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Ruifeng Yan, Tapan Kumar Saha

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Voltage Variation Sensitivity Analysis for Unbalanced Distribution Networks Due to Photovoltaic Power Fluctuations

Ruifeng Yan, *Student Member, IEEE*, and Tapan Kumar Saha, *Senior Member, IEEE*

***Abstract*—In a geographically small distribution area fast moving clouds may cover the whole area within a short period causing photovoltaic (PV) power to drop. When a feeder loses PV power support bus voltages will decrease. In an unbalanced network asymmetrical spacing and non-transposition of line configurations can result in different voltage drops for each phase. This may potentially cause some voltage problems after a decline in PV generation, such as an extremely low voltage magnitude of a certain phase and an unacceptable voltage imbalance level at a remote bus. This paper proposes a method of analyzing voltage variation sensitivity due to PV power fluctuations in an unbalanced network (unbalanced line configuration and phase loading levels). Based on this method a network reconfiguration solution is developed to solve the voltage problems. This solution utilizes unbalanced line characteristics and realizes the potential of the network, so no extra compensation devices are needed for network support.**

***Index Terms*—Voltage variation sensitivity, unbalanced network, power distribution, photovoltaic system, reconfiguration method, voltage regulation.**

I. Introduction

THE penetration level of photovoltaic (PV) power is increasing each year in distribution networks. Especially in urban residential areas elevated PV penetration is expected as a result of lower PV cost, government incentives and public concern for the environment. However, with more and more PV units integrated into the existing grid it is becoming harder to maintain network voltage within an acceptable range as PV systems are small variable generators depending on weather conditions. Distribution networks were not designed to incorporate such dispersed generation units.

According to the standards [1, 2], small PV units should not produce reactive power for voltage regulatory purposes and the current feed-in policy does not provide any benefits for reactive power generation. Moreover, this generation may place more stress on power inverters and reduce their lifetime. Therefore PV applications for residential customers are generally controlled to maximize profits by producing real power only. In distribution systems, line R/X ratio is much greater than that of transmission lines. Thus, loss of PV power support may have a comparable effect on network voltage drop to that of reactive power.

In a geographically small region there is a chance that most PV systems can be affected by clouds at the same time. However, on a large scale a network is very unlikely to suffer from cloud coverage, because the overall effect is smoothed by dispersion of PV units [3]. As a cloud moves into one area causing PV power reduction, that cloud also leaves another area where PV power production increases. Thus if the whole feeder is spread in a vast area the PV power generation is stabilized. Hence, the cloud effect should generally not be a serious issue. Therefore the PV power swing problem should focus on a geographically small distribution feeder, which can be shaded by a cloud within a short time. Further, it should be noticed that real power fluctuations induced by clouds are insignificant in distribution networks compared to the total power consumption in the whole power system. As a result, system frequency is hardly affected and the problem is strongly related to voltage variations rather than frequency fluctuations.

Traditionally, most feeders connected to the same major transformer have similar peak and bottom loading hours with slow power consumption changes, so the voltage regulators in the transformer are able to adequately maintain grid voltages within an acceptable level. However, uneven PV penetration and unpredictable cloud coverage in each area change the tendency of daily loading profiles and the speed of power variations among feeders. As a result, these feeders may seem to peak at different time of a day and suffer fast load fluctuations. This adds difficulties in voltage regulation, which have not been encountered before.

In reality, some wealthy suburbs may have a much higher PV penetration level than their neighboring suburbs which are served by the same transformer equipped with automatic tap changers. Fast moving clouds can quickly cover an entire feeder with a high PV penetration level. Consequently the voltage of the feeder will drop. However, if the decrease of the PV power generation in only one feeder is not significant enough for triggering the tap position to increase, the tap changer is effectively fixed during the cloud transient. This impact may not have much influence on other feeders (suburbs), but it can have a very serious impact on the affected feeder and resulted in a low voltage problem. If the cloud induced power drop does cause the tap position to step up, the feeder may still suffer a low voltage problem. Because it generally takes several tens of seconds for the first tap change

R. Yan (ruifeng@itee.uq.edu.au) and T. K. Saha (saha@itee.uq.edu.au) are with School of Information Technology & Electrical Engineering, University of Queensland, Australia.

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in distribution systems to avoid the hunting effect of the tap changers between a high voltage level and a low voltage level. This process may be much slower than the speed of cloud coverage. Moreover, after the automatic tap changer has increased its tap position to compensate the voltage drop, there will be a PV power surge potentially causing an over-voltage problem when the clouds are leaving the area. These issues have raised utility's concern on network operation.

These discussed problems may be further exacerbated by network unbalance at a distribution level. Imbalance is a part of low voltage distribution systems due to unbalanced line configurations and phase loading levels. Distribution lines are rarely transposed in practice, because generally it is not economical and it is hard to find space for transposition in some situations. In the load planning stage much effort is concentrated on making loading levels uniform for each phase; however phase loads will never be balanced due to consumers' behaviors. Therefore, in an unbalanced network PV power drop may result in unbalanced voltage variations for each phase. This may cause an undesirable low voltage of a certain phase or unacceptable three phase voltage imbalance at a remote bus, which is potentially harmful for electric appliances. In this paper a method is developed to analyze phase voltage variation sensitivities due to PV power fluctuations. By applying this method a low cost network reconfiguration solution is proposed to solve voltage problems and this can also be regarded as a recommendation for network planning.

The paper is organized as follows. Section II formulates the voltage problems encountered after PV power drops, which provides a rationale for consequent investigation. In Section III, a voltage variation sensitivity theory is established for a certain line configuration. This is further extended to other line configurations with different line geometries, phase sequences and conductor types in Section IV. A case study is conducted to show how this theory can be used for analysis in Section V. It demonstrates the network reconfiguration strategy based on the proposed method can effectively improve voltage profiles and reduce voltage imbalance. Section VI further examines and validates the developed methodologies in a more comprehensive unbalanced network. Finally, conclusions are drawn in Section VII.

II. Voltage Problems With High Photovoltaic Penetration

The IEEE 13 bus system (Fig. 1) [4] is modeled in PSCAD/EMTDC [5] as a baseline. This is a typical unbalanced distribution system. Due to individual phase regulators, asymmetrical line geometries and uneven phase loads, bus voltages are unbalanced. In this study the network is assumed to be equipped with fixed tap changers to simulate the worst case scenario.

PV penetration of 40% is allocated, which is proportionate to the load of every bus. This is based on the assumption that the probability of PV installation is the same as in the feeder. The higher the loads are the more residents are situated in the spot. Therefore more PV units are likely to be integrated. During a cloud covering period, it is assumed that the sun radiation level drops from $1000W/m^2$ to $70W/m^2$ over a 45s period of time. As shown in Fig. 2, PV power generation decreases with sunlight intensity.

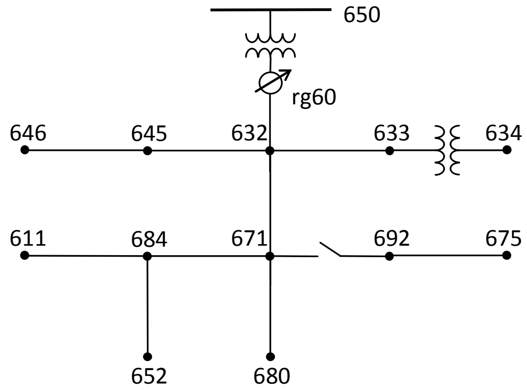


Fig. 1. IEEE 13 node test feeder [4]

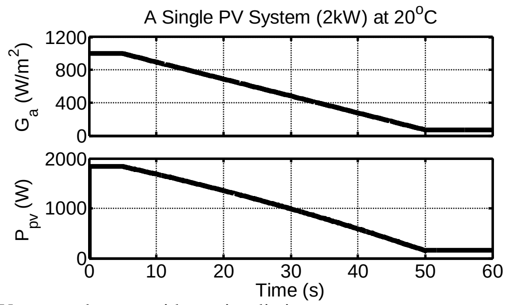


Fig. 2. PV power changes with sun irradiation

The sun irradiation drop is selected in a such way that the simulated PV power drop ratio can approximately match the recorded power drop ratio as shown in Table I [6]. Moreover, based on line lengths of the IEEE 13 bus system it should be located in a small geographical area. The reported cloud speed can reach $43feet/s$ [7]; therefore fast moving clouds may cover this area within 40-50s. A cloud coverage time of 45s is chosen for the simulation.

