The following publication Q. Hu, S. Bu, S. Xia and H. Cai, "A Novel Voltage Regulation Strategy for Secure Operation of High Renewable Penetrated Distribution Networks with Different R/X and Topologies," 2019 IEEE Innovative Smart Grid Technologies - Asia (ISGT Asia), 2019, pp. 3424-3229 is available at https://doi.org/10.1109/ISGT-Asia.2019.8881753

A Novel Voltage Regulation Strategy for Secure Operation of High Renewable Penetrated Distribution Networks with Different R/X and Topologies

Qian Hu[1], Siqi Bu[1], *Senior Member, IEEE,* Shiwei Xia[2] , *Member, IEEE,* Hui Cai[3]

1. Department of Electrical Engineering, The Hong Kong Polytechnic University
2. School of Electrical and Electronic Engineering, North China Electric Power University
3. Jiangsu State Grid Economic Research Institute

***Abstract*—Based on a newly developed simulation platform, this paper proposes a fully distributed phase-independent voltage regulation strategy. The strategy offers both real and reactive power support options from distributed energy resources (DERs) and accommodates the impact of different *R/X* of the lines and different topologies of a distribution network. A linear sensitivity analysis is first carried out to explain the essential impact mechanism of *R/X* on the voltage sensitivity. Then a perturbation approach, as the substitute of conventional Jacobian analysis, is employed for an accurate voltage sensitivity analysis on a three-phase unbalanced nonlinear distribution network model. The impact of *R/X* on the voltage sensitivity is quantified, which can then be used to indicate which type of power and critical bus can provide the most effective voltage support under the specific *R/X* in the planning stage of the regulation strategy. It also provides a guidance for DERs droop constant tuning during the operational stage to ensure the effectiveness of the proposed strategy. The voltage regulation includes two stages: the first is consensus stage based on the consensus algorithm to achieve an average voltage deviation without the need of central controllers; the second is droop control stage to proportionally allocate the available P/Q of DERs. The modified IEEE-13 bus distribution network with different *R/X* and topologies is used for the case study. Results verify that the proposed regulation strategy can effectively deal with the unbalanced voltage problems in the network.**

***Index Terms*-- consensus control, distributed energy sources, distribution network, *R/X*, voltage regulation**

I. Introduction

The extensive deployment of renewable distributed energy resources (DERs) is one of the features in future low voltage (LV) active distribution networks. The existence of DERs in such networks can satisfy the local load demand in a more flexible manner but further escalates the complexity of the secure operation of distribution network. On the one hand, the topologies of the networks would change frequently. On the other hand, due to the nature of relatively higher ratio of line resistance and reactance, i.e., *R/X*, in the distribution level than that in the transmission level, $P\theta$-QV decoupling is no more valid in the LV distribution network [1][2]. Under such circumstance, for the secure operation of distribution network, it is important to figure out how real power and reactive power compensation effectively regulate the voltage under different *R/X* of the line. With the proper control of power electronics interface, DERs usually can be utilized to provide the reactive power compensation in the case of undervoltage, which has been discussed in some work, such as [3] and [4]. Yet in [1] real power is considered as the main factor affecting the voltage magnitude and used to regulate voltage in the distribution network. Although the impact of *R/X* on the effectiveness of reactive power support was examined in [5], real power was not considered in this work.

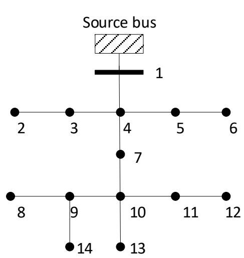
The voltage sensitivity approach based on the Jacobian matrix is used as a common tool to analyze the bus voltage variation with respect to the real and reactive power variation, which are demonstrated in [2],[6] and [7] to regulate the voltage. It is worth noting that assumptions and simplifications of the network are made in the workings when using the Jacobian matrix. In fact, several nonlinear elements in the network such as loads make the pure mathematical linear analysis of Jacobian matrix complicated and become inaccurate when it comes to the complex large-scale network. Therefore, a perturbation approach, which is a simulation-based sensitivity analysis method, is developed in this work as the substitute of conventional Jacobian matrix sensitivity analysis to locally investigate the impact of *R/X* on the effectiveness of voltage regulation through *P/Q* compensation. The results indicate the optimal location to install DERs by comparing the value of sensitivity terms. Such results can be taken as the reference for the distribution network operator (DNO) to plan the appropriate voltage regulation approach under various network conditions.

