Flexibility exchange strategy to facilitate congestion and voltage profile management in power networks

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Flexibility Exchange Strategy to Facilitate Congestion and Voltage Profile Management in Power Networks

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***Abstract*-- This paper proposes a novel flexibility exchange strategy to facilitate the management of congestion issues and voltage profiles (e.g. avoiding voltage violation and reducing voltage fluctuation) via minimum participation from customers or aggregators. In the proposed approach, the expectation of voltage profiles and power flow is determined by network constraints and customers' requirement, and it is used to guide the estimation of network state towards the expected state so that the pre-defined expectation (regarding voltage profile and power flow) is fulfilled. Availability of flexibility exchange from customers is integrated in estimation process. Flexibility factors are proposed to constrain the variation of network variables including voltage, power consumption/generation and power flow. A genetic algorithm based optimisation procedure is applied to obtain the minimum power variation from customers (i.e., minimum power variation from customers) while the defined expectation and constraints of flexibility availability are met. The approach is tested out on two representative distribution networks and the results have demonstrated the feasibility of the proposed approach in obtaining optimal flexibility exchange strategy that meets the pre-defined requirement/expectation whilst involving the least power variation from customers.**

***Index Terms*—Flexibility exchange, constraint management, demand-side management, genetic algorithm.**

I. Introduction

Constraint management is becoming more important in active distribution networks nowadays, especially with the heavy load demand and increased integration of intermittent renewable energy which exposes the network to more constraint violation issues. The constraints can be derived from standards, requirements from sensitive customers or the constraints due to ageing status of network facilities, etc. Violation of constraints may result in economic losses to both utilities and customers due to end user power apparatus damage or instability in the power system [1]. Therefore proper constraint management can maximise the use of network assets, enhance the network stability and avoid the unwanted financial loss.

Relevant regulatory agencies in individual countries set requirements regarding the service voltage variation range, including the mandatory regulation which involves relevant laws and regulatory acts from the governmental legislative body. Usually these limits are given by very strict standards, with specified lower and upper nodal voltage limits. The voltage regulation varies in different countries, in the UK for example, the voltage variation range in distribution network is -6.0% / +10.0% [2]. Violation of these regulations can cause severe penalty to the utilities. Furthermore, customers may have differentiated requirement regarding voltage profiles. For instance, some customers may expect stricter voltage variation range and less voltage fluctuation than the service normally supplied [3]. These sensitive customers may be willing to pay utilities extra amount of tariff in order to receive higher standard of supply of service with reduced voltage fluctuation. With the consistent load increments in some industries, the possibilities of power congestions issues are inevitable during peak time especially with deferred system infrastructure expansion [4]. Utilities however should ensure that the network operates at all times within the specified limits. For some utilities constraint management is implemented through either direct communication with potential providers or through an invitation to tenders [5, 6] to change their generation outputs.

Within the concept of smart grids, the implementation of constraint management can be also implemented through the flexibility exchange among different stakeholders in power grids. Flexibility exchange between utilities and demand-side is recently developed concept in smart grids and is becoming feasible thanks to the fast development of advanced communication networks in smart grids. Demand-side management (DSM), together with the integration of distributed generation (DG) and storage, is considered essential element for implementing the smart grid concept and can be used to facilitate network operation and management [7]. The use of DSM has been extensively explored for load shift strategy [8] and has been integrated in a centralized scheme to smooth peak-to-average ratio of power usage in the grid in order to reduce the waste of fuel and emission of greenhouse gas [9]. Short-term facility over-load/congestion problem in distribution systems can also be alleviated via DSM and DG. Various congestion management approaches have been studied and the benefits of demand flexibility on alleviating network congestion have been investigated, e.g., optimal power flow and demand response mechanisms, etc [10-12]. In [13], a short-term phase of a cooperative energy

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management algorithm is used to exploit the flexibilities arising from the charging and discharging of thermal storage. In [1], a decentralized approach is used for real-time management of local voltage and thermal constraints via controlling DG active and reactive power outputs.

Especially with the new concept of smart pricing in smart grids, control of the customer's energy usage will be influenced by real-time penalty and incentive schemes at all levels of supply chain [14]. The integration of pricing with DSM functionality for various purposes such as facilitating safe and satisfactory network operation has been investigated in [11, 12, 15]. In this case, flexibility exchange strategy can potentially be used as reference for determining real time pricing. The investigation on the flexibility exchange for the purpose of constraint management is still limited in current smart grid development.

This paper mainly contributes on:

1) Defining an emerging problem in current smart grid development, namely power variation resulting from customer (equipped with DSM sources, DG or storages) activities, for the purpose of constraint management, i.e., minimization of the impact of customer power variation on the state of the network.
2) Proposing a new approach to define flexibility exchange strategy for solving the problem mentioned above. Availability and priority of flexibility exchange (e.g., flexibility exchange contract or preference of location or stakeholders) are considered in the study. The expected values of network variables are defined and integrated in the estimation process in order to guide the estimation towards the expectation.
3) A set of flexibility factors is proposed to confine the variation of different variables in order to address the flexibility provided by customers.

The proposed strategy can be used to determine the potential sources/location of the flexibility exchange that when deployed can help with network constraint management. The proposed approach has been tested in a 24-bus section of real UK distribution network and a 96-bus distribution network. The results have demonstrated that the proposed approach is able to generate optimal flexibility exchange strategy which ensures the network constraints are met and at the same time involving the minimum power variation from customers.

II. Problem Description and Methodology

The problem addressed in the study is to generate optimal flexibility exchange strategy to facilitate the constraint management (requirements on voltage constraint and fluctuation, and congestion issues) whilst ensuring the minimum variation in power consumption/generation among stakeholders. The problem mainly considers two objectives: constraint management and minimum power variation from customers. This paper proposes a novel approach which addresses these two objectives using two core procedures: Expected Profile State Estimation (EPSE) and Minimum Power Variation Optimisation (MPVO). EPSE is to estimate the state of the network which ensures the expected profiles are met, whilst the expected profiles can be defined based on customer requirements, network constraints and availability of flexibility exchange service, etc. MPVO is to search the optimal levels of participation from customers so that the minimum variation of power consumption/generation is required from customers involved in flexibility exchange.