TABLE I
PV Power Fluctuation Data [6]

PV Power	Area	Date	Time	P_{Total} (kW)	Max/Min
Rise (Recorded)	800m by 250m	11/08/2011	12:25:00	92	10.2
		11/08/2011	12:26:00	119	
		11/08/2011	12:27:00	192	
		11/08/2011	12:28:00	437	
		11/08/2011	12:29:00	937	
Drop (Recorded)	800m by 250m	01/10/2011	11:10:00	906	7.3
		01/10/2011	11:11:00	124	
Drop (Assumed)	Around 600m by 300m	–	45s	1386	11.3
				123	

Important simulation results are summarized in Table II. Before the PV power drops, the network operates in a healthy state. Regulator voltage levels are within the correct range [121V - 123V]. All bus voltages are greater than 0.974 pu and less than 1.035 pu, which lies in the acceptable band [0.95pu - 1.05pu] defined in the ANSI standard [8]. The highest voltage imbalance is 1.26%, which is less than the 2% limit so no corrective action is required [9]. However, after PV power decreases, voltages of phase-C at Bus 675 and Bus 611 drop below 0.95 pu and voltage imbalance at Bus 675 increases to over 2%. Although these values are in close proximity to the limits they certainly draw concerns on the network performance due to PV power fluctuations.

According to the voltage profiles in Table II, the voltages of phase-A and C dropped around 0.012 pu and 0.026 pu respectively, but the phase-B voltage is slightly increased after losing PV power support. What are the reasons causing different voltage variations for each phase and how can they be analyzed and improved? A method will be developed in the following sections to answer these questions.

TABLE II
SIMULATION RESULTS OF THE IEEE 13 BUS SYSTEM BEFORE AND AFTER (IN BRACKET) PV POWER DROP

	Phase-A	Phase-B	Phase-C
$V_{rg60}\ (pu)$	1.0436	1.0310	1.0436
$Tap\ position$	7	5	7
$V_{regulator\ level}\ (V)$	120.959	121.009	120.912
$V_{632}\ (pu)$	1.0098 (1.0019)	1.0236 (1.0224)	1.0030 (0.9915)
$P_{632}\ (MW)$	0.7546 (1.1866)	0.5685 (0.9411)	0.7920 (1.2519)
$\Delta P_{632pv}\ (MW)$	0.4297	0.3800	0.4579
$Q_{632}\ (MVAr)$	0.5561 (0.5989)	0.3330 (0.3490)	0.5512 (0.5922)

VOLTAGE PROFILES OF REMOTE BUSES

V_{Bus} (pu)	Phase-A	Phase-B	Phase-C	$V_{imbalance}$
V_{671}	0.9805 (0.9705)	1.0318 (1.0329)	0.9759 (0.9515)	1.18% (**1.94%**)
V_{675}	0.9761 (0.9639)	1.0337 (1.0353)	0.9749 (**0.9494**)	1.26% (**2.07%**)
V_{611}	–	–	0.9743 (**0.9476**)	–
V_{652}	0.9749 (0.9633)	–	–	–

III. METHOD FOR VOLTAGE VARIATION SENSITIVITY ANALYSIS

A. Line Configurations

In the IEEE 13 bus system, voltage performance of the backbone (Bus rg60-632-671) system almost determines voltage profiles of the whole network since other buses are connected to it through relatively short lines (several hundred feet). Therefore this research will focus on the backbone of the system. The lines used to connect Bus rg60 to Bus 632 and Bus 632 to Bus 671 are two identical 2000ft (about 609.6m) overhead lines called configuration 601 with phase sequences – BACN and 556,500 26/7 ACSR for phase conductors (4/0 6/1 ACSR for neutral) [4]. In this paper only one section (Bus rg60 to Bus 632) is investigated. All downstream loads and PVs are aggregated to Bus 632 as shown in Fig. 3 (a). The line configuration 601 is a four wire overhead configuration with the phase sequence named from left to right on the crossed arm illustrated in Fig. 3 (b) [10]. The neutral is located 4 feet below the other conductors. This configuration has an unbalanced geometry. Without transposition the line impedance matrix contains unequal diagonal and off diagonal elements [4], which can be calculated according to [11].

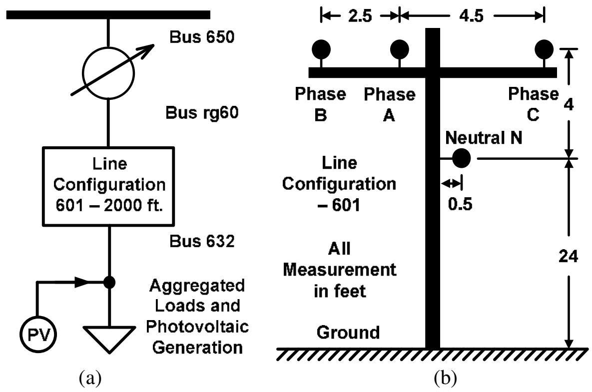


Fig. 3. (a) The first section of the network backbone; (b) Line configuration – 601-BACN [10]

B. Voltage Variation Sensitivity to PV Power Decrease [12]

As shown in Table II, the upstream voltages at Bus rg60 are unbalanced because of the individual voltage regulators in each phase. The phase loads and PV units are also different due to the nature of the network. In addition, distribution lines are unbalanced as indicated in Fig. 3 (b). In summary, nothing is balanced in the network including source, lines, loads and PVs. Therefore although the system has been simplified as in Fig. 3 (a), it is still hard to analyze voltage variations from PV power fluctuations due to the unbalanced conditions. In order to examine the impacts on voltage variations purely from the unbalanced line configuration, all other conditions (sources, loads and PV power) are set to be balanced based on the data from Table II ($V_{rg60} = 1.04\,pu$, $S_{632} = 0.75MW + j0.47MVAr$, $\Delta P_{632pv} = 500kW$). Voltage variations under unbalanced conditions will be analyzed in the next part of this section.

The simplified network in Fig. 3 (a) should be governed by (1) (with “1” for upstream and “2” for downstream) [11]. However, this is formed by a set of non-linear equations and it is difficult to obtain their analytical solutions. Therefore, a numerical approach is chosen to investigate dominant factors of voltage variations. In the following sections Matlab [13] is used to solve the non-linear equations.

$$\begin{bmatrix} \overrightarrow{V_{2\,a}} \\ \overrightarrow{V_{2\,b}} \\ \overrightarrow{V_{2\,c}} \end{bmatrix} = \begin{bmatrix} \overrightarrow{V_{1\,a}} \\ \overrightarrow{V_{1\,b}} \\ \overrightarrow{V_{1\,c}} \end{bmatrix} - L_{Length} \cdot \begin{bmatrix} \overrightarrow{Z_{aa}} & \overrightarrow{Z_{ab}} & \overrightarrow{Z_{ac}} \\ \overrightarrow{Z_{ba}} & \overrightarrow{Z_{bb}} & \overrightarrow{Z_{bc}} \\ \overrightarrow{Z_{ca}} & \overrightarrow{Z_{cb}} & \overrightarrow{Z_{cc}} \end{bmatrix} \cdot \begin{bmatrix} \overrightarrow{S_{2\,a}^{*}/V_{2\,a}^{*}} \\ \overrightarrow{S_{2\,b}^{*}/V_{2\,b}^{*}} \\ \overrightarrow{S_{2\,c}^{*}/V_{2\,c}^{*}} \end{bmatrix} \quad (1)$$

1) Voltage Variation Characteristics

Simulations conducted in PSCAD and Matlab show approximately linear trends for short distribution lines in voltage variations during PV power decreases as illustrated in Fig. 4. The voltage drops are seemingly proportional to the amount the PV power declines. It is just that each phase has a different voltage drop rate. Therefore, two typical characteristics of linearity may be applied for analysis – superposition and scalability.