Based on the prior knowledge of effectiveness of *P/Q* under different *R/X*, a comprehensive two-stage voltage regulation strategy is then proposed in this paper. The aim of this strategy is to make sure the bus phase voltage can be maintained locally and independently to a certain level for the secure operation without the need of central controllers by utilizing the available *P/Q* capacity of DERs. In the most current research work towards the satisfied voltage regulation in distribution networks, it is often assumed the network is three-phase balanced and the regulation strategy is developed based on this assumption, e.g. the work in [2] and [8]. However, in real life, the network is significantly unbalanced due to imbalance in loading and the untransposed lines. Therefore, in this work, rather than designing for the ideal three-phase balanced network in [3][9], the detailed unbalanced network model is developed and the phase voltage is regulated independently to improve the unbalanced voltage profile, which is the outstanding feature of this regulation strategy. The second feature is the regulation is in fully distributed manner on the basis of the discrete consensus algorithm described in [9] and [10]. There is no need for the central controller and only local neighboring bus voltage information is needed.

The contributions of this paper can be summarized as follows: 1). An interactive simulation platform is established based on OpenDSS and MATLAB, consisting of the detailed three-phase unbalanced distribution network and the generic DER model. 2). A linear sensitivity analysis method is conducted to explain the mechanism how *R/X* influence the effectiveness of P/Q compensation on the voltage support in the distribution network. 3). A perturbation approach is proposed to locally obtain the accurate voltage sensitivity for the unbalanced nonlinear system. This can be used not only to facilitate the voltage regulation strategy planning by DNO (e.g. DER installation location selection and P/Q compensation capability evaluation) but also to guide the tuning of DER droop coefficient during the regulation. 4). A fully distributed two-stage phase-independent voltage regulation scheme is developed to allocate the available power of DERs phase by phase to deal with the phase-unbalanced voltage problems in the network.

The remainder of this paper constructs as follows. In Section II, simulation platform is described. In Section III, linear sensitivity analysis and perturbation approach are introduced. Section IV proposes two-stage phase-independent consensus voltage regulation strategy. Case studies on the test network with different *R/X* and topologies are illustrated in Section V. Section VI gives the conclusion of the paper.

II. SIMULATION PLATFORM



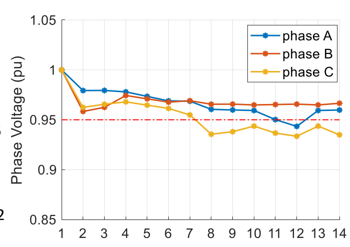


Figure 1. Schematic diagram of IEEE-13 bus distribution network(left)
Figure 2. Bus phase voltage under R/X = 3.11 (right)

OpenDSS is a distribution system simulator specifically for unbalanced multi-phase power distribution system modelling, which can be driven by a COM interface, such as MATLAB, for use-defined functions. In this paper, a platform interacting between OpenDSS and MATLAB is established to conduct the sensitivity analysis as well as the regulation strategy. The modified IEEE 13-bus three phase unbalanced distribution network used as the test network is built in OpenDSS. Sensitivity analysis and strategy verification is developed in MATLAB.

Shown in Fig.1, for convenience, the bus index is renumbered from 1 to 14. Bus 7 indicates the concentrated point of load of the distributed load on line 4 to 10 located at the midpoint. The voltage of bus 1 is regulated at a constant voltage $1\ p.u.$ All distribution lines are modelled in three-phase with identical *R/X* configuration. Positive sequence resistance R_{seq} and inductance X_{seq} converted from the line parameters in three-phase expression are used to define *R/X* of the network. *R/X* hereafter refers to R_{seq}/X_{seq} of the equivalent sequence network. Constant $P + jQ$ model is used for the unbalanced three-phase load.

Fig.2. shows a snapshot of the phase voltage at all buses when the network is under heavy load at *R/X* = 3.11, where the phase unbalanced phenomenon and undervoltage at phase B and C is observed. To deal with these concerns, DER with available real and reactive power can be utilized properly to provide voltage support phase by phase. A generic three-phase DER model is also built in OpenDSS, which can be further extended to the specific type of active distributed element, such as photovoltaics and electric vehicle. It is assumed total capacity of each DER is allocated in average division to three unbalanced phases.