A. Expected Profile State Estimation (EPSE)

EPSE is the procedure to find out the expected network state so that the profiles are met as expected. The expected profiles in the network include voltage profiles, the profiles of power flow and power consumption/generation. Thus the variables of interest (denoted as $\boldsymbol{Z}$) consist of bus voltage, power injection (real power or reactive power) at buses, and power flow at lines. The expected values of variables $\mathbf{Z}$ are denoted as $\boldsymbol{Y}$ ($\boldsymbol{Y}$=[$y_1 \ldots y_n$]). If the network state is given as $\boldsymbol{X}$, the values of variables $\boldsymbol{Z}$ can be calculated from $\boldsymbol{X}$ based on network configuration and power balance equations. The difference between the values of $\boldsymbol{Z}$ that are derived from network state $\boldsymbol{X}$ and the expected variable values $\boldsymbol{Y}$ can be calculated from:

$$\boldsymbol{E}=\boldsymbol{Y}-H(\boldsymbol{X}) \tag{1}$$

where $H(\boldsymbol{X})$ is a nonlinear set of equations that describes the relationship between the variables of concern (i.e., $\boldsymbol{Z}= H(\boldsymbol{X})$) and the power system state presented by the state variables of $\boldsymbol{X}$. Each variable of $\boldsymbol{Z}$ can be linked to the network state (usually defined as voltages and phase angles) via specific power balance equation which is usually applied for distribution system state estimation [16]. For instance, power flow at one line can be calculated from network state using the line flow equation as given in (2). In the same way, a set of equations $H(X)$ can be defined to link the network state $\boldsymbol{X}$ with the network variables of interest $\boldsymbol{Z}$.

$$P_{ij}^{p}=\sum_{m=\{a,b,c\}} G_{p,m} V_i^m V_i^p\left[\cos\left(\theta_i^m-\theta_i^p\right)\right]-B_{p,m} V_i^m V_i^p\left[\sin\left(\theta_i^m-\theta_i^p\right)\right]+G_{p,m+3}\left[\cos\left(\theta_i^m-\theta_i^p\right)\right]-B_{p,m+3}\left[\sin\left(\theta_i^m-\theta_i^p\right)\right] \tag{2}$$

where $G_{p,m}$ and $B_{p,m}$ are elements of 3×6 line admittance matrices $\boldsymbol{G}_{\mathrm{L}}$ and $\boldsymbol{B}_{\mathrm{L}}$ relating voltage ($\boldsymbol{V}_{ij}$=[$V_i^{(a)}$, $V_i^{(b)}$, $V_i^{(c)}$, $V_j^{(a)}$, $V_j^{(b)}$, $V_j^{(c)}$]) and current ($\boldsymbol{I}_{ij}$=[$I_{i,j}^{(a)}$, $I_{i,j}^{(b)}$, $I_{i,j}^{(c)}$]) between buses i and j in the form $\boldsymbol{I}_{i,j}=(\boldsymbol{G}_{\mathrm{L}}+\mathrm{j}\boldsymbol{B}_{\mathrm{L}})\boldsymbol{V}_{ij}$.

With the definition of discrepancy given by (1), the objective of EPSE is to find an optimal network state which is able to minimize the discrepancy in (1). Since the expectation regarding how close these variables should reach their expected values is different, the participation from various variables in influencing the determination of the optimal network state is different as well. This differentiated participation is addressed in EPSE by Flexibility Factors (denoted as Flexi). In this case, the estimation of optimal network state can be considered as an optimisation problem, and the objective is defined as:

$$F_{\mathrm{Estimation}}=\min_{\boldsymbol{X}}[\boldsymbol{Y}-H(\boldsymbol{X})]^{\boldsymbol{T}}\boldsymbol{W}\,[\boldsymbol{Y}-H(\boldsymbol{X})] \tag{3}$$

where $\boldsymbol{W}$ is a weight matrix defined as $\boldsymbol{W}=\boldsymbol{F}^{-1}$, and $\boldsymbol{F}$ is the Flexi. If the variable has high flexibility, it means that its value derived is allowed to deviate from the expected one with higher freedom. In this case, the corresponding Flexi is set to a larger value. In this way, the discrepancy between the derived and expected values has smaller influence on the objective function (3) and contributes less in estimating the network state. On the other hand, smaller Flexi suggests less flexibility for the corresponding variables to deviate from the expected values, which suggests stricter requirement applied to enforce the derived variable values to be close to the expected. For the convenience of illustration later, the Flexi for different types of variables are denoted differently. The Flexi corresponding to power consumption or generation at buses is denoted as Flexi^{P}. Flexi for power flow in lines and the voltage at buses are denoted as Flexi^{F} and Flexi^{V} respectively.

It can be seen from (3) that EPSE is to estimate the network state so that the concerned variables approach their expected values to certain extent as expected. The equation can be solved iteratively using Newton-Raphson method, and the state variables can be updated according to:

$$\boldsymbol{X}_{k+1} = \boldsymbol{X}_k + (\boldsymbol{H}_X^T \boldsymbol{W} \boldsymbol{H}_X)^{-1} \boldsymbol{H}_X^T\, \boldsymbol{W}[\boldsymbol{Y} - H(\boldsymbol{X}_k)] \tag{4}$$

$$\boldsymbol{H}_X = \frac{\partial H(\boldsymbol{X}_k)}{\partial \boldsymbol{X}} \tag{5}$$

where $\boldsymbol{X}_{k+1}$ is the estimate for the state variables at the $(k+1)^{\text{th}}$ iteration, and $\boldsymbol{H}_X$ is the Jacobian matrix.

Different from distribution system state estimation [17] which estimates the voltages at unmetered buses based on the information collected from metered buses, the EPSE procedure presents novelty from two aspects: inclusion of profile expectation in estimation while determining the network state, and the use of Flexi to present the differentiated participation from various variables in determining the optimal network state.