According to Table II, real power changes at Bus 632 are approximately equal to PV power fluctuations for each phase. This is the main reason for bus voltage drops and it can easily be estimated by tracing PV installation records. However it should be noticed that reactive power consumption increases after a PV power drop. It is very hard to predict the amount of reactive power changes for each phase. Since PV power swing is mainly related to real power, so it is assumed that reactive power remains unchanged when solving non-linear equations.

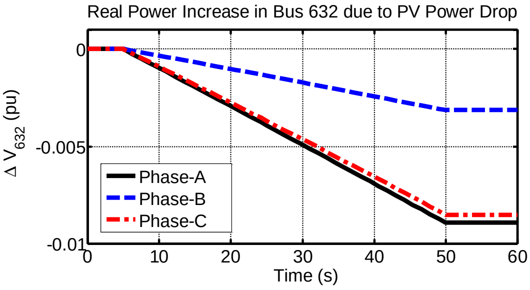


Fig. 4. Voltage variations due to PV power drop under balanced conditions

When PV power decreases due to cloud coverage, the equivalent real power loads seen at Bus 632 are effectively increased. As superposition may be used, the impacts of PV power drops on voltage variations are examined separately for each phase. The results are summarized in Table III which indicates real power change of each phase has a different contribution to voltage variations of all phases. When superposition is applied to calculate the overall voltage variations of each phase, the total variations are very close to those with simultaneous PV power drops for all phases. The total voltage variation under balanced conditions represents how sensitive a phase is to PV power fluctuation and is termed in this paper as 'voltage variation sensitivity'.

In Table III, the voltage drop contribution from a PV power decrease in its own phase is relatively higher compared to the falling contribution from other phases. This contribution is named in this paper as 'self-contribution'. The values of self-contribution are nearly the same in the table (-0.0136 pu). Except for self-contribution, the voltage drop contribution to other phases can either be a relatively low voltage drop contribution (called negative contribution) or a voltage rise contribution (called positive contribution). Bus 632 phase-B has the smallest voltage drop – 0.0031 pu, which is almost one third of those in phase-A and C. This is because phase-B has the lowest self and negative contributions and the highest positive contribution. While phase-A has the largest negative contribution and phase-C contains the lowest positive contribution, which makes them more sensitive to PV power fluctuations.

TABLE III

ESTIMATED VOLTAGE VARIATIONS OF LINE CONFIGURATION 601 (2000 FT.)

Voltage variations at Bus 632 (Balanced Conditions, $\Delta P_{pv} = 500kW$)					
$V_{variation}$ (pu)	$P_{632\,a}\uparrow$ $only$	$P_{632\,b}\uparrow$ $only$	$P_{632\,c}\uparrow$ $only$	$Total\ \Delta V$ (Superposition)	$Total\ \Delta V$ (Simulation)
$\Delta V_{632\,a}$	-0.0136	-0.0105	$+0.0152$	-0.0089	-0.0089
$\Delta V_{632\,b}$	$+0.0177$	-0.0131	-0.0076	-0.0030	-0.0031
$\Delta V_{632\,c}$	-0.0086	$+0.0138$	-0.0135	-0.0083	-0.0085

2) Dominant Factors

According to (1), the downstream voltages ($\overrightarrow{V_{632\,abc}}$) are not only related to line impedance matrix, but they also depend on the upstream voltages ($\overrightarrow{V_{rg60\,ABC}}$) and loading levels ($P_{632\,abc}$, $Q_{632\,abc}$). Simulation results show that self-contribution from a PV power drop of phase-A is mainly affected by the initial phase loading level of phase-A ($P_{632\,a}$, Fig. 5) and other factors ($\overrightarrow{V_{rg60\,ABC}}$, $P_{632\,bc}$ and $Q_{632\,abc}$) have very minor effects on voltage variations. This pattern is also true for the voltage drop contributions of other phases. Therefore, look-up graphs can be constructed for voltage variation sensitivity study. Fig. 5 shows one such graph.

3) Characteristic Verification

Next, the established method based on the simplified network needs to be checked with the simulation results of the IEEE 13 bus system in Section II to verify whether this method can provide an acceptable estimation. If the results are confirmed the proposed theory can be applied for analysis of voltage variation sensitivity.

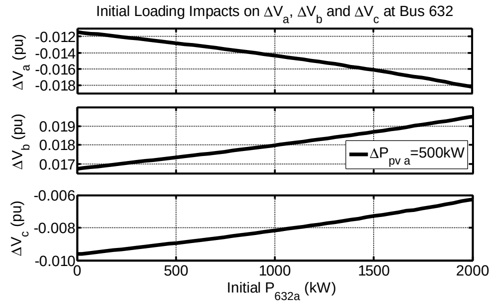


Fig. 5. Impact of initial loading levels on voltage variations

First, phase loading levels are recorded and then voltage variation contributions are read from the look-up graphs according to the loading levels. Because the graphs are constructed based on PV power drop of 500kW, variation contributions should be scaled to the PV power drop levels before superposition. Table IV shows the estimation results.

TABLE IV

ESTIMATED VOLTAGE VARIATIONS AT BUS 632 IN THE IEEE 13 BUS SYSTEM

Initial loads: $P_{632\,a} = 0.75MW$, $P_{632\,b} = 0.57MW$, $P_{632\,c} = 0.79MW$					
ΔV (pu)	$P_{632\,a}\uparrow only$ $(\Delta = 430kW)$	$P_{632\,b}\uparrow only$ $(\Delta = 380kW)$	$P_{632\,c}\uparrow only$ $(\Delta = 458kW)$	ΔV(Superposition)	ΔV(Simulation)
ΔV_{632a}	$-0.0136\cdot\frac{430}{500}$	$-0.0108\cdot\frac{380}{500}$	$+0.0152\cdot\frac{458}{500}$	-0.0060	-0.0079
ΔV_{632b}	$+0.0177\cdot\frac{430}{500}$	$-0.0126\cdot\frac{380}{500}$	$-0.0076\cdot\frac{458}{500}$	-0.0013	-0.0012
ΔV_{632c}	$-0.0086\cdot\frac{430}{500}$	$+0.0136\cdot\frac{380}{500}$	$-0.0137\cdot\frac{458}{500}$	-0.0096	-0.0115

As can be observed from Table IV, there are some estimation errors when compared with the complete network simulation results. These errors occur due to the following reasons.

(1) Unpredictable reactive power changes are not considered in the method. The backbone lines have an R/X ratio of 1/3, so reactive power can still have a considerable effect on bus voltages. From Table II, reactive power is slightly increased after a PV power drop, thus voltage magnitudes are expected to become lower. This explains the greater voltage drops in the IEEE 13 bus system than those from estimation.

(2) A constant power load model is assumed during the derivation of the voltage variation sensitivity matrix. However, the loads in the IEEE 13 bus system consist of a combination of constant power, current and impedance loads. This assumption can cause inaccuracy during estimation.
(3) The observed linearity is only approximate, and this can also contribute to estimation errors.
(4) The non-dominant factors are neglected; however they do have impacts on the voltage variations.