III. IMPACT EVALUATION OF R/X ON THE VOLTAGE SENSITIVITY WITH P/Q SUPPORT

From the perspective of distribution network planning, it is important to know how *R/X* of the lines influence the voltage sensitivity in order to design an effective voltage regulation strategy. In this section, two voltage sensitivity analysis methods are described. The first one is the linear analysis, derived from the simplified balanced network model, which explains the mechanism but only indicates the general trend of the impact of *R/X*. Secondly the perturbation approach is proposed to give a more accurate sensitivity analysis and can be further used for the planning and operation of voltage regulation strategy.

A. Voltage Sensitivity Linear Analysis

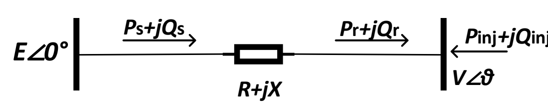


Figure 3. Schematic diagram of two-bus network

Fig. 3 demonstrates a simple two bus network, where the voltage of sending end $\bar{E}$ is regulated as a constant input $1\ p.u.$ Receiving end voltage and apparent power transmitted through the line can be expressed as follows:

$$\bar{V} = \bar{E} - (R + jX)\bar{I}^* \tag{1}$$

$$\bar{S} = \bar{E}\,\bar{I}^* = P_s + jQ_s \tag{2}$$

From (2), we can know

$$\bar{I} = \frac{P_s - jQ_s}{E} \tag{3}$$

where $\bar{E} = E\angle 0^{\circ}$

By rearranging (1) and (3), we can get

$$E - \bar{V} = (R + jX)\frac{P_s - jQ_s}{E}$$
$$= \frac{RP_s + XQ_s}{E} + j\frac{XP_s - RQ_s}{E} \quad (4)$$

For small voltage angle θ, voltage magnitude can be approximated to:

$$V \cong E - \frac{RP_s + XQ_s}{E} \quad (5)$$

Real and reactive power injected into the receiving bus can be expressed as:

$$P_r = P_s - P_{loss} \quad (6)$$
$$Q_r = Q_s - Q_{loss} \quad (7)$$

where P_{loss} and Q_{loss} are the real and reactive power losses respectively of the line after the sending bus. It is assumed here the losses are negligible compared to the power sent to the receiving bus, therefore the approximation can be made:

$$P_r = P_s \quad (8)$$
$$Q_r = Q_s \quad (9)$$

And voltage magnitude can be rewritten as:

$$V \cong E - \frac{RP_r + XQ_r}{E} \quad (10)$$

Our interest is to see how injected power to the receiving end bus influences the voltage variation ΔV. Therefore, ΔV can be formulated in the linearization expression:

$$\Delta V = \frac{\partial V}{\partial P_r}\Delta P_r + \frac{\partial V}{\partial Q_r}\Delta Q_r \quad (11)$$

The first part of (11) is defined as *V-P* sensitivity term, which is equal to the partial derivative of (10) with respect to the real power multiplied by total injected power to that bus. Similarly, the second part is called *V-Q* sensitivity term. From (11), the sensitivity coefficient of voltage variation with respect to the real and reactive power at the receiving end is calculated respectively as:

$$S_{vp} = \frac{\partial V}{\partial P_r} = -\frac{R}{E} \quad (12)$$
$$S_{vq} = \frac{\partial V}{\partial Q_r} = -\frac{X}{E} \quad (13)$$

If there is an extra power P_{inj} injected into the receiving end bus, P_r is updated to $P_r - P_{inj}$ and $\Delta P_r = (P_r - P_{inj}) - P_r = -P_{inj}$ which is a negative value. Consequently, we can know ΔV is a positive value that indicates the voltage is increased due to the negative sensitivity coefficient. Furthermore, the sensitivity ratio S_{Ratio} can be defined as $\frac{S_{vp}}{S_{vq}}$, as (14). An important conclusion is drawn here that the sensitivity ratio of S_{vp} and S_{vq} is equal to *R/X* of the line between the sending and receiving bus.

$$S_{Ratio} = \frac{S_{vp}}{S_{vq}} = \frac{R}{X} \quad (14)$$

A phase balanced 4-bus radial distribution system is built to validate this conclusion by calculating the Jacobian matrix in MATPOWER, as shown in Fig.4. *R/X* of all lines are set to be identical. Based on (11), the general expression of variation of voltage magnitude of a certain bus can be written as follows:

$$\Delta V_n = \sum_{m=1}^{N} S_{vp\_nm}\Delta P_m + \sum_{m=1}^{N} S_{vq\_nm}\Delta Q_m \quad (15)$$

where *N* is the total number of buses in the system; *n* is the index of the target bus where the voltage variation is of interest; *m* is the index of all buses in the network. For the test network, voltage sensitivity of bus 2 was investigated under the line condition of *R/X* = 0.5, 1 and 3 respectively. Table I below records the value of S_{vp_2m}, S_{vq_2m} (m=3,4). The results show that S_{Ratio} is equal to the corresponding *R/X* of the lines, which is consistent with the conclusion in (14).