B. Minimum Power Variation Optimisation (MPVO)

As mentioned earlier, the goal of the defined problem is to generate a flexibility exchange strategy to 1) ensure the expectation is met 2) while minimum variation in power consumption or generation from customers is required. The former is addressed by EPSE as introduced in Section II-A. The latter is addressed by the procedure of Minimum Power Variation Optimisation (MPVO). In MPVO, the minimum variation from customer is again considered as an optimisation problem. Flexi^{P} for power consumption/generation at customers' sites that are involved in flexibility exchange is used as input to the optimisation, as the Flexi to some extent determines the participation levels (i.e., influence) of power variables at buses in determining the network state, as discussed in Section II-A. The optimisation objective is defined as:

$$F_{\text{optimisation}}(R) = \sum_{i=1}^{N}\Big(\sum_{j=1}^{K}\big|(P_{ij,\text{adj}}(R) - P_{ij,\text{ori}})\big| + \big|\sum_{j=1}^{K}(Q_{ij,\text{adj}}(R) - Q_{ij,\text{ori}})\big| + \beta \times \Big(\sum_{j=1}^{K}\big|P_{ij,\text{adj}}(R) - P_{ij,\text{lim}}\big|_{P_{ij,\text{adj}}(R) > P_{ij,\text{lim}}} + \sum_{j=1}^{K}\big|Q_{ij,\text{adj}}(R) - Q_{ij,lim}\big|_{Q_{ij,\text{adj}}(R) > Q_{ij,lim}}\Big)\Big) \tag{6}$$

where R is a set of Flexi^{P} corresponding to the power consumption that is subject to adjustment (i.e. flexibility exchange); β is a Lagrange multiplier which imposes the penalty to the selected R if the constraints are violated. Parameter β can be set to a value which ensures the violation point is not corresponding to the minimum objective value in the solution space. In this study β is set to 10. N denotes the total number of buses which are involved in flexibility exchange. K is the total number of phases which are involved in adjustment at the bus. $P_{ij,\text{ori}}$ and $Q_{ij,\text{ori}}$ are the original real and reactive power consumption at buses prior to any adjustment from customers. $P_{ij,\text{ori}}$ and $Q_{ij,\text{ori}}$ are usually obtained from general state estimation. $P_{ij,\text{adj}}$ and $Q_{ij,\text{adj}}$ are the derived real and reactive power consumption after the customers' power variation/adjustment. $P_{ij,\text{adj}}$ and $Q_{ij,\text{adj}}$ are obtained from EPSE while the Flexi^{P} of $\boldsymbol{F}$ in EPSE is set as R. $P_{ij,\text{lim}}$ and $Q_{ij,\text{lim}}$ are the maximum limit allowed for power variation.

To obtain the minimum variation of power consumption and generation from customers, a widely used optimisation algorithm, Genetic Algorithm (GA) is used to search the optimal set of Flexi^{P} by optimising the objective function defined by (6).

C. Flowchart of The Proposed approach

The flowchart of the approach is given in Fig. 1, which shows that EPSE is a sub-process of MVPO. For each R generated by GA, an EPSE is required to assess $F_{\text{optimisation}}$.

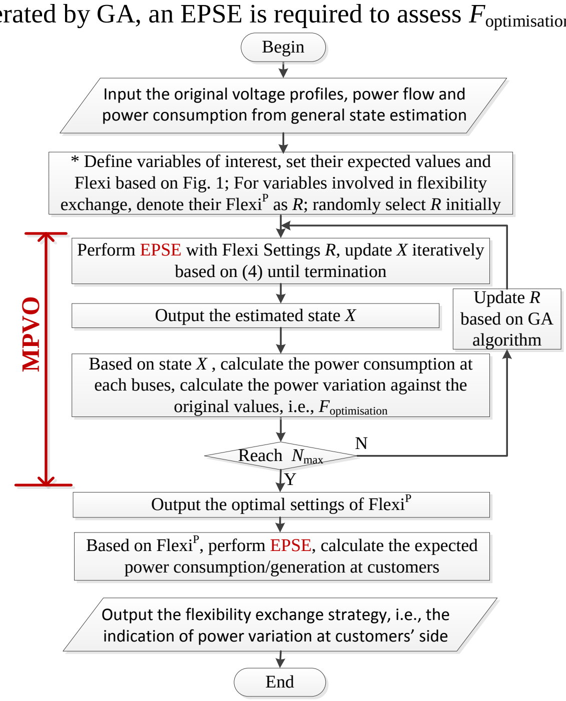


Fig. 1 Flow chart of the decision making approach to obtain flexibility exchange strategy.

For the step marked with "*" in Fig. 1, the detailed process of determining variables of interest and parameter settings prior to the procedure of estimation and optimisation is given in Fig. 2. The variables (including bus voltage, power injection and power flow at lines) are classified into four groups based on their requirements and constraints. Groups 1-3 are the selected variables of interest and will be used for the subsequent estimation and optimisation process, while group 4 is discarded and will be not involved in estimation. Fig. 2 also provides the guidance of setting Flexi and expected values Y. The selection of parameter setting for α_1 will be further discussed in Section III-B. Parameter α_2 is the weight reference and is set to 1 to allow the variables to vary around their original values, following the same approach in power flow analysis in which equal weights are set for observable variables.

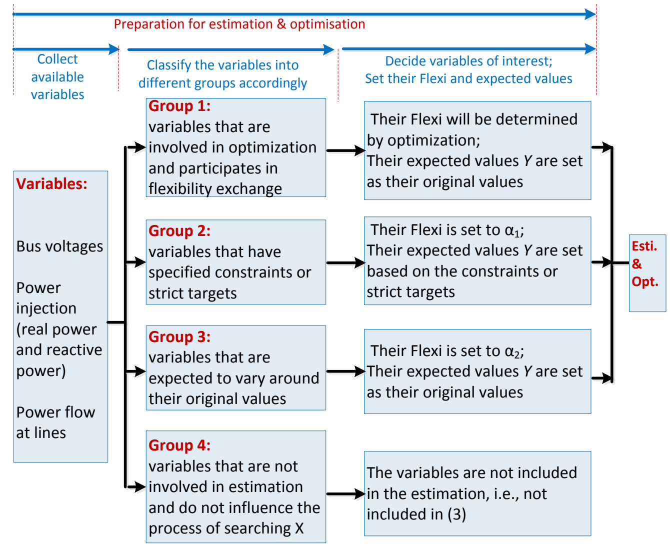


Fig. 2. Determination of variables of interest and parameter settings.