Nevertheless, the estimation is generally good enough to prove the validity of the proposed method in terms of phase voltage variation sensitivity levels. Therefore this method can be used for the purpose of sensitivity analysis.

C. Voltage Drop Sensitivity under Unbalanced Conditions

The voltage variation contributions are previously investigated under balanced conditions. However, a distribution network normally operates in unbalanced circumstances. Therefore, the key question is how the developed theory of voltage variation sensitivity may vary under unbalanced situations?

(1) Unbalanced upstream voltage level: as pointed out in Part B, upstream voltages have minor impacts on voltage variations.
(2) Unbalanced phase loads: this issue can be solved by using look-up graphs. Only self-contribution is considerably affected by real power loads of its own phase and other phase loads are regarded to be insignificant.
(3) Unbalanced PV power fluctuations: the contribution matrix (Table III) or look-up graphs (Fig. 5) can set a baseline for voltage variation contributions. Since the approximately linearity is valid as shown in Fig. 4, for different PV penetration levels in each phase the contributions can be scaled up and down according to the baseline values. Then superposition can be used to obtain the overall effect.

D. Distance Effect on Voltage Drop Sensitivity

Hitherto, the voltage drop sensitivity is only valid for a 2000ft line. What will be the impact if the line is of a different distance (L_{Length})? This is illustrated in Fig. 6.

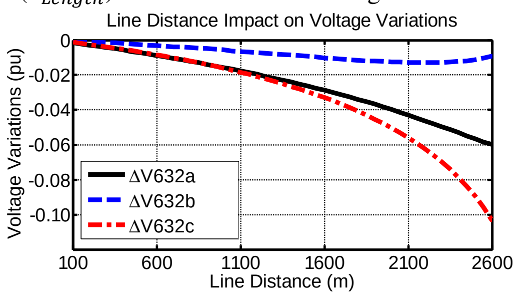


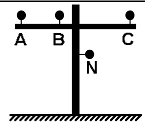
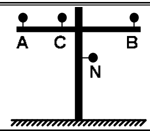
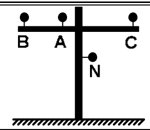
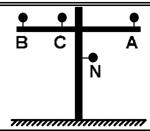
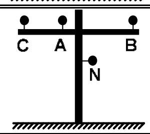
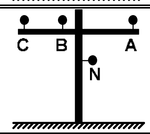
Fig. 6. Distance effect for line configuration – 601 (balanced conditions)

In general, the voltage variations of phase-A and C are much larger than that of phase-B and the difference of voltage variations between phase-B and other phases increases with line distances. This makes phase-B the least sensitive phase to PV power drop.

IV. Line Configuration Impact on Voltage Variation Sensitivity

In the last section the factors which can possibly affect voltage variation sensitivity for a fixed line configuration have been examined, such as upstream voltages, phase loads, PV power and line distance (every part in (1) except the line impedance matrix). In this section different line configurations are investigated to show unbalanced impedance matrix impacts on voltage variation sensitivity. In order to reveal the impact of only an unbalanced line configuration, balanced conditions are adopted. Table V lists all possible phase combinations for line configuration 601. For phase sequence BACN, phase-B on the left is the least sensitive phase. However, phase-B can become the most sensitive phase by just swapping the physical positions between phase-A and C as in BCAN. What would be the reason to make such a significant difference? Next, a method is established to explain phase voltage variation sensitivities in different configurations. General principles are developed to analyze line configuration impacts regarding phase sequence, line geometry and conductor type.

TABLE V
Phase Position Effects (Balanced Conditions)

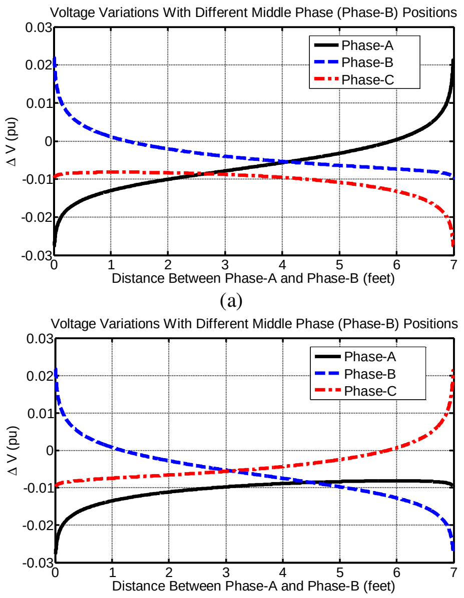
Phase Positions	Phase Sequence	Phases	Total ΔV
	ABCN	A	−0.0104
		B	−0.0041
		C	−0.0061
	ACBN	A	−0.0031
		B	−0.0085
		C	−0.0089
	BACN	A	−0.0089
		B	−0.0031
		C	−0.0085
	BCAN	A	−0.0061
		B	−0.0104
		C	−0.0041
	CABN	A	−0.0041
		B	−0.0061
		C	−0.0104
	CBAN	A	−0.0085
		B	−0.0089
		C	−0.0031

A. Analysis for Phase Shift Sequence

Table V in fact only contains two different sets of voltage variation values – [-0.0089, -0.0031, -0.0085] and [-0.0104, -0.0041, -0.0061]. Therefore there is a possibility that all six combinations can be categorized into two groups, which can simplify sensitivity analysis.

1) Voltage Variation Curves

As indicated in Table V, phase sequences BACN, CBAN and ACBN have the same voltage variation sets. However this observation is only based on one particular line geometry. It is unknown whether this result is purely coincident or valid for all geometries. For phase sequence BACN, the neutral position and the longest distance between phases (D_{BC}) are fixed during analysis. Voltage variation curves are obtained by changing the relative positions of the middle phase (phase-A). Following the same principle, voltage variation curves can be drawn for other phase sequences. The curves are identical considering phase physical positions – left, middle and right instead of phase names – A, B and C (Fig. 7 (a)). When the same process is conducted for the other voltage variation sets, an approximate mirror image graph is obtained (Fig. 7 (b)). This is due to the fact that the neutral is almost located in the middle of the structure. When phase-A of BACN moves across the middle point, it roughly becomes phase sequence CABN. Therefore, only the left half of the graph is generally considered for analysis.



(a)

(b)

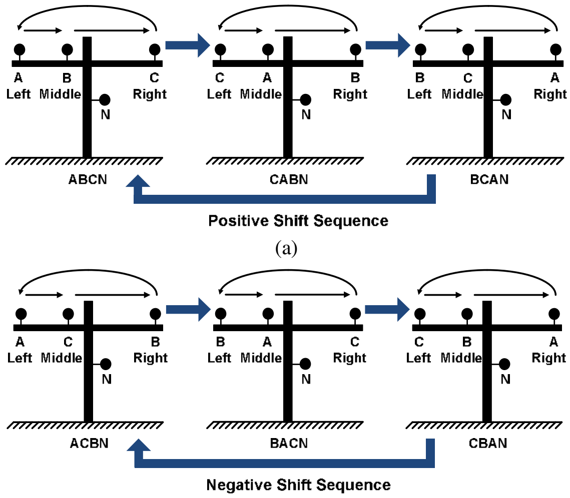
Fig. 7. Voltage drop curves of line configuration 601 (a) BACN, (b) ABCN

In conclusion, all six possible combinations can be classified into two groups and this is true for any middle phase positions on the cross arm of the pole.

2) Positive and Negative Shift Sequences

As proven previously, phase sequences ABCN, CABN and BCAN have the same voltage variation characteristics. Since their phases can be shifted in an anticlockwise manner as illustrated in Fig. 8 (a), they are named positive shift sequences in this paper. Based on the same rules, phase sequences ACBN, BACN and CBAN are called negative shift sequences (Fig. 8 (b)).