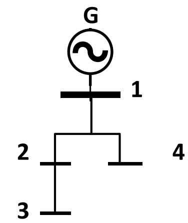


Figure 4. Schematic diagram of 4-bus radial distribution network

Table I Sensitivity coefficient of bus 2 under three *R/X* ratio

	***R/X*= 0.5**		***R/X*= 1**		***R/X*= 3**	
S_{vp_2m}	m=3	m=4	m=3	m=4	m=3	m=4
	-0.53	-0.50	-0.53	-0.50	-0.53	-0.50
S_{vq_2m}	m=3	m=4	m=3	m=4	m=3	m=4
	-1.06	-1	-0.53	-0.50	-0.18	-0.17
S_{Ratio}	**0.5**	**0.5**	**1**	**1**	**3**	**3**

The sensitivity coefficient of other buses in the network are also examined and the same sensitivity ratio pattern regarding to different *R/X* can be obtained. Therefore, we can conclude when *R/X* is less than 1, the change of bus voltage magnitude is more sensitive to the variation of reactive power, which means reactive power is the more effective power to regulate the voltage. When *R/X* is larger than 1, real power is seen to be the more desirable power to regulate the voltage.

B. Perturbation approach

A large-scale distribution network is more complex and unbalanced, therefore the conventional linear sensitivity analysis, i.e. Jacobian matrix sensitivity analysis would become extremely complicated and inaccurate. In addition, global information is needed to build a Jacobian matrix, which cannot be applied in the fully distributed scheme. Therefore, a perturbation approach is introduced here to locally investigate the voltage sensitivity. A cluster of voltage magnitude at a target bus can be collected by consecutively injecting a certain amount of power perturbation at any certain bus in the network. An accurate voltage sensitivity of this target bus with respect of real or reactive power injection at a certain bus can be acquired. An example of IEEE 13-bus network explains the working principle of this approach.

Table II Sensitivity coefficient of bus 13 with different buses (*R/X* = 1.34)

Bus	**3**	**5**	**6**	**8**	**9**	**11**	**12**	**13**	**14**
$S_p(10^{-3})$	6.4	6.5	6.4	12.8	**13.1**	**13.8**	**14.0**	**19.7**	**12.8**
$S_q(10^{-3})$	4.2	4.3	4.2	8.3	**8.5**	**8.6**	**8.3**	**13.0**	**8.3**
S_{Ratio}	1.5	1.5	1.5	1.5	1.5	1.6	1.7	1.5	1.5

Bus 13 located at the end of a feeder is taken as the targeted bus where the voltage will be regulated under *R/X* = 1.34. Real and reactive power is respectively injected into an examined bus from 0 to 2MW at increments of 0.1MW and the corresponding voltage magnitude can be obtained to draw a line. The slope of the line represents the voltage sensitivity of bus 13 with respect to the power injection at the examined bus. Table II demonstrates the slope of the plotted lines, i.e. sensitivity coefficient regarding to different examined buses.

From Table II, there are four observations: 1). Real power support is obviously more effective than reactive power for the power injection at the same bus when *R/X* is 1.34. However, the installation location of DER significantly matters as the reactive power compensation works better from bus 8 than real power compensation from bus 3, 5 and 6. 2). It is not surprising to find that the voltage at bus 13 is most sensitive to the power injection from itself. 3). Bus 12, bus 11, bus 9 and bus 14 are the buses where DERs should be integrated into due to the larger voltage sensitivity coefficient. 4). Sensitivity ratio $\boldsymbol{S_{Ratio}}$ here is no longer exactly equal to *R/X* but slightly higher, which indicates the limited accuracy of linear analysis in the previous section A for a complex nonlinear network model.

The results indicate that the perturbation approach can be used to plan the pre-set for a voltage regulation strategy under specific *R/X*, i.e., where the effective type of power and critical buses with DER can be identified. Moreover, it can provide the guidance for tuning the droop coefficient for the operation of regulation strategy, which will be discussed more next.