III. Simulation Results

The proposed approach is tested on several cases involving different optimisation problems with different scenario assumption. Cases 1-3 are to present the capability of varying Flexi and expected value settings in EPSE in order to achieve purposes of constraint management; while cases 4-5 include optimisation procedure, i.e., MPVO, to search for optimal Flexi for flexibility exchange.

A. Case 1: Achieving Expected Voltage Profiles

The proposed approach is tested on a 24-bus section of real UK distribution network [17], as shown in Fig. 3, in which the power generated from the generators at Bus B1 is feeding the network to provide the power consumption at buses B15-B24.

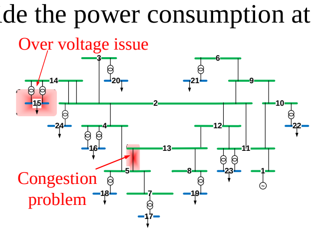


Fig.3. 24-bus distribution network.

1) Expectation. The goal of this case is to drag the violated voltages back to the upper limit via customers' power adjustment, without changing the power injection from generators at Bus B1. The original voltage profiles at buses of concern (that can be obtained from general state estimation) are given in Fig. 4. It can be seen from the Fig. 4 that voltage at bus B15 is asymmetric and the voltage at phase C is higher than 1.1 p.u. In this case, assume the voltage of phase C at B15 is expected to be within a strictly defined upper limit, 1.08 p.u. Although in practice the upper limit is higher than 1.08p.u., this case is to present the capability of the proposed approach in meeting stricter requirement. Furthermore assume that the other two phases at bus B15 are expected to retain the same voltages as before, i.e., the ones without customers' power adjustment, in order to minimize the impact to the customers connected at these two phases. Simultaneously the voltages at buses B16-19 are expected to remain the same as original voltage profiles. The illustrative constraints mentioned above could vary in practice based on network and customer requirements. They are used here to test the capability of the proposed approach in meeting different requirements simultaneously.

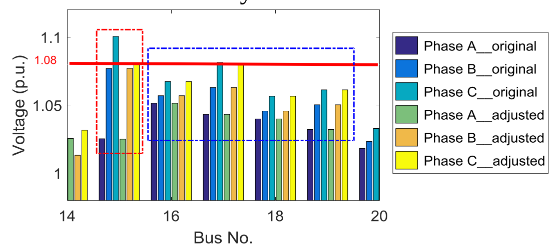


Fig. 4. Voltages obtained without and with power variation from customers.

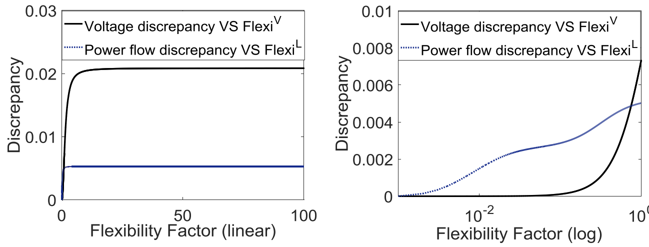
2) Settings and implementation. The parameter settings of Flexi are based on Fig. 2. As mentioned above, the voltage at phase C is expected to reduce to 1.08 p.u while the voltages at phase A and B should retain the same as original. Based on Fig. 2, the expected voltage at phase C of B15 is set to 1.08 p.u., and the corresponding Flexi^V is set as α_1 (α_1=0.001 is used in the study which will be explained later). The expected values for voltages at phases A and B of Bus B15 and all phase voltages at Buses B16-B19 are set as their original values, and the corresponding Flexi^V is set to α_1. Power injection from the generators at B1 is expected to remain the same. Thus the power Flexi^P at B1 is set to α_1. The power Flexi^P at buses where no loads or DGs are connected (i.e., buses B1-B14 in the test network) are set to α_1, as it is for certain that the power consumption/generation at these buses is zero. The rest of power Flexi^P is set to α_2 so that the power variation is expected to occur around the original values. Similarly, the retained voltage Flexi^V and power flow Flexi^L are set to α_2, while their expected values are set as original values. EPSE is applied to estimate the network state. Based on the estimated network state, the voltages obtained after the power adjustment (i.e., power variation at customer side) are derived and given in Fig. 4. It can be seen that with the power adjustment, the expectation of voltages at buses B15-19 are met, and the voltage at phase C of bus B15 is capped within 1.08 p.u., as the Flexi^V corresponding to voltages profiles at bus B15-B19 is set to 0.001 to ensure their derived voltages should be as expected. The power generation at B1 remains the same as their original value in the results obtained.

To evaluate the suitability of the obtained voltage profiles against the expectation at critical buses (mainly the buses whose corresponding Flexi^V is set as 0.001), voltage discrepancy level is defined by (7). It is to measure how far the actual voltage at critical buses is away from the expected voltages.

$$\text{Voltage discrepancy} = \sum_{i=1}^{3}\left|V_{i,O} - V_{i,E}\right| \tag{7}$$

where $V_{i,O}$ denotes the voltages at phase i obtained after adjustment, and $V_{i,E}$ is the expected voltage at phase i. Smaller voltage discrepancy suggests better performance.

