

The Advanced Voltage Regulation Method for ULTC in Distribution Systems with DG

Mi-Young Kim[†], Yong-Un Song* and Kyung-Hwa Kim*

Abstract – The small-scaled onsite generators such as photovoltaic power, wind power, biomass and fuel cell belong to decarbonization techniques. In general, these generators tend to be connected to utility systems, and they are called distributed generations (DGs) compared with conventional centralized power plants. However, DGs may impact on stabilization of utility systems, which gets utility into trouble. In order to reduce utility's burdens (e.g., investment for facilities reinforcement) and accelerate DG introduction, the advanced operation algorithms under the existing utility systems are urgently needed. This paper presents the advanced voltage regulation method in power systems since the sending voltage of voltage regulators has been played a decisive role restricting maximum installable DG capacity (MaxC_DG). For the proposed voltage regulation method, the difference from existing voltage regulation method is explained and the detailed concept is introduced in this paper. MaxC_DG estimation through case studies based on Korean model network verifies the superiority of the proposed method.

Keywords: Distributed generation (DG), Distributed generations (DGs), Distribution systems, Voltage regulation, Under load tap changer (ULTC), Line drop compensation (LDC), LDC parameters (equivalent impedance, load center voltage)

1. Introduction

The climate change and energy problems (security and demand) are changing our life mechanism dramatically, and the countermeasures against such crisis are establishing around the world. Energy efficiency, decarbonization and natural sink as technical countermeasures are becoming the main issue of society. As decarbonization countermeasure, many countries are competitively developing new & renewable sources that can be dispersed in distribution systems (nominal voltage is 22.9kV in Korea), and those nontraditional sources are called the distributed generators (DGs). These DGs are connected to utility systems due to the high initial investment and then the positive actions of the utilities are core. However, the utilities nowadays have been concerned about grid stabilization because of intermittent DG output. Specially, in distribution system, the utilities also stickle about more DG interconnection since they have to provide more money for additional facilities and operating system changing.

In order to reduce utility's burdens and increase DG introduction, the advanced operation algorithms are absolutely indispensable to existing distribution systems.

Particularly, the voltage problem is one of the operational constraints in distribution systems and the impact of DG interconnection on voltage profile has been discussed in

several papers. The development of a simulator for Closed Loop Voltage Control (CLVC) that utilizes real-time data feedback from zone substations and ends of feeders to effectively manage and reduce customer over and undervoltage issues was discussed in [1]. The effect of other control functions on proper parallel operations such as LDC (Line Drop Compensation) or reverse power operation setting is also noted in [2]. Also, the discussion of new techniques of the Enhanced Automatic Paralleling Package and SuperTAPP n+ relay schemes have been introduced in [3]. The additional ampere meters in order to solve this problem that the magnitude of voltage drops cannot be predicted and voltage violations might occur are introduced in [4]. A fuzzy based voltage regulator which rationalizes the number of transformer tap changes and improves the voltage profile at the point of consumption while acting only on the distribution system was proposed in [5].

The typical voltage problem is to maintain customers' receiving voltage (Cus_Vol) (refer to $V1(t) \sim V4(t)$ of Fig. 4 in [6]) within a proper range. Whereupon, some devices are installed in distribution systems to maintain Cus_Vol: under load tap changer (ULTC) at the substation, step voltage regulator (SVR) on feeder and capacitor bank or a static var compensator (SVC). ULTC and SVR control the sending voltage maintaining Cus_Vol levels (207 ~ 233V in Korea). ULTC manages multiple feeders all together and SVR manages the area uncontrolled by ULTC alone. Namely, ULTC and SVR boost sending voltage when the load increases or DG output is low, and vice versa. The

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major method regulating both ULTC and SVR is LDC (Line Drop Compensation) method, as its name indicates, LDC method compensates line voltage drop due to a varying load current. In LDC method, the sending voltages of voltage regulators depend on LDC parameters (equivalent impedance and load center voltage) that restrict the maximum installable DG capacity (MaxC_DG).

This paper presents the advanced voltage regulation method since MaxC_DG depends on the sending voltage of ULTC. Compared with LDC method, this study uses two pairs of the predesigned LDC parameters to increase MaxC_DG. Thereby, the proposed voltage regulation method is called as ‘‘tap selection’’ in LDC method (TS_LDC). The detailed concept and mathematical explanations for TS_LDC algorithm are introduced, and MaxC_DG is estimated in this paper. The validation of TS_LDC algorithm is ascertained through case studies based on Korean model network and the superiority over the conventional LDC method is also discussed from the perspective of MaxC_DG.