Certain principles should be followed to categorize other line configurations. For example, phase sequence ABCN is defined to have the longest phase distance between phase-A and C (D_{AC}) and the shortest between phase-A and B (D_{AB}). Positive shift sequences are formed by shifting ABCN. While negative shift sequences are achieved by rotating ACBN with D_{AB} being the longest distance and D_{AC} the shortest.



(a)

(b)

Fig. 8. (a) Positive shift sequences, (b) Negative shift sequences

3) Summary

(1) Only two voltage variation sets exist instead of six. Once a phase sequence has been categorized into positive or negative shift sequences, voltage variations can be linked to phase physical positions. Phase sequence system – ABC – is no longer needed.

(2) The left phase of positive shift sequences always has the highest voltage variation sensitivity. But the left phase becomes the least sensitive phase in negative shift sequences.

(3) Voltage variation curves are not only valid for line configuration 601 and should indicate a more general relationship between voltage variations and line geometries. If the longest phase distance is regarded as 100%, the scheme applied to construct voltage variation curves can be considered as examining the relative positions of the middle phase. This varies the ratios between the second longest and shortest phase distances. Therefore, the magnitudes of voltage variations may be changed by absolute phase distances, loading levels, PV power fluctuations and so on, the tendency of voltage variation sensitivity may be valid for a verity of line geometries similar to configuration 601.

B. Analysis for Another Line Geometry

A 4-wire overhead line configuration widely implemented by a local distribution utility in Australia is illustrated in Fig. 9 [14]. This configuration is used in this section to demonstrate how the voltage variation sensitivity matrix may change for different line geometries. In order to acquire comparable results to Table III for configuration 601 – BACN, the same simulation conditions in Section III Part B are adopted. Meanwhile, their phase positions are assigned according to the definition of negative shift sequence BACN – the longest distance D_{BC} and the shortest D_{AB}. The voltage variation sensitivities are summarized in Table VI.

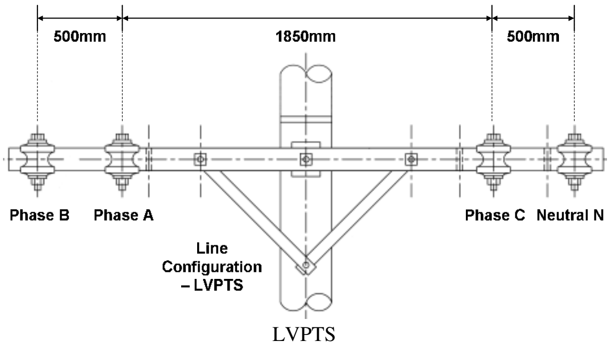


Fig. 9. A different line configuration [14]

Phase-B is the least sensitive phase, which is exactly what has been predicted by the proposed theory. However, the voltage variation contributions in the sensitivity matrix are quite different from those in Table III of line configuration 601. Analyses for this line configuration should take these contribution changes into consideration.

TABLE VI
ESTIMATED VOLTAGE VARIATIONS OF DIFFERENT LINE GEOMETRIES

Line Config	ΔV (pu)	$P_{632\,a} \uparrow only$ (Δ= $500kW$)	$P_{632\,b} \uparrow only$ (Δ= $500kW$)	$P_{632\,c} \uparrow only$ (Δ= $500kW$)	$Total\ \Delta V$
LVPTS	ΔV_{632a}	-0.0134	-0.0133	$+0.0134$	-0.0133
	ΔV_{632b}	$+0.0210$	-0.0125	-0.0067	$+0.0018$
	ΔV_{632c}	-0.0068	$+0.0125$	-0.0144	-0.0087

C. Analysis for Other Conductor Types

The line configurations in the IEEE 34 bus system utilize the same line geometry and pole structure as configuration 601, but they are given new names for different conductors used in phases and neutral – 1/0 ACSR for line configuration 300 and #2 6/1 ACSR for line configuration 301 [15]. For the purpose of comparison, phase sequences are fixed to BACN and balanced conditions are applied in simulation. Therefore, the difference between configuration 601 and configuration 300/301 can only come from the choice of conductor. The simulation results are shown in Table VII. As the conductors of line configuration 300 and 301 are more resistive and have a higher R/X ratio than that of line configuration 601 they are generally used for low power distribution (about 60%). The results are also included in Table VII.

TABLE VII
ESTIMATED VOLTAGE VARIATIONS OF LINE CONFIGURATION 300 AND 301

Line Configurations	300		301		601 (Table III)
Loads / ΔV (pu)	100% Load	60% Load	100% Load	60% Load	100% Load
ΔV_{632a}	-0.0479	-0.0257	-0.0797	-0.0400	-0.0089
ΔV_{632b}	-0.0396	-0.0216	-0.0686	-0.0354	-0.0031
ΔV_{632c}	-0.0481	-0.0254	-0.0812	-0.0399	-0.0085

According to Table III, phase-B in configuration 601 has about one third of voltage variation compared to other phases. In configuration 300 and 301, phase-B is still less sensitive than other phases. However, for these high resistive conductors the ratio of the differences in voltage variations is not as high as that in configuration 601.

V. NETWORK RECONFIGURATION SOLUTION: A CASE STUDY

In this section network re-configuration solution is presented to show how the voltage variation sensitivity theory can be used to solve voltage problems raised in Section II. Depending on construction of the network, re-configuration in remote buses may be hard to achieve. Because not all phases are available at reconnection points and there may be obstacles in the way. Therefore, reconfiguration is planned along the backbone of the network.

A. Phase-B and Phase-C Loads and PV Swap

Phase-B (less sensitive phase) of the original IEEE 13 bus system in Section II has the least PV power and phase-C (the more sensitive phase) is integrated with the most PV units as in Table II. Therefore voltage problems resulted from this bad combination. This caused more voltage drop in phase-C than that in phase-B during PV power decrease. Now, the idea of re-configuration is relatively simple. More PV systems should be reconnected from phase-C to phase-B to avoid extremely low voltage of a certain phase or high voltage imbalance. However, this is really difficult to achieve as there may be many PV units to be reconnected. Moreover, phase-B is not always available in some areas. Therefore, re-configuration is carried out along the backbone of the network by simply swapping lateral connections between phase-B and C as illustrated in Fig. 10.

It should be pointed out that this is not a complete swap between phase-B and C. The distributed loads and PV systems between Bus 632 and Bus 671 are not reconfigured as many connection points exist along the line. The connections of the loads and PVs which are directly connected to Bus 671, are not involved in re-configuration either due to the same reason. Therefore, re-configuration is only conducted at Bus 632 and Bus 671 and only four connections are repositioned in this re-configuration scheme as shown in Fig. 10.

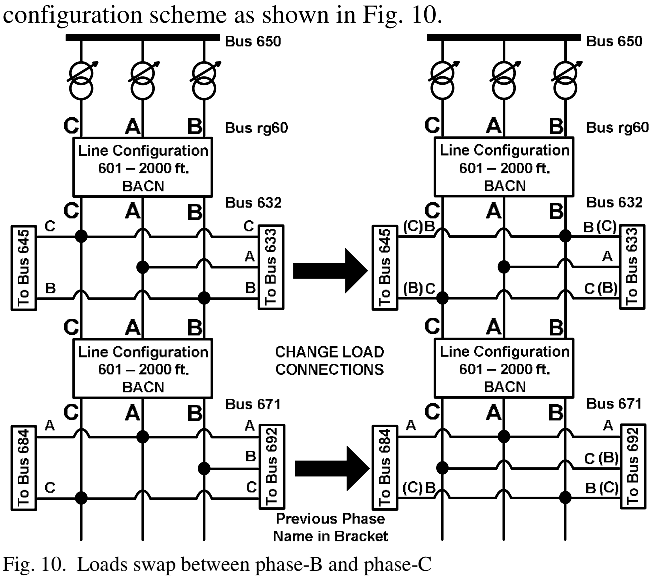


Fig. 10. Loads swap between phase-B and phase-C

According to the simulation results shown in Table VIII, this swap improves voltage performance of phase-C, but it makes voltage profiles of phase-A worse. Firstly, this is because the swap is not purely happening between phase-B and phase-C and it also increases phase-A loading level due to the delta connected load between phases, such as Bus 692 load c-a. An example is demonstrated in Fig. 11 to explain phase power consumption changes during re-configuration. This could lower phase-A voltages prior to PV power drop. Secondly, according to Table III the negative contribution to phase-A voltage drop should increase, while its positive contribution declines with more PV units moving from phase-C to phase-B. This makes phase-A much more sensitive to PV power drop.