It is worthy to mention that in the real network this approach can be realized by deploying special designed sensor and controller at targeted bus and DER units, which won't be discussed as it is not the focus of this paper.

IV. Proposed Voltage Regulation

To effectively ensure the secure operation of unbalanced distribution networks, particularly dealing with the unbalanced voltage problems, a comprehensive voltage regulation strategy is developed. Fig.5 depicts the general structure of a proposed two-stage strategy working on the electrical network and the communication network. It has three main features: 1) The planning of the regulation strategy carries out further actions suggested by the perturbation analysis under the specific line and network configuration, so that a more effective regulation set-up, i.e. which type of power and where to install DER, can be specified. 2) It is fully distributed as only local information is needed and exchanged in the consensus stage. 3) It operates in the phase-independent mode. The voltage at each phase is monitored and regulated accordingly. The detailed working principle will be discussed more in the following.

A. *Discrete-time consensus algorithm and communication network topology*

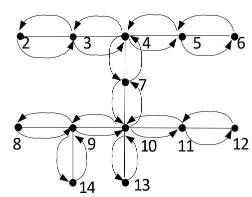
Discrete-time consensus algorithm can be briefly expressed as (16), where $k = 0,1,2 \ldots$ is the discrete time index. x_k^i and x_k^j are the local state of the agent i and agent j at iteration k. n is the total number of the agents in the system. At next iteration $k+1$, the state of agent i is updated from its previous state and the state of neighboring agents x_j. a_{ij} is the communication coefficient between agent i and agent j and $d_i = \sum_j^n a_{ij}$.

$$x_{k+1}^i = x_k^i + \frac{1}{d_i+1} \sum_{j=1}^n a_{ij} \left(x_j - x_i\right) \tag{16}$$

When $k \rightarrow \infty$, the state variable of agent x_{k+1}^i will converge to the average value of the initial state x_0^i, as shown in (17).

$$\lim_{k\rightarrow\infty} x_{k+1}^i = \frac{1}{n} \sum_{i=1}^n x_0^i = \bar{x} \tag{17}$$

An undirected graph is configured as the communication topology, where the information between the neighboring buses can be transmitted in bidirectional way, shown in Fig.6. Based on the graph, adjacency matrix $A = [a_{ij}]$ that carries the communication weights can be developed. All edge weights are set to one in this work. $a_{ij} = 1$ if two buses are directly connected otherwise $a_{ij} = 0$. According to the consensus algorithm and graph theory, with the well-designed communication graph, the targeted control variable can achieve a global agreement given a set of conditions without the need of central controller. Fig.7 shows an example of how the voltage deviations of different buses converge to a steady value in 150 steps after consensus algorithm.



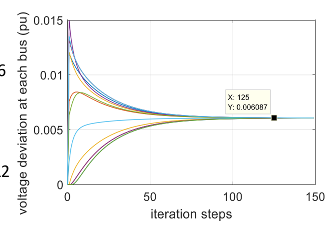


Figure 6. Communication network of IEEE-13 bus network (left)
Figure 7. Convergence of voltage deviations (right)