2. Constraints for MaxC_DG [7]

As is known, MaxC_DG in distribution systems is not infinite due to various reasons that are derived from operational constraints and regulation methods of existing facilities. Here are some of the details.

2.1 Operational constraints

It is widely recognized that power systems have some operational constraints regardless of DG output. These constraints should be satisfied in all situations and are basic conditions determining MaxC_DG.

- (i) The reverse power flow at distribution substation is prohibited since the existing facilities are operated without regard to it. Therefore, MaxC_DG should be smaller than offpeak load.
- (ii) The allowable current capacity on feeder is limited since line burns out due to too much current flow. Therefore, MaxC_DG should be smaller than allowable current capacity.
- (iii) Cus_Vol should exist within an acceptable range defined by law, since electrical appliances are designed based on that range.
- (iv) ULTC is operated within designed range (0.9 ~ 1.1 (p.u.) in Korea) owing to cost problem. Therefore, MaxC_DG should be decided while ULTC range is kept.

2.2 Voltage regulation method

Among facilities being operated in distribution system, ULTC is studied in this paper. This Chapter specifies the

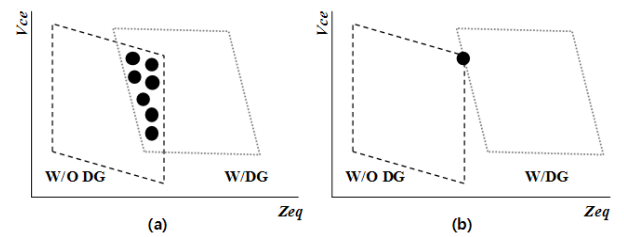


Fig. 1. Feasible LDC parameters for a varying DG

reasons why regulation method of ULTC restricts MaxC_DG. A reason is due to LDC voltage regulation method that is commonly employed to control ULTC.

To be brief, LDC method compensates line voltage drop due to a varying load current. The LDC method estimates the sending voltage based on a linear function of sending current. More specifically, the sending voltage achieved can be written as follows.

$$\begin{aligned} V_{send}(t) &= V_0 \times Xmtr(t) \\ &= V_{ce} + Z_{eq} \times I_{Bank}(t) \times Xmtr(t) \end{aligned} \quad (1)$$

where, V_0 is the base voltage [p.u.], $Xmtr(t)$ is voltage compensation rate at time t , V_{ce} and Z_{eq} are the LDC parameters called the load center voltage and the equivalent impedance [p.u.], $I_{Bank}(t)$ is the sending current measured at bank at time t [p.u.].

As expressed in Eq. (1), the sending voltage of ULTC is achieved with the accurate LDC parameters; therefore, there is no doubt that the estimation of LDC parameters is extremely important. A pair of LDC parameters (V_{ce} and Z_{eq}) in Eq. (1) is predesigned in order that ULTC sending voltage guarantees Cus_Vol for a varying load. The predesigned LDC parameters is used unchanged for a period, which should be kept even though DG output varies from 0% to 100%. Actually, the feasible LDC parameters for a varying load has a range (squares of Fig. 1 (a)), not a single pair (refer to Chapter III.C in [7]). Moreover, the range of LDC parameters is different according to a varying DG output: black dotted square without DG and gray dotted square with DG in Fig. 1(a). Hence, the dots (●) in intersection of both squares are the feasible LDC parameters for a varying DG output. It is clear that feasible LDC parameters does not exist when more DG injects power into distribution systems (refer to Chapter IV in [7]). Therefore, MaxC_DG can be decided while a pair of LDC parameters (dot (●) in Fig. 1(b)) exists for a varying load and DG output. That is to say, the existence of LDC parameters is a constraint for MaxC_DG estimation.