TABLE VIII
REMOTE BUS VOLTAGES WITH PHASE-B AND PHASE-C LOADS AND PV SWAP

	Before and After (in bracket) PV Power Drop (Voltages in pu)			
V_{Bus}	Phase-A	Phase-B	Phase-C	$V_{imbalance}$
V_{671}	0.9717 (**0.9473**)	1.0111 (1.0078)	1.0032 (0.9963)	0.44% (0.37%)
V_{675}	0.9688 (**0.9422**)	1.0088 (1.0044)	1.0048 (0.9983)	0.50% (**0.51%**)
V_{611}	–	1.0093 (1.0046)	–	–
V_{652}	0.9657 (**0.9390**)	–	–	–

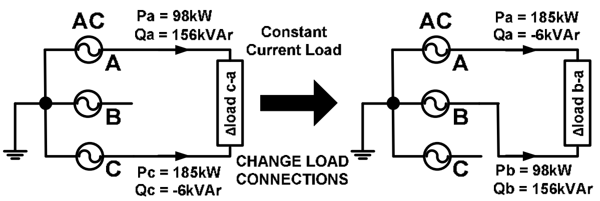


Fig. 11. Phase power consumption changes due to re-configuration

B. Connect Bus 684 Phase-A to Phase-C

If all loads and PVs of phase-B and C can be completely swapped, the re-configuration would be a success. However, such a swap may become very expensive due to a huge number of reconnection points required and this can be very complicated because of the presence of delta connected loads and distributed loads. Therefore, further re-configuration is needed to reduce phase-A loading level and total voltage variation contribution. This can be achieved by simply connecting phase-A to phase-C at Bus 671 from Bus 671 to Bus 684 direction (Fig. 12) since phase-C is lightly loaded after the load swap. This can decrease power consumption of phase-A and at the same time this scheme can reduce self-contribution and increase positive contribution, which results in a lower voltage variation.

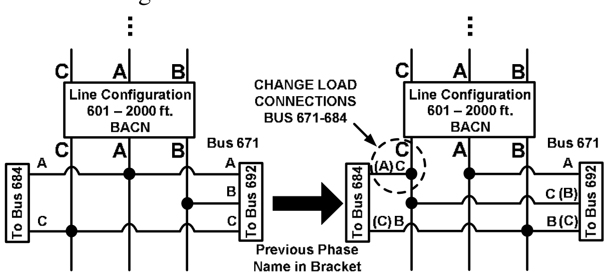


Fig. 12. Further re-configuration: connect phase-A to phase-C (Bus 671-684)

The simulation results (Table IX) indicate that the voltage profiles of remote buses are much improved for each phase. Voltage magnitudes and imbalance percentages are all within the ranges specified by the standards with good margins.

TABLE IX
REMOTE BUS VOLTAGES WITH CONNECTING PHASE-A TO C (BUS 671-684)

	Before and After (in bracket) PV Power Drop (Voltages in pu)			
V_{Bus}	Phase-A	Phase-B	Phase-C	$V_{imbalance}$
V_{671}	0.9863 (0.9675)	1.0054 (0.9971)	0.9924 (0.9847)	0.32% (0.22%)
V_{675}	0.9835 (**0.9625**)	1.0031 (0.9937)	0.9939 (0.9866)	0.33% (**0.12%**)
V_{611}	–	1.0036 (0.9932)	–	–
V_{652}	–	–	0.9870 (0.9774)	–

C. Analysis of Voltage Improvement in Steady State

It should be pointed out that the benefits of the phase swap are not only to balance voltage variations between phases. The swapping method also improves the network structure at the same time. In a two-bus system connected by the backbone line of the IEEE 13 bus system (configuration 601 – BACN 2000ft.) Bus 1 provides perfectly balanced voltage sources with a magnitude of 1.0 pu, and the load of each phase at Bus 2 is 1MW balanced with 0.9pf lagging. The simulation results are summarized in Table X. The top table indicates the asymmetrical line configuration results in less voltage drop on phase-B. The bottom table further proves this point. Around 15% more loads should be connected to phase-B in order to achieve the same amount of voltage drop in each phase. Therefore, by connecting more loads to phase-B the network should have a more balanced voltage profile. This can be seen from the results in Table VIII and Table IX.

TABLE X
VOLTAGE DROPS WITH BALANCED SOURCES AND LOADS

Phases	$\lvert V_1 \rvert$ (pu)	$\lvert V_2 \rvert$ (pu)	V_{drop} (pu)
A	1.0000	0.9640	−0.0360
B	1.0000	0.9743	−0.0257
C	1.0000	0.9632	−0.0368

PHASE LOADING LEVELS TO ACHIEVE THE SAME VOLTAGE DROPS WITH BALANCED SOURCES AND 0.9PF FOR LOADS IN EACH PHASE

$\lvert V_1 \rvert = 1.000$ (pu);	$\lvert V_2 \rvert = 0.9645$ (pu);	$V_{drop} = -0.0355$ (pu)
Phases	P (MW)	Q (MVAr)
A	1.0000	0.4843
B	1.1486	0.5563
C	1.0513	0.5092

D. Summary

Voltage variation profiles along with the re-configuration processes are compared in Fig. 13. The solid lines represent bus voltage variations due to PV power drop in the original IEEE 13 bus system. Voltage variations of phase-B are very low, but phase-C suffers much larger voltage drops. As more PVs are connected to the more sensitive phase-C than the less sensitive phase-B, this result is expected. This situation is effectively improved by swapping phase-B and C loads and PVs (dashed lines). Unfortunately, voltage variations of phase-

A are increased because of the incomplete swap and delta connected loads. This problem is further fixed by reattaching phase-A to phase-C from Bus 671 to Bus 684 direction (dot-dashed lines). Phase voltage variations are more balanced after re-configuration processes. Furthermore, for a more unbalanced line geometry with a higher R/X ratio more voltage variation differences may be observed. Therefore, this re-configuration solution may become more beneficial under these conditions. In addition, the swapping procedure improves the network structure and provides a much stronger base of the network before PV power fluctuations.

With only 5 connection changes the entire network becomes more robust. Therefore, the network re-configuration method should be an attractive technique which is worth considering for unbalanced network improvement. The IEEE 13 node test feeder is a small system, so to further validate the proposed methodologies a more extensive network needs to be introduced.