To investigate the impact of the setting of Flexi^V for voltage at B15 on the performance of voltage discrepancy at B15, the Flexi^V of the voltages at B15 is varied from 0.001 to 100. This is to illustrate how the voltage at B15 approaches the expected values as Flexi^V is decreased. The voltage discrepancy calculated based on Flexi^{V} at the range of [0.001, 100] is presented by black solid line in Fig. 5 (a). With a large Flexi^{V}, the voltage at B15 is far away from the expected value. The performance of using small Flexi^{V} at the range [0.001, 1] is also given in Fig. 5(b) in which Flexi is presented in log. With smaller Flexi^{V}, the voltage discrepancy is smaller, which suggests the voltages are closer to the expectation. It can be seen that the strictness of achieving the expectation is enhanced by setting smaller Flexi^{V}.



(a) (b)

Fig. 5. Voltage discrepancy at B15 against Flexi^{V} setting for voltage at B15

Furthermore, the voltage profiles at B15 obtained with different settings of Flexi^{V} are shown in Fig. 6, together with the original and expected voltage profiles. The figure shows that the voltage at Phase C is gradually approaching the expected one when Flexi^{V} decreases. The Flexi^{V} can be selected based on the strictness of the expectation/requirement.

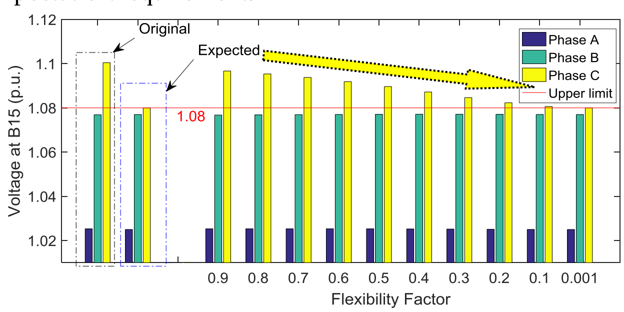


Fig. 6. Voltage profiles at B15 with various Flexi settings

B. Case 2: Congestion mitigation while meeting voltage profile expectation

The goal of this case is to mitigate congestion issue while simultaneously meeting the voltage profile requirements as defined in Case 1, under the condition that the power injection from generators at B1 remains the same. In the original power flow profiles, the per-phase power flow at line B5-B13 (i.e., the line between buses B5 and B13) is 0.0192, 0.0165 and 0.0127 p.u. respectively, and the goal in this case is to limit the power flow at phase A within 0.017 p.u. and reduce the power flow in phase B and C slightly to 0.015 and 0.011 p.u. respectively. In EPSE, the expected power flow at the three phases of this line is set to 0.017, 0.015, 0.011 p.u. respectively. The corresponding Flexi^{L} is set to different values, ranging from 0.001 to 100. The rest of the settings are the same as those in Case 1. The Flexi^{V} for voltages at B15 is constantly set to α_1 when varying the Flexi^{L}.

Similar to the definition of voltage discrepancy, the power flow discrepancy is defined as the difference between expected power flow and the power flow obtained from EPSE with given Flexi^{L} settings. The power flow discrepancy at line B5-B13 against various settings of Flexi^{L} is presented in Fig. 5. Similar to case 1, it also shows that the power flow approaches the expectation with smaller setting of Flexi^{L}.

Shown in Fig. 5, both voltage and power flow discrepancies are smaller than 0.0009 when Flexi<0.007. Thus setting α_1<0.007 is preferred in order to ensure small discrepancy from the expected values. In this study, α_1 is set to 0.001.

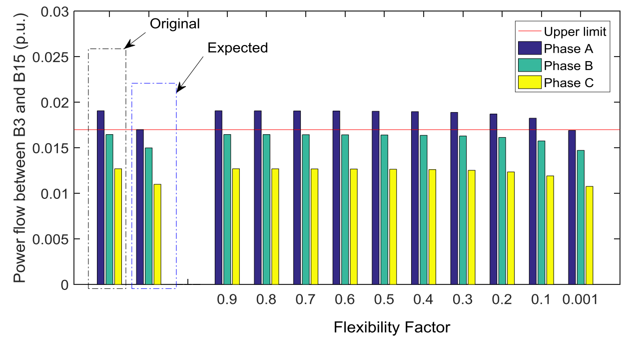


Fig. 7. Power flow profiles at line B5-B13 with various Flexi^{L} settings

The power flow in line B5-B13 obtained with different settings of Flexi^{L} is also given in Fig. 7. With 0.001 Flexi^{L}, the obtained EPSE result is able to cap the power flow within 0.017 p.u., while the power flow in phase B and C are the same as expected. Fig. 8 presents the voltage profiles at B15 when Flexi^{L} of the power flows in lines B5-B13 are set to different values. It can be seen that the voltage requirements are met at all times in this case (The voltage Flexi at bus B15 was constant and equal to 0.001, as mentioned above).

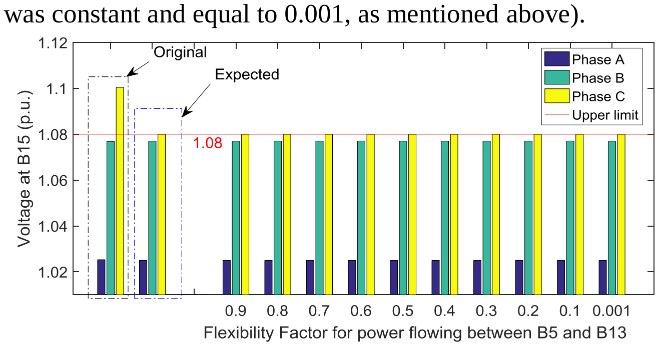
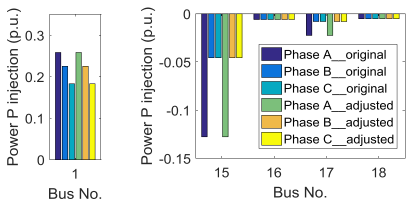


Fig. 8. Voltage profiles at B15 when varying Flexi^{L} for power flow at line B5-B13.