Another reason restricting MaxC_DG is ULTC operation with bandwidth. ULTC supplies the sending voltage with tap position considering bandwidth discretely owing to ULTC lifetime. Fig. 2 shows a schematic image for ULTC operation: the several tap positions (# 1~# 5, actually more), bandwidth (ϵ) and tap step (typically 0.00625 (p.u.) or

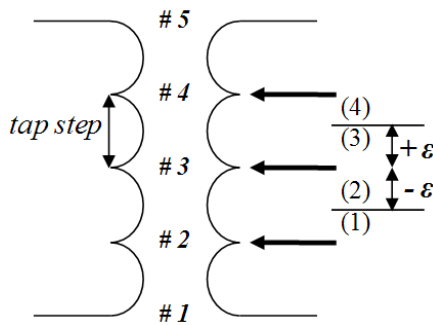


Fig. 2. ULTC operation with bandwidth

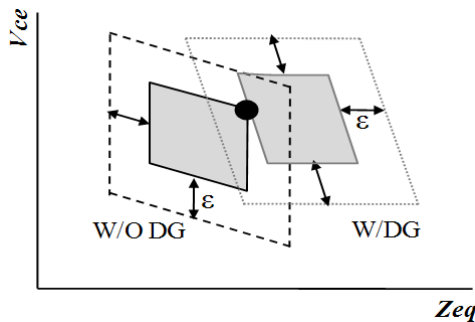


Fig. 3. Feasible LDC parameters with bandwidth for a varying DG output

0.0125 (p.u.). When the present tap position is # 3, ULTC tap position keeps # 3 if the sending voltage calculated by Eq. (1) exists within (2)~(3), ULTC tap position rises to # 4 if the calculated value is more than (4) and ULTC tap position drops to # 2 if the calculated value is less than (1).

Therefore, LDC parameters should be designed with attention to the discreteness of tap position and the effect of bandwidth. Fig. 3 illustrates that bandwidth decreases the range of feasible LDC parameters; the range (gray filled square) with bandwidth is smaller than the range (no filled square) without bandwidth. Thus, the range (gray filled square) is actually used for ULTC operation in distribution systems (refer to Chapter III.B in [7]).

In summary, we can say that MaxC_DG is influenced by LDC parameters considering bandwidth. Hence, this paper presents voltage regulation method by LDC parameters not considering bandwidth. As a result, the range of feasible LDC parameter becomes large and more MaxC_DG can be interconnected to distribution systems.

3. Proposed Voltage Regulation Method

In this paper, the proposed voltage regulation method is named as “tap selection” in LDC method (TS_LDC), because this method applies LDC method and ULTC tap is selected. The specific differences between LDC method and TS_LDC method are as follows.

- (i) LDC method uses a pair of LDC parameters, while

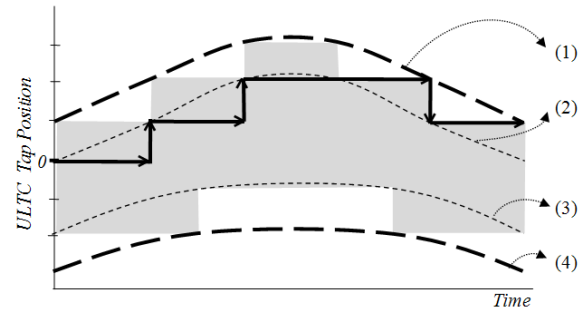


Fig. 4. Concept of TS_LDC method over LDC method

TS_LDC uses two pairs of LDC parameters.

- (ii) ULTC tap is moved automatically regard of bandwidth in LDC method, while ULTC tap is selected automatically regardless of bandwidth in TS_LDC.

3.1 Conceptual explanation

For ULTC voltage regulation, Fig. 4 shows the concept of TS_LDC method over LDC method. More specifically, (1) means upper sending voltage satisfying upper Cus_Vol level (233V in Korea), (4) means lower sending voltage satisfying lower Cus_Vol level (207V in Korea), (2) means upper sending voltage minus bandwidth and (3) means lower sending voltage plus bandwidth. As illustrated in Fig. 4, ULTC tap is moved as bold arrow considering line (2) and the available tap position is only one for each time in LDC method. However, actually, ULTC has available tap positions (gray area in Fig. 4) for each time. Namely, the range of available tap positions for each time exists. Conceptually, TS_LDC method estimates that range, and MaxC_DG is increased when the lowest tap position within that range is used. The mathematical algorithm for TS_LDC method is expressed minutely in next Chapter.

3.2 Estimation of available tap positions

TS_LDC method that decides the range of available tap positions is achieved by two pairs of LDC parameters, after that, Eq. (1) is applied for estimating sending voltages in real time. The estimation of available tap positions includes the following processes.

