique which is able to solve the power flow problem for three-phase active distribution network (ADS). This method is attracting some attention in the state of art. The formulation-based nodal current injection written in phase farm reference. The method was initially developed by Costa et al. [165]. Afterwards, it was developed to handle with three-phase unbalanced LV network in [166–168], de Araujo et al. [169] implemented a comparison study between the current injection method and FBS for three-phase power flow calculation. Moreover, Ghatak and Mukherjee [170] proposed an improved version of the current injection method which is able to solve the power flow problem for three-phase's active LV network. In addition, a multi-phase power flow methodology called CCI based was evolved from the complex admittance matrix methodology which is reported in [171]. The complex admittance matrix allows representation of any number of phases and Earth conductors in the system. It obtains by definition of self and mutual coupling between the phases [171]. Indeed, the current injection method was initially presented in [172]. Afterwards, it has enhanced in [173].

6.2.3 Probabilistic power flow techniques: The uncertainty could be defined as the probability of difference between the anticipated and actual values. On LV networks, many variables have a stochastic nature such as the load demand and the renewable DGs output. Therefore, deterministic values for the voltages and currents can often give an incomplete view of the LV network. Hence, when analysing the LV network operation, it is essential to model the system stochastic variables using appropriate and practicable methods. These methods can be either a numerical or analytical. In this context, many research papers have been developed a probabilistic power flow technique. The most common way of applying a probabilistic power flow is using Monte Carlo simulation which is used in [174–178]. In [143], multi-objective probabilistic power flow method considering three-phase unbalanced LV network was developed. The method employs a three-phase ANM scheme and employed a Monte Carlo simulation and fuzzy satisfying method for system uncertainty modelling. Gurosso et al. [174] developed a populistic power flow method which is able to analyse daily network operation under uncertain and stress conditions. The proposed technique based on the generalised polynomial chaos algorithm, Monte Carlo simulation and probabilistic density factor PDF. Temiz and Guven [175] developed a Monte Carlo-based power flow methodology to assess the impacts of EV on LV networks. The method employed Gaussian distribution function to model the EV plug-in times and Weibull distribution function to model the daily travel times. Klonari et al. [176] developed a three-phase probabilistic power flow to evaluate the effectiveness of PV inverter in mitigation voltage unbalance. In addition, fuzzy set theory has been used to analyse the LV networks with uncertainties in load and renewable DGs and storage systems in [179–181]. In [81], Gaussian mixture distribution is used to model the load demand uncertainty. Point estimate method is applied in [182] to develop a probabilistic power flow for unbalancing distribution networks. Moreover, the probability density evolution method applied in [183] to develop a probabilistic power flow algorithm. Constant impedance-current-power (ZIP) model used in [184, 185] to model the load demand and renewable DGs. Di Fazio et al. [184] proposed linear methods for steady-state analysis of LV networks. The ZIP model is employed to represent the uncontrolled loads, both P–Q and P–V control for DGs. Bi-directional power flow was proposed [186] considering the uncertainties associated with wind.

6.2.4 Other power flow techniques: In addition to the aforementioned methods, different published papers have employed different algorithms to solve the power flow for LV networks. In [144], Dahl and Salehfar have proposed PF method for siting DGs into a multi-phase LV distribution network using PSO technique. The effectiveness of the proposed technique is evaluated by a case study of the multi-phase 123 IEEE test bed. The results proved the accuracy of the proposed method in the allocation of DGs. In [146], Yaghboobi et al. proposed analytical optimal PF algorithm to assess the loadability of the LV network to host high level of PV with considering the three-phase unbalanced conditions of the networks to ensure the system voltage stability. A three-phase LV network operation, dynamic reconfiguration operation technique is proposed in [147]. The method employs the ANM scheme and OPF aimed at improving the system reliability and minimising the line power losses.
6.3 LV network reconfiguration

The network reconfiguration is changing the structure of the network feeders by changing the state of tie switches (open/close). The feeder reconfiguration used to enhance the system reliability and the quality of supply under steady-state operation condition as well as under fault conditions [80]. In LV network operation studies, the network reconfiguration caught high attention in recent published literature. The different researcher has studied the LV network reconfiguration as a method to mitigate some technical challenges such as losses, load unbalance, overloaded, voltage variation, and faults [187]. Loss reduction and load balancing are using an objective function in [44-48, 147, 188-190].

7 Conclusion and recommendation

Around the world, the energy industry is moving toward a more sustainable system with high penetration of renewable DGs and LCTs at the end-user side. While the significant portion of this technology is installed on the LV distribution network, new planning, and operation frameworks were developed by different researchers and research organisations around the globe. In this context, this paper provides a comprehensive review of various LV distribution networks planning and operation frameworks. Starting with highlighting the key challenges facing the LV networks, which are posed by the high penetration of DGs, then highlights the key characteristic and topologies of LV networks. Thereafter, different planning and operation aspects have been investigated.

7.1 Remarks for future research

(i) The LV networks are typically operated in a radial topology. However, based on the operation conditions and the served load, the LV networks can be operated in different topologies such as mesh, parallel interconnected, and so on. For instance, normally in the urban networks the adjacent feeders are interconnected through a link boxes and so form a mesh configuration. Hence, for network planning and operation, it is recommended to consider the mesh topology and the actual network topology by developing a network model which is considered and measuring the current flow through the link boxes rather than assumed to be zero aimed at improving the accuracy of the network impedances model.

(ii) With the deployment of ICS such as AMI, the SG will enable two-way flows of power and data. In this context, there are opportunities to apply big-data analytics and IoT in the future power system. Deployment of such information technologies represents a very promising research direction which has not yet studied in the literature. Among these, studying the benefits of applying big-data analytics to enhance DR, detect the faults, planning, and operation of the LV networks and reduce the impact of uncertainties.

(iii) The majority of the reviewed papers is addressing the planning of HV/MV network with high penetration of DGs. However, a few papers have developed network dynamic models to implement a long-term planning of DGs in LV network. Hence, an accurate dynamic network model needs to be implemented for long-term planning of LV network, which is able to address the presence of high level of uncertainties posed by various sources such as LCTs and loads.

(iv) An accurate and fast probabilistic power flow method for three-phase unbalance networks needs to be developed.

7.2 Remarks for practises

(i) With the introduction of high penetration of LCTs, the practises and regulations used in network planning need reformulation, where the impacts of the LCTs are highly risky if not handled in the planning and operation regulation. For instance, the traditional practises and regulations based on conventional will not necessarily have the correct safety margins for the different characteristics of embedded generation or new types of loads. As a result, the networks will be operated in conditions that are closer to the rated limits, which might follow by different technical issues such as voltage unbalanced. The new practises must consider making ‘before’ and ‘after’ assessments of the LCTs impacts.

(ii) It is recommended for the distribution network operators (DNO) to reform the network to more intelligent network, by adding the SG technologies such as smart meters and replacing all the manual switches by automatic switches, installing distributed transformer adapted with OLTC in order to prepare the networks to move toward fully automated networking smart cities.

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