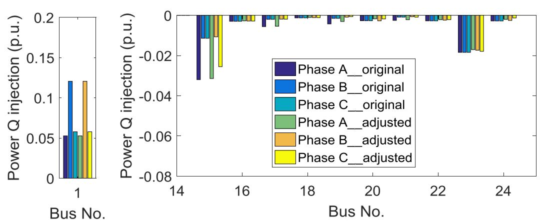
If the alleviation results in overloading at other lines, EPSE will be performed again while taking into account the constraints of these overloaded lines as well. If no strategy can be obtained by this process or if no flexibility is available at all, it means that the network does not have the resource to facilitate the congestion alleviation by using flexibility exchange. In this case other congestion alleviation solutions will be considered (e.g., curtailment, FACTS Devices, etc.). The study of these mitigation approaches is not within the scope of the paper, as it focuses on implementing constraint management using flexibility exchange approach.

C. Case 3: Power variation at customer side

It can be seen from Case 2 that over-voltage and congestion issues can be mitigated with power variation from customers' side without changing generation from B1. Apart from the requirements of voltage profiles and power flow constraints mentioned in Case 2, it is assumed furthermore that the real power consumption at buses B15-B18 are not subject to variation due to the unavailability of flexibly exchange from the aggregators/customers connected at these buses or areas. The original power profiles are presented in Fig. 9. Positive values mean injection of power, and negative values denote consumption of power. In EPSE, the Flexi^{P} for real power at Buses B15-B18 are set to 0.001, with the expected values set as original profiles. The rest of the settings are the same as in Case 2. EPSE is performed with the given Flexi settings and the expected values. The power variation (including real and reactive power) at buses obtained from EPSE is given in Fig. 9. With the adjusted power profiles generated by EPSE, the constraints of voltage and power flow described in Case 2 are met in the simulation. In the results, the power injection at B1 remains the same, and the real power consumption at buses B15-B18 is not changed as well, which fulfils the assumption given above.



(a) Power P



(b) Power Q

Fig. 9. Power consumption/generation at buses.

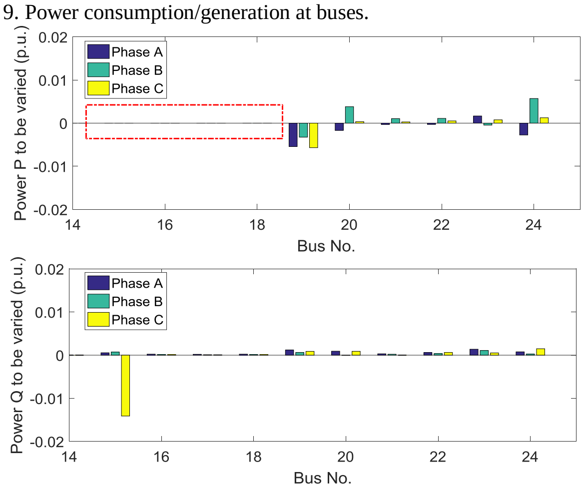


Fig. 10. Indication of power variation from customers at different buses.

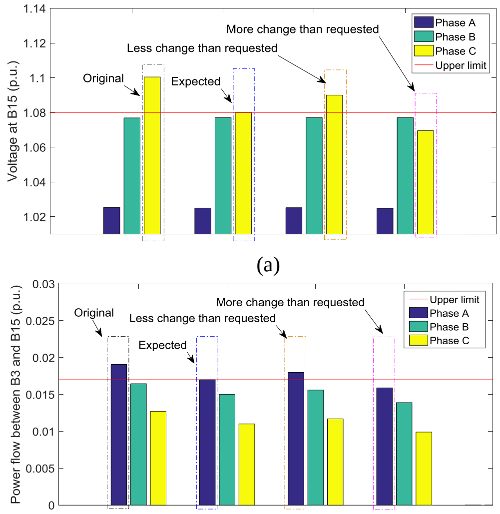
By comparing the original and the adjusted power profiles, the indication of flexibility exchange from customers can be obtained as shown in Fig. 10. The positive values mean increasing consumption (or equally reducing DG outputs or charging batteries), while the negative values mean reducing power consumption (or equally increasing DG outputs or releasing the power from batteries). This indication as given in Fig. 10 not only provides the information regarding whether it is expected to increase or decrease power from customers at different sites, but also indicates how much power variation is expected from different sites.

D. Case 4: minimum power variation from customers while meeting requirements

For previous cases, the power Flexi^{P} is set to 1 for all buses except for bus B1, B15-18. As shown in case 3, since the real power at buses 15-18 are not subject to variation, their participation in flexibility exchange is limited, so their Flexi^{P} is set to 0.001. As discussed in Section II, Flexi^{P} can somehow reflect the participation levels from different customers in flexibility exchange. In this case, Flexi^{P} associated with the power variation at customers' side is optimised using the flowchart given in Section II-C. GA with population of 20 and 100 generations is applied to search the optimal Flexi^{P} (except for the Flexi^{P} for B1, B15-B18). The initial population in GA is randomly selected within the range of [0.001, 1]. The optimal Flexi^{P} settings obtained from the optimization procedure is used to generate the indication of power adjustment/variation. The obtained indication is given in Fig. 11. It can be seen that the power at buses B15-B18 are not changed, as their Flexi^{P} is set to 0.001 and not used as the input variables during optimisation. The total power variation in this case is 0.052 p.u., which is less than that obtained in case 3 (0.064 p.u.) in which the constraints are considered but the minimum power variation is not targeted.

Although the optimal indication of power variation/adjustment is given, in reality the power may not vary as expected, due to the uncertainty in on-line customers' engagement. Thus receiving less or more demand variation than expected is possible. To address this uncertainty, assume that less variation is achieved than the expected as suggested in Fig. 11. With less power variation, load flow is run to obtain the voltage and power flow profiles. The power flow results, including the voltage at B15 and power flow at line B3-B15, are shown in Fig. 12. The profiles obtained with 50% more power variation than expected are also presented in Fig. 12. It can be seen that when the power varies based on the indication of increase or decrease only, even though the exact expected variation may not be achieved, the voltage violation and congestion issues are still mitigated to a certain extent.

Fig. 11. Indication of power variation from customers at different buses with minimum power variation.



(a)

(b)

Fig. 12. The performance with less or more power variation than expected.