- (i) First of all, the proper sending voltages should be calculated. The sending voltages must be achieved so as to maintain Cus_Vol within a proper range. Therefore, the upper sending voltage for upper Cus_Vol level and the lower sending voltage for lower Cus_Vol level are exist, eventually, sending voltage has an acceptable range. The upper and lower sending voltages can be calculated by compensating voltage drops along the feeder: voltage drops arise at pole transformers, secondary feeders and service lines for a varying load and DG output

(refer to Chapter III.A in [7]).

- (ii) The range of feasible LDC parameters should be estimated. LDC parameters should always be designed so that ULTC sending voltage stays within the above acceptable range. The range of feasible LDC parameters can be obtained easily by finding four values: the upper and lower sending voltages and sending currents at peak time and bottom time (refer to Chapter III.C in [7]).

- (iii) Two pairs of LDC parameters should be decided. One of two pairs is called as upper LDC parameters, and they are decided by the upper sending voltages and sending currents at every time as expressed in Eq. (2). Surely, Eq. (2) only shows relevance for peak time and bottom time, however, the relevance for every time must be considered. Similarly, another pair of LDC parameters is called as lower LDC parameters, and they are decided by the lower sending voltages and sending currents at every time as expressed in Eq. (3).

$$\begin{aligned} \overline{V_{send}(bottom)} &= \overline{V_{ce}} + \overline{Z_{eq}} \times I_{Bank}(bottom) \\ \bullet \\ \bullet \end{aligned} \quad (2)$$

$$\begin{aligned} \overline{V_{send}(peak)} &= \overline{V_{ce}} + \overline{Z_{eq}} \times I_{Bank}(peak) \\ \underline{V_{send}(bottom)} &= \underline{V_{ce}} + \underline{Z_{eq}} \times I_{Bank}(bottom) \\ \bullet \\ \bullet \\ \underline{V_{send}(peak)} &= \underline{V_{ce}} + \underline{Z_{eq}} \times I_{Bank}(peak) \end{aligned} \quad (3)$$

where, $\overline{V_{send}(bottom)}$, $\underline{V_{send}(bottom)}$ are upper and lower sending voltages at bottom time [p.u.], $\overline{V_{send}(peak)}$, $\underline{V_{send}(peak)}$ are upper and lower sending voltages at peak time [p.u.], $\overline{V_{ce}}, \overline{Z_{eq}}$ are upper LDC parameters and $\underline{V_{ce}}, \underline{Z_{eq}}$ are lower LDC parameters and $I_{Bank}(bottom)$, $I_{Bank}(peak)$ are sending currents at bottom and peak times.

- (iv) Finally, the available tap positions should be estimated. The upper and lower sending voltages are calculated in real time as shown Eq. (4) and available tap positions are decided as shown Eq. (5), the upper and lower LDC parameters decided in (iii) are used. Therefore, available tap positions are taps within upper and lower sending voltages, and ULTC is operated by any tap within available tap positions.

$$\begin{aligned} \overline{V_{send}(t)} &= \overline{V_{ce}} + \overline{Z_{eq}} \times I_{Bank}(t) \\ \underline{V_{send}(t)} &= \underline{V_{ce}} + \underline{Z_{eq}} \times I_{Bank}(t) \end{aligned} \quad (4)$$

$$\underline{V_{send}(t)} \leq Tap(t) \leq \overline{V_{send}(t)} \quad (5)$$

where, $\overline{V_{send}(t)}$, $\underline{V_{send}(t)}$ are upper and lower sending voltages at time t [p.u.], is available tap positions at time t [p.u.].

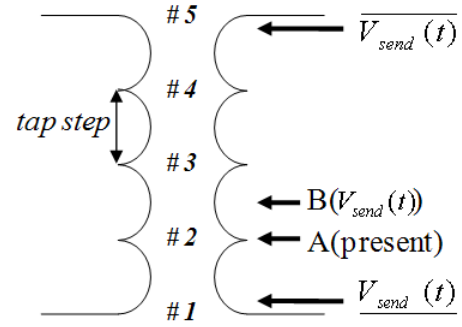


Fig. 5. Available tap positions in TS_LDC method

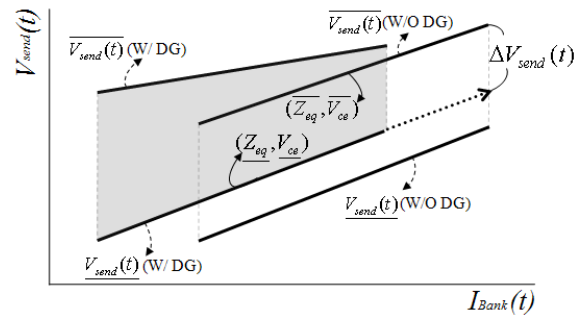


Fig. 6. Estimation of MaxC_DG

3.3 Tap selection

ULTC tap is moved automatically regard of bandwidth in LDC method, while ULTC tap is selected automatically regardless of bandwidth in TS_LDC. Fig. 5 shows the available tap positions in TS_LDC method; #2~#4 are decided by Eq. (5). To select tap position increasing MaxC_DG, the following procedures are needed.