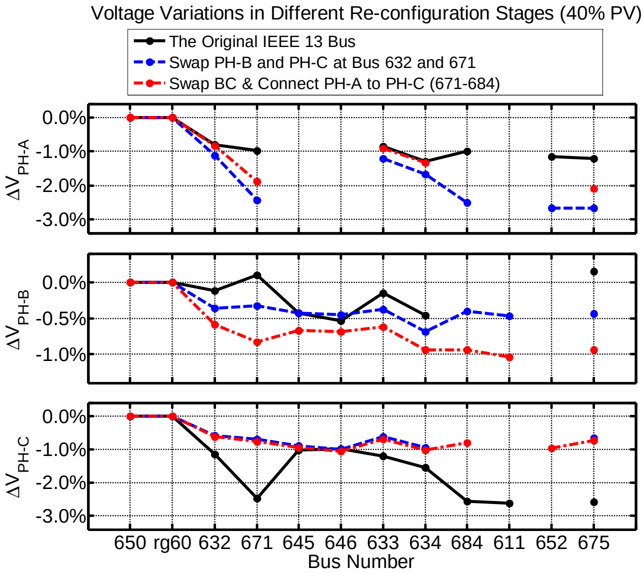


Fig. 13. Comparison of voltage variations due to PV power drop

VI. Analysis of the IEEE 123 Bus System

A. System Settings

A more comprehensive unbalanced network – the IEEE 123 node test feeder [16] has been constructed to verify the proposed methods. The loads of the network can be redirected by operating certain switches if needed. In this study, a case with the switches 18-135 opened and 151-300 closed is considered. The cloud coverage path is illustrated in Fig. 14. The following assumptions are adopted during the simulation.

(1) The network PV penetration level is 50%.
(2) PV power output drops to 10% during cloud coverage.
(3) The cloud speed is $40 feet/s$. It takes roughly around 82s for a complete coverage of the area of the network.
(4) According to the local distribution utilities in Queensland Australia, tap changers generally have a time delay of 65s for the first position change and 5s for the consecutive changes at a low voltage level. This has been adopted for the settings of the tap changers in this study. Generally, a hysteresis characteristic should be introduced to tap changers to avoid unnecessary changes and to prolong their life time. A hysteresis function with a band of $[-0.6V\ +0.3V]$ for the lower boundary and $[-0.3V\ +0.6V]$ for the upper boundary has been chosen.

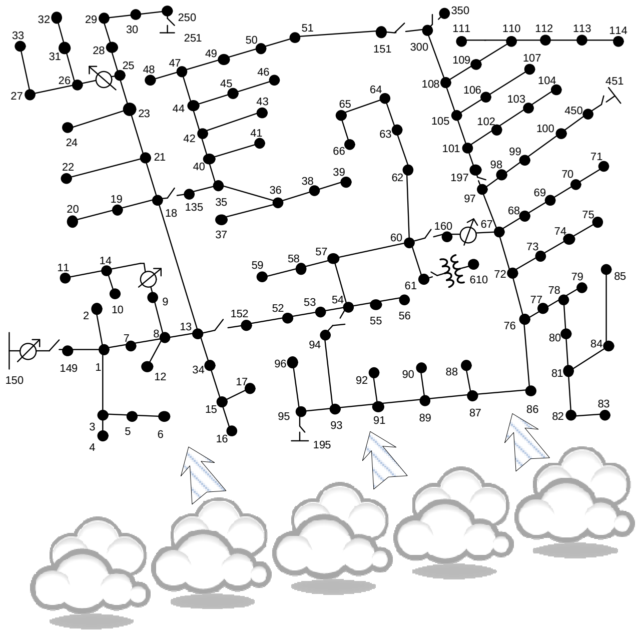


Fig. 14. Cloud coverage path of the IEEE 123 bus system [16]

B. Line Configuration Analysis of the Network Backbone

The line configuration of the network backbone has the same pole top geometry as the configuration 601 (Fig. 3 (b)); however, it is called line configuration 1 due to the application of different phase conductors (336,400 26/7 ACSR) and phase sequences (ABCN). Under the same simulation conditions of Table III, the voltage variation sensitivity matrix is derived and shown in Table XI. Compared to the results of the ABCN sequence in Table V, phase-A and phase-B are still the most and least sensitive phases to PV power fluctuations, respectively. Therefore, more PV units should be connected to phase-B for a more balanced voltage variation of each phase during cloud coverage.

TABLE XI
Voltage Variation Sensitivity Matrix of Line Configuration 1 – ABCN in the IEEE 123 Bus System (2000 ft.)

Obtained in the same conditions as Table III ($\Delta P_{pv} = 500kW$)				
$V_{variation}$ (pu)	$P_{632\,a}\uparrow$ only	$P_{632\,b}\uparrow$ only	$P_{632\,c}\uparrow$ only	Total ΔV (Superposition)
$\Delta V_{632\,a}$	-0.0180	-0.0107	$+0.0142$	-0.0145
$\Delta V_{632\,b}$	$+0.0182$	-0.0178	-0.0086	-0.0082
$\Delta V_{632\,c}$	-0.0078	$+0.0155$	-0.0179	-0.0102

C. Cloud Coverage Analysis

The simulation results are shown in Fig. 15. Based on the path of the clouds, PV power generation for each phase gradually decreased as illustrated in the second figure of Fig.

15. The voltage profiles of the lowest voltage bus (Bus 65) and the parameters of the main voltage regulator are also recorded to show the network performance during cloud coverage. The results validate the voltage variation sensitivity matrix proposed in this paper. For example, around 32s only the PV units of phase-C at Bus 74 and Bus 75 were covered by the clouds. According to the fourth column in Table XI, the voltage of phase-A should increase, and the voltages of phase-B and phase-C should decrease. Moreover, phase-C should have more voltage drop than phase-B. These predictions based on the proposed sensitivity theory have been verified by the voltage profile curves of Bus 65.

It can be seen from Fig. 15 that due to the initial voltage margin from the lower limit for changing tap positions the regulator did not sense the urge for stepping up its tap until about 29s. This is the reason why the first tap change occurred around 94s. During the period of the PV power drop the voltages of phase-A and phase-C at Bus 65 dropped by 0.0235 pu and 0.0206 pu, which were much greater than 0.0089 pu in phase-B. As a result, phase-A experienced an under-voltage (less than 0.95 pu) in a period of about 30s before the tap changer improved the voltage to a normal level. As analyzed in the Part B of this section, some PV units should be moved from phase-A to phase-B in order to balance the voltage variation of each phase.

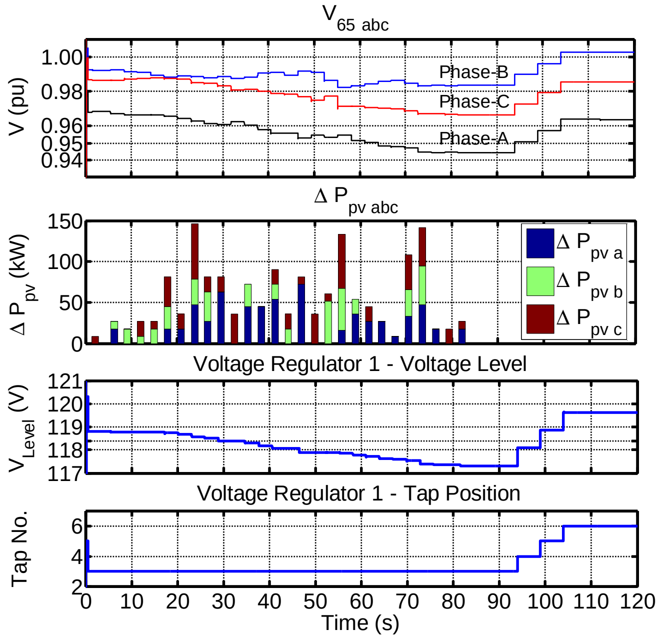


Fig. 15. Cloud coverage response of the IEEE 123 bus system

One of the easiest ways is to detach line 108-109 from phase-A and reconnect it to phase-B. The simulation results in Fig. 16 demonstrate the effectiveness of this re-configuration scheme. The voltages of phase-A to phase-C at Bus 65 decreased 0.0203 pu, 0.0172 pu and 0.0163 pu respectively, which were much more balanced than those before re-configuration. Moreover, as presented in Section V Part C the re-configuration procedure also improved the phase voltage profiles before the PV power drop. Consequently Bus 65 did not have a time when the voltages dropped below the limit (0.95 pu) defined in the standard [8], even with deliberately setting initial tap position of the main voltage regulator one tap less than that of the case before re-configuration.