E. Case 5: study based on 96-bus generic distribution network

The approach is further validated on a 96-bus generic distribution network. The single line diagram of the network is given in Fig. 13, which indicates the location where voltage violation and congestion issues exist. The voltages at Phase A of buses B59-B63 are 0.9394, 0.9388, 0.9377, 0.9377 and 0.9347 p.u. respectively, which are less than the lower limit of voltage defined as 0.94 p.u. The power flow from B93 to B91 (Phase A) is 0.0142 p.u. To address the congestion issues in the study, assume the upper limit of power flow at line B93-B91 is 0.01 p.u. The goal of this case is to mitigate these issues with minimum power variation at customers' sides, without modifying the power injected from feeder at higher voltage level 33 kV.

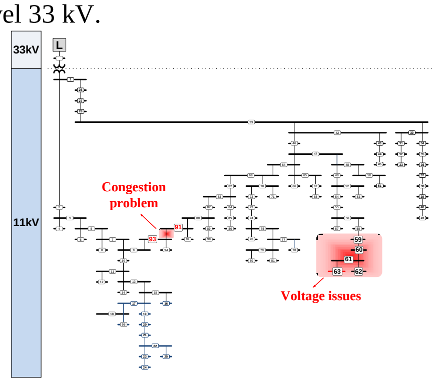


Fig. 13. The single-line diagram of 96-bus generic distribution network.

The power Flexi^P at B1 where the feeder is connected is set to 0.001. Similar to the settings in previous cases, the Flexi^P at buses without load connection is set to 0.001 p.u. The rest Flexi^P (corresponding to the power variation involved in flexibility exchange) will be optimised, and their expected power consumption/injection is set to their original values. The expected power flow at line B91-B93 is set to 0.01 p.u. and the corresponding Flex^L is set to 0.001. The expected voltage at the bus with the most severe voltage issue (i.e., B63 in this case) is set to 0.94 p.u. while the corresponding Flexi^V is set to 0.001 p.u. The rest variables non-mentioned above are not involved in estimation. Similar to Case 4, the goal here is to find out the optimal Flexi^P so that the minimum customer power variation can be achieved. The optimisation procedure is applied using GA with 500 generations and the population size of 30. The initial population in GA is randomly selected within the range of [0.001, 1]. The indication of power variation is derived from the obtained optimal Flexi^P, and provided in Fig. 14, in which the power variation mainly occurs at Phase A due to the issues existing at Phase A. The total power variation in this case is 0.0106 p.u.

As it can be seen, with the suggested power variation, the voltage and congestion issues are mitigated. Fig. 15 provides the voltage profile comparison between the original voltages and the voltages obtained with suggested power variation. As shown in highlighted dashed red box in Fig. 15, the voltages at these buses originally are less than the lower limit. With the power variation, B63 reaches the voltage lower limit, i.e., 0.94 p.u., while voltages at other buses within the dashed red box are higher than 0.94 p.u. As for the congestion issue, the power flow at line B93-B91 is changed from 0.0142 p.u. to 0.01 p.u., which meets the expectation.

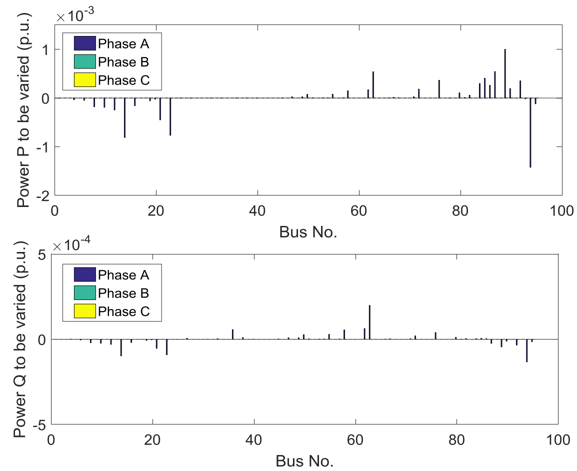
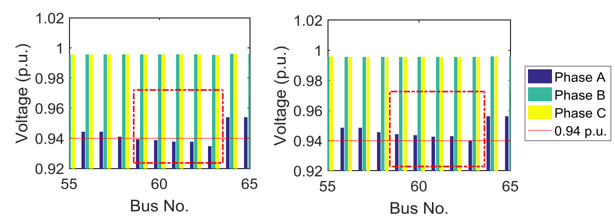


Fig. 14. Indication of power variation from customers at different buses with minimum power variation.



(a) Original profiles (b) Profiles obtained with power variation

Fig. 15. The voltage profiles obtained without and with power variation.

To illustrate the performance without optimisation (i.e., without optimising Flexi^P values), EPSE is run with all Flexi^P set to the same value, ranging from 0.001 to 5 with a step of 0.005. The obtained total power variation against Flexi^P is given in Fig. 16. It can be seen that there is a minimum power variation (0.0129 p.u.) when Flexi^P is within the range of [0.7, 0.85]. The power variation obtained using Flexi^P =0.8 is given in Fig. 17. It can be seen that it requires an extra 21.7% ($\frac{0.0129-0.0106}{0.0106}$%) of power variation compared to the solution presented in Fig. 14. This highlights the benefit of using the MPVO for optimising Flexi^P in solving the problem.

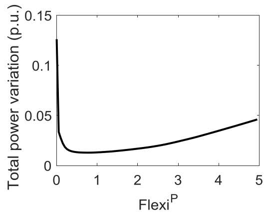


Fig. 16. Results obtained by EPSE when applying universal Flexi^P.

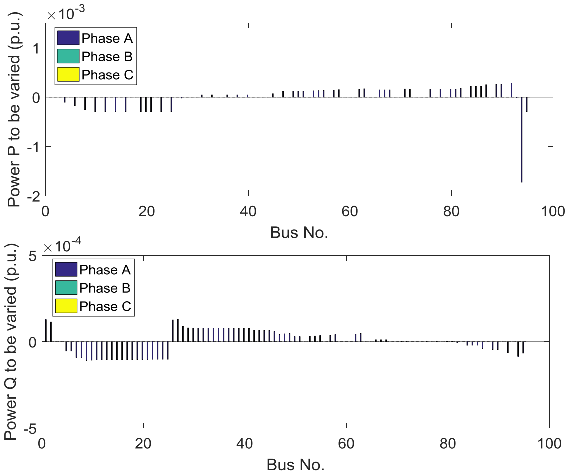


Fig. 17. The power variation obtained with Flexi^P =0.8.