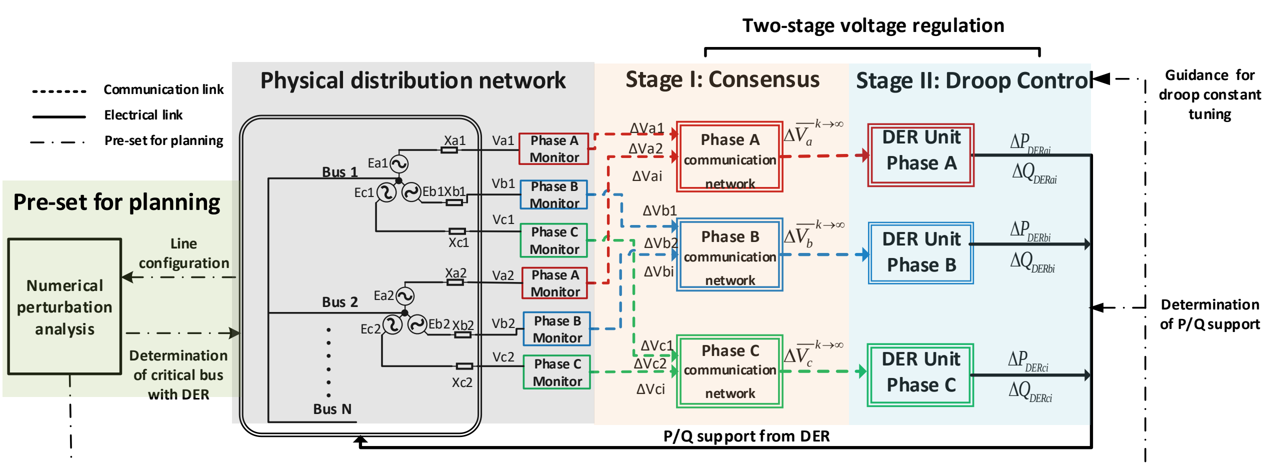


Figure 5. Schematic diagram of proposed voltage regulation strategy

B. Description of two-stage voltage regulation strategy

The previous perturbation approach is used to compare the voltage sensitivity with respect to real and reactive power. The results are taken as the prerequisite for the strategy planning.

To cope with the unbalanced phase voltage in the distribution network, the individual phase of each bus is monitored and regulated independently at every discrete pre-set time step. Once any one of local voltage at bus i is out of the legal limitation (1.0 pu $\pm$ 5%), the first consensus stage will be activated. The voltage deviation ΔV_i can be calculated and this information is transmitted to its neighboring buses in the communication network. Within several iteration steps, average voltage deviation $\Delta\overline{V}$ of the buses which are experiencing the voltage issues can be acquired, as (18) shows.

$$\lim_{k\to\infty} \Delta V_{k+1}^{i} = \frac{1}{n}\sum_{i=1}^{n} \Delta V_0^{i} = \overline{\Delta V} \qquad (18)$$

$\Delta\overline{V}$ is the subsequent input signal of the second stage, where the constant droop-based local controller is installed at each DER unit to implement the droop control, shown in Fig.8. Two factors contribute the tuning of droop coefficient D: 1) Local voltage sensitivity indicated by the perturbation analysis. 2) Instantaneous available capacity of DER. The capability of each DER to provide the real and reactive power to the network varies frequently depending on different factors, such as the installed capacity so the contribution of each DER to the voltage support varies accordingly. Due to this fact, in the second stage, available DER capacity P_{i_rate} and Q_{i_rate} is designed as the determinant part of droop coefficient to meet the flexible need of supporting power and achieving the efficient utilization of available capacity.

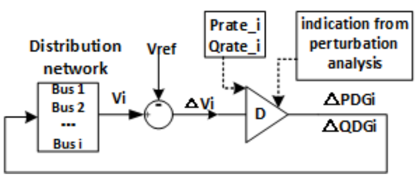
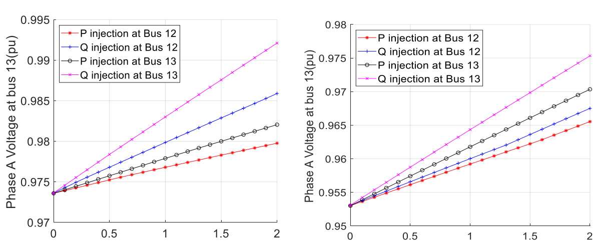


Figure 8 Diagram of second stage droop control

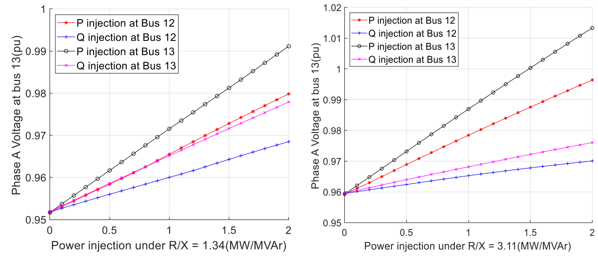
V. CASE STUDY

To validate the application of perturbation approach for planning of regulation strategy under specific *R/X*, two steps are conducted as below:

1. Choose buses with DER (e.g. bus 12 and bus 13) to inject real / reactive power and collect the voltage at bus 13.
2. Which type of power is more effective to regulate the voltage can be known by comparing the slope of the line, which is also the sensitivity coefficient. Simulation results with four IEEE network linecodes are shown in Fig.9.