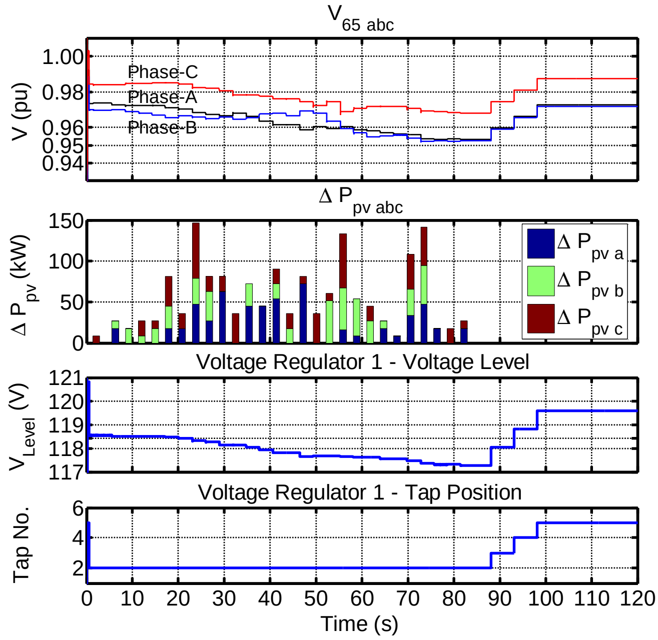


Fig. 16. Cloud coverage response of the IEEE 123 bus system after the re-configuration

D. Full Cloud Transient Analysis

The fast moving clouds should pass the distribution area at some time after the full coverage. However, if this happens after the response of tap changers to a PV power drop, the subsequent power surge may cause an over-voltage problem as the regulator cannot react fast enough to support the voltage. Fig. 17 illustrates the voltage profiles at Bus 83 during the full cloud transient, which was the bus with the highest voltage in the network

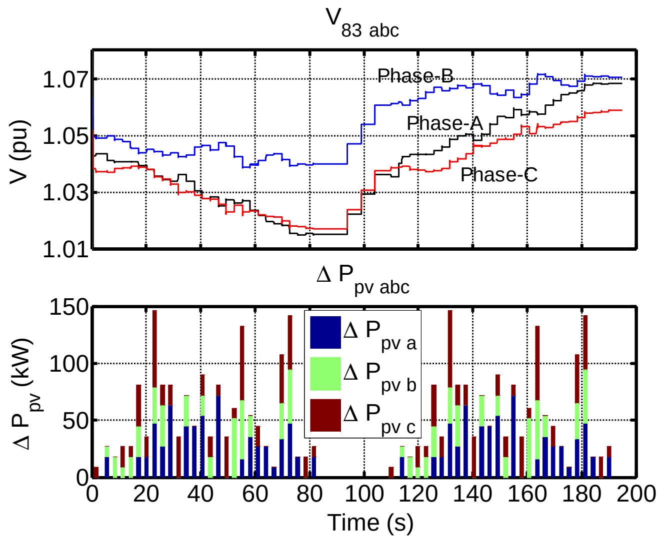


Fig. 17. Full cloud transient of the IEEE 123 bus system

The simulation results show all three phase voltages exceeded the upper limit (1.05 pu) defined in the standard [8] and phase-A clearly had much more voltage variation than those of other phases. The over-voltage problem was mainly due to the voltage level setting (124V) of the voltage regulator 4. If this level can be lowered, it should be helpful to mitigate the high voltage issue.

After the re-configuration process (Fig. 18) although the voltages were still greater than the voltage limit, phase voltage variations became more balanced. This may be beneficial for the further modification of the tap changer settings.

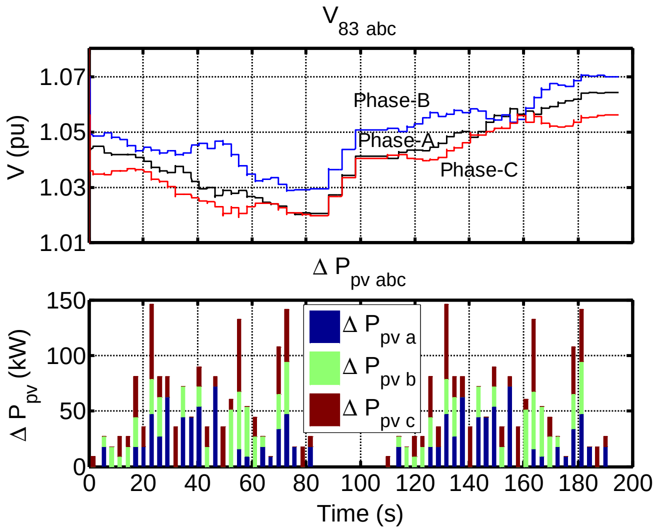


Fig. 18. Full cloud transient of the IEEE 123 bus system after re-configuration

VII. Conclusions

This paper proposes a method for analyzing unbalanced voltage variations in a geographically small area caused by PV power drop due to moving clouds. The voltage variation sensitivity theory developed in this study takes many related factors into account, including upstream sources, phase loads, PV power fluctuations, distribution line length, phase sequences, line geometries and conductor types.

Approximate linearity is observed in simulation. This characteristic is utilized to form voltage variation contribution matrix (Table III or look-up graphs Fig. 5) for sensitivity analysis. The method is further investigated for line configuration impacts using voltage variation curves and positive/negative shift sequences. All line configurations can be categorized into two groups where phase physical positions determine voltage variation sensitivity. The case study demonstrates how the proposed method can be used to solve the potential voltage problems after a PV power drop, i.e. – severe low voltage of a certain phase and unacceptable high voltage imbalance. A network re-configuration solution is presented and shows its effectiveness of voltage improvement. This solution utilizes the potential of an unbalanced network and does not require extra supporting devices (e.g. storage, STATCOM, or SVC) or an expensive re-conductoring process, which is economical for network upgrade deferral. A more comprehensive network – the IEEE 123 bus system is studied. Its simulation results validate the theories of voltage variation sensitivity matrix and re-configuration method developed in this paper. A further full cloud transient demonstrates a potential over-voltage problem after cloud moving out of the distribution region. The re-configuration approach helps to balance phase voltage variations, but tap changer settings need to be adjusted to alleviate the over-voltage problem.

Future work will focus on incorporating the proposed method with network compensation devices, such as capacitor banks, energy storage units and FACTS equipment. The established theory should be further developed considering the impacts of these devices.

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Biographies

Ruifeng Yan (S'2009) received the B. Eng. (Hons.) degree in Automation from University of Science and Technology, Beijing, China, in 2004 and the M. Eng degree in Electrical Engineering from the Australian National University, Canberra, Australia, in 2007. He is currently pursuing Ph.D. degree in power and energy systems at the University of Queensland, Brisbane, Australia.

Tapan K. Saha (SM'97) was born in Bangladesh and immigrated to Australia in 1989. Currently, he is Professor of Electrical Engineering in the School of Information Technology and Electrical Engineering, University of Queensland, Brisbane, Australia. Before joining the University of Queensland, he taught at the Bangladesh University of Engineering and Technology, Dhaka, for three- and half years and then at James Cook University, Townsville, Australia, for two and half years. His research interests include power systems, power quality, and condition monitoring of electrical plants. Dr. Saha is a Fellow of the Institution of Engineers, Australia.