Fig. 16 shows that the optimal point is within the range of [0.001, 1], which justifies the choice of selecting the initial population for GA within this range. The range [0.001, 1] for initial population is selected based on prior studies and experience with the aim to reduce the computational burden during the optimisation. Although the initial population is chosen within [0.001, 1], the search space during the optimisation is extended to cover the range between 0 and 5. To ensure the optimality of the solution obtained, the final solution is selected from multiple tests where each simulation is carried out with different randomly chosen initial population. The optimisation is run for over 20 times while making sure the final results are repeatable with 0.0001 variation.

IV. Conclusions

This paper proposes a flexibility exchange strategy approach to facilitate network constraint management while minimizing the participation (power variation) from customers. The proposed approach mainly consists of Expected Profile State Estimation (EPSE) and Minimum Power Variation Optimisation (MPVO). In EPSE, the expected network variables are defined based on network requirements against the original network profiles. Each variable is assigned a Flexibility Factor to confine its freedom of variation during the estimation. With the expected network variable values and Flexibility Factors, the feasible network state is estimated. In MPVO, a Genetic Algorithm based optimisation is applied to find the optimal settings of the Flexibility Factors corresponding to the network variables that can be adjusted by customers. The illustrative results have demonstrated that the proposed approach can generate an appropriate network state that meets the network constraints while involving the least power variation from customers. The impact of having less or more variation than expected is also investigated in the paper. The proposed approach is compared with the estimation without optimisation procedure (i.e., MPVO), and the results show the benefits of including the optimisation procedure.

References

[1] T. Sansawatt, L. F. Ochoa, and G. P. Harrison, "Smart Decentralized Control of DG for Voltage and Thermal Constraint Management," *IEEE Trans. on Power Syst.*, vol. 27, pp. 1637-1645, 2012.

[2] C. L. Su, "Comparative analysis of voltage control strategies in distribution networks with distributed generation," in *2009 IEEE Power & Energy Soc. Gen. Meeting*, 2009, pp. 1-7.

[3] M. Michalski and G. Wiczyński, "Determination of the parameters of voltage variation with voltage fluctuation indices," in *2016 17th Int. Conf. on Harmonics and Quality of Power (ICHQP)*, 2016, pp. 460-465.

[4] L. Cheng-Tsung, H. Kuo-Yuan, M. E. Galicia, and L. Sheng-Yang, "Systematic integration guidance for alleviating substation congestions of steel mill power systems by distributed generation units," in *2013 IEEE Industry App. Society Annual Meeting*, 2013, pp. 1-7.

[5] N. Grid, "Constraint Management -Service Description," 2013.

[6] J. H. Grundy, H. P. Johnson, and C. Proudfoot, "Transmission constraint management on the National Grid system and the effect upon the commercial market place," in *Fourth Int. Conf. on Power System Con. and Man. (Conf. Publ. No. 421)*, 1996, pp. 31-36.

[7] I. Atzeni, L. G. Ordóñez, G. Scutari, D. P. Palomar, and J. R. Fonollosa, "Demand-Side Management via Distributed Energy Generation and Storage Optimization," *IEEE Trans. on Smart Grid,* vol. 4, pp. 866-876, 2013.

[8] C. Li, X. Yu, W. Yu, G. Chen, and J. Wang, "Efficient Computation for Sparse Load Shifting in Demand Side Management," *IEEE Trans. on Smart Grid*, vol. 8, pp. 250-261, 2017.

[9] F. Ye, Y. Qian, and R. Q. Hu, "A Real-Time Information Based Demand-Side Management System in Smart Grid," *IEEE Trans. on Par. and Dist. Systems,* vol. 27, pp. 329-339, 2016.

[10] B. Hayes, I. Hernando-Gil, A. Collin, G. Harrison, and S. Djokić, "Optimal Power Flow for Maximizing Network Benefits From Demand-Side Management," *IEEE Trans. on Power Syst.*, vol. 29, pp. 1739-1747, 2014.

[11] R. A. Verzijlbergh, L. J. D. Vries, and Z. Lukszo, "Renewable Energy Sources and Responsive Demand. Do We Need Congestion Management in the Distribution Grid?," *IEEE Trans. on Power Syst.*, vol. 29, pp. 2119-2128, 2014.

[12] T. H. Vo, A. N. M. M. Haque, P. H. Nguyen, I. G. Kamphuis, M. Eijgelaar, and I. Bouwman, "A study of congestion management in smart distribution networks based on demand flexibility," in *2017 IEEE Man. PowerTech*, 2017, pp. 1-6.

[13] I. Stoyanova, M. Biglarbegian, and A. Monti, "Cooperative energy management approach for short-term compensation of demand and generation variations," in *2014 IEEE Int. Syst. Conf. Proc.*, 2014, pp. 559-566.

[14] T. Logenthiran, D. Srinivasan, and T. Z. Shun, "Demand Side Management in Smart Grid Using Heuristic Optimization," *IEEE Trans. on Smart Grid,* vol. 3, pp. 1244-1252, 2012.

[15] M. H. Albadi and E. El-Saadany, "A summary of demand response in electricity markets," *Electric power syst. res.*, vol. 78, pp. 1989-1996, 2008.

[16] N. C. Woolley, "Identification of weak areas and worst served customers for power quality issues using limited monitoring and non-deterministic data processing techniques," Ph.D. dissertation, Faculty Eng. and Phys. Sci., Univ. Manchester, 2012.

[17] N. C. Woolley and J. V. Milanović, "Statistical estimation of the source and level of voltage unbalance in distribution networks," *IEEE Trans. Power Del.*, vol. 27, pp. 1450-1460, 2012.

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