(a) *R/X*= 0.31 (b) *R/X*=0.78



(c) *R/X*=1.34 (d) *R/X*=3.11

Figure 9. Voltage sensitivity of bus 13 with respect of real and reactive power injection at bus 12 and 13 under various *R/X*

As indicated in Section III-B, DERs will be integrated into bus 9, bus 11, bus 12 and bus 14 for the cases below to achieve a satisfied regulation. Both original radial test network and the mesh network which is modified as shown in Fig.10 are used to verify the regulation strategy. Two test networks have the same network configuration except for the different topology. The instantaneous phase voltage magnitude of each bus before and after regulation is examined.

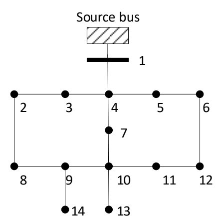
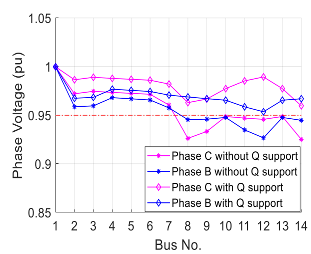


Figure 10 Schematic diagram of mesh network

A. Case One--R/X = 0.31



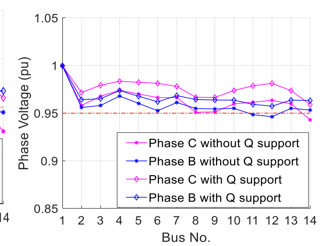


Figure 11. Phase voltage under R/X = 0.31, radial network (left)
Figure 12. Phase voltage under R/X = 0.31, mesh network (right)

In this case, phase A voltage is under the normal condition, while the phase B and phase C voltage of the buses at the farther end of the network, i.e. bus 8 to bus 14 are below the minimum limitation 0.95pu. Thus, the regulation will be initiated only for phase B and phase C. For R/X = 0.31, reactive power compensation is chosen as a more effective way to support the voltage. The snapshot of voltage before and after regulation is shown in Fig. 11 and Fig.12 for both the radial and meshed network, where we can see the violated voltage has been increased to the normal value.

B. Case Two – R/X = 3.11

In case 2, for radial network, undervoltage occurs at phase A and phase C while only at phase C for mesh network. The regulation with real power support is activated accordingly. From Fig.13 and Fig.14, we can see the bus phase voltage is increased to normal after the regulation for both networks.

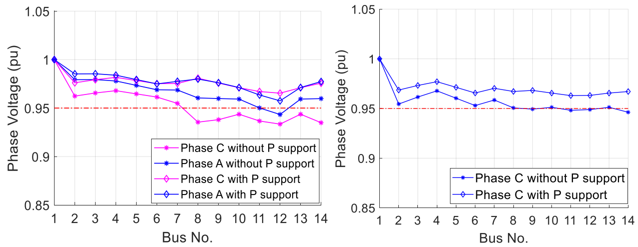
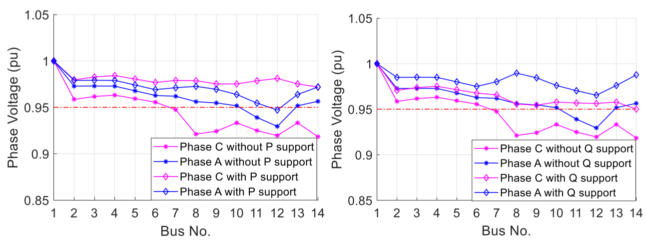


Figure 13. Phase voltage under R/X = 3.11, radial network (right)
Figure 14. Phase voltage under R/X = 3.11, mesh network (left)

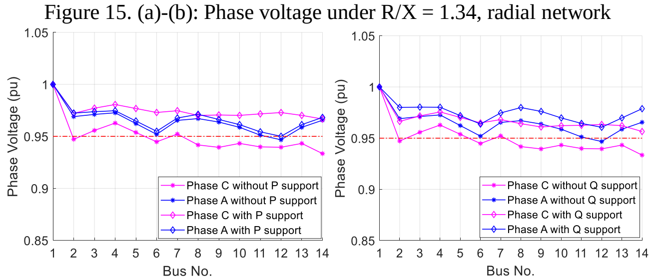
C. *Case Three -- R/X=1.34*

In this case, the performance of voltage regulation is compared for both radial and mesh network. Both real and reactive power can regulate voltage back to the normal value as shown in Fig.14 and Fig.15. However, it can be observed that real power is more effective for the regulation of bus voltage in phase C while the reactive power support is more effective for the regulation of bus voltage in phase A. It can be justified again that there is no absolute advantage for two types of power support when *R/X* is around 1.



(a) real power support (b) reactive power support

Figure 15. (a)-(b): Phase voltage under R/X = 1.34, radial network



(a) real power support (b) reactive power support

Figure 16. (a)-(b): Phase voltage under R/X = 1.34, mesh network

VI. CONCLUDING REMARKS

This paper proposed a fully distributed two-stage phase-independent voltage regulation strategy to deal with unbalanced voltage in a distribution network by providing real and reactive power support options from DERs. In order to develop an appropriate strategy which can accommodate the impact of *R/X* on the voltage regulation, the impact mechanism of *R/X* on voltage sensitivity was explained by introducing a linear analysis based on a simplified balanced network model. A more accurate perturbation approach was then employed to quantify the voltage sensitivity for the nonlinear unbalanced three-phase network with different *R/X*. Comparing to the conventional Jacobian matrix analysis which needs global network information, this perturbation approach only needs the collection of local bus voltage. This approach was implemented on the test network to demonstrate its essential application on the voltage regulation strategy: DER installation location selection and P/Q compensation capability evaluation on the planning stage; the guidance for the droop constant tuning on operational stage. Case studies conducted on the modified IEEE-13 bus network have validated the proposed strategy can effectively deal with the voltage problems in the unbalanced network in a phase-independent manner and meanwhile successfully accommodate the impact of *R/X* and network topology.

ACKNOWLEDGMENT

The authors would like to acknowledge the support from the HKPolyU for the Start-up Fund (1-ZE68), HK RGC for the Projects (25203917) and (15200418), and NSFC for the Project (51807171).

REFERENCES

[1] D. Wang, K. Meng, X. Gao, J. Qiu, L. L. Lai, and Z. Dong, "Coordinated Dispatch of Virtual Energy Storage Systems in LV Grids for Voltage Regulation," *IEEE Trans. Ind. Informatics*, vol. 3203, no. c, 2017.

[2] M. Brenna *et al.*, "Automatic distributed voltage control algorithm in smart grids applications," *IEEE Trans. Smart Grid*, vol. 4, no. 2, pp. 877–885, 2013.

[3] B. A. Robbins, C. N. Hadjicostis, and A. D. Domínguez-García, "A two-stage distributed architecture for voltage control in power distribution systems," *IEEE Trans. Power Syst.*, vol. 28, no. 2, pp. 1470–1482, 2013.

[4] Q. Shafiee, V. Nasirian, J. C. Vasquez, J. M. Guerrero, and A. Davoudi, "A Multi-Functional Fully Distributed Control Framework for AC Microgrids," *IEEE Trans. Smart Grid*, vol. 9, no. 4, pp. 3247–3258, 2018.

[5] M. N. Kabir, Y. Mishra, G. Ledwich, Z. Y. Dong, and K. P. Wong, "Coordinated control of grid-connected photovoltaic reactive power and battery energy storage systems to improve the voltage profile of a residential distribution feeder," *IEEE Trans. Ind. Informatics*, vol. 10, no. 2, pp. 967–977, 2014.

[6] R. Aghatehrani and R. Kavasseri, "Sensitivity-analysis-based sliding mode control for voltage regulation in microgrids," *IEEE Trans. Sustain. Energy*, vol. 4, no. 1, pp. 50–57, 2013.

[7] L. Zhang, Y. Chen, C. Shen, W. Tang, and J. Liang, "Coordinated voltage regulation of hybrid AC/DC medium voltage distribution networks," *J. Mod. Power Syst. Clean Energy*, vol. 6, no. 3, pp. 463–472, 2018.

[8] K. Zhang, D. Recalde, T. Massier, and T. Hamacher, "Fast Online Distributed Voltage Support in Distribution Grids using Consensus Algorithm," *Int. Conf. Innov. Smart Grid Technol. ISGT Asia 2018*, pp. 350–355, 2018.

[9] B. A. Robbins, A. D. Domínguez-García, and C. N. Hadjicostis, "Control of distributed energy resources for reactive power support," *NAPS 2011 - 43rd North Am. Power Symp.*, 2011.

[10] A. D. Dominguez-Garcia and C. N. Hadjicostis, "Coordination and control of distributed energy resources for provision of ancillary services," in *2010 1st IEEE International Conference on Smart Grid Communications, SmartGridComm 2010*, 2010.