- (i) Within available tap positions, the nearest them to the present tap position are selected; #2~#3 when sending voltage calculated by Eq. (1) is B and the present tap position is A
- (ii) Within nearest tap positions, the lowest tap position is selected; #2 is selected.

3.4 Estimation of MaxC_DG

ULTC should be well operated regardless to DG output; for each time, the one or more available tap positions should exist in any case. Hence, as explained in Eq. (6), the difference of both upper and lower sending voltages for each time should be more than tap step (0.00625 or 0.0125(p.u.)). Fig. 6 describes Eq. (6); the bold lines show upper/lower sending voltages for a varying DG output. Y-intercept and slope of bold line are LDC parameters (V_{ce} and Z_{eq}). Since the predesigned LDC parameters is used unchanged for a period, the upper LDC parameters is ($\overline{V_{ce}}, \overline{Z_{eq}}$) and the lower LDC parameters is ($\underline{V_{ce}}, \underline{Z_{eq}}$).

Therefore, MaxC_DG should be decided while Eq. (6) is

satisfied.

$$\overline{V_{send}(t)} - \underline{V_{send}(t)} = \Delta V_{send}(t) \geq tap\ step \quad (6)$$

4. Simulation Results

4.1 Simulation conditions

Availability of the proposed voltage regulation method for multiple feeders is ascertained through numerical case study using model network and load curve illustrated in Fig. 7 and Fig. 8. The following conditions are applied in simulation;

- Base voltage: 22.9 (kV), Base power: 100 (MVA)
- Service voltage: 220 (V)
- Acceptable customer receiving voltage: 207~233 (V)
- Voltage drops at peak time: $\Delta v_1 = 8 (V)$, $\Delta v_2 = 16(V)$
- Tap step of ULTC: 0.0125 (p.u)
- Bandwidth (e): $\pm 0.0125 (p.u)$
- Power factor of load and DG: 0.9. The Korean distribution Grid Code defines that DG over power factor of 0.9 must be only connected to distribution system.
- Peak load: 0.45 (p.u)
- Ratio of pole transformer (differentiated according to the voltage drop along primary feeder (ΔV_{feeder})):

$$\Delta V_{feeder} \leq 5(\%): 22.9(kV) / 230(V)$$

$$5(\%) < \Delta V_{feeder} \leq 10(\%): 21.8(kV) / 230(V)$$

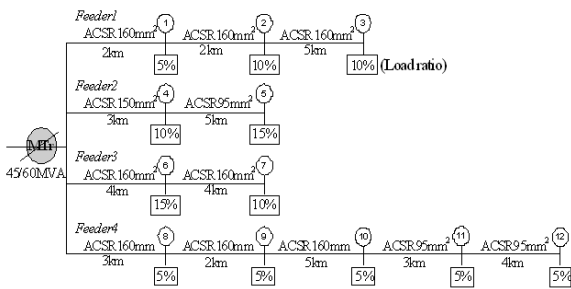


Fig. 7. Model network

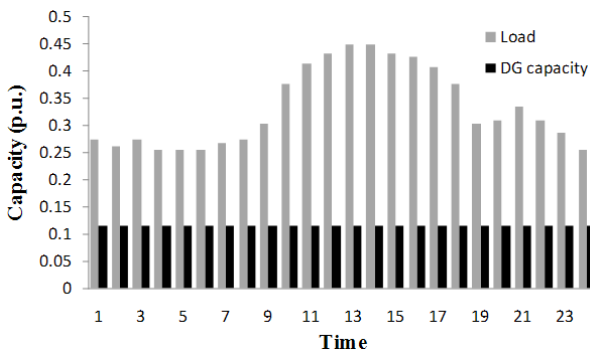


Fig. 8. Load curve and DG output curve

- DG generates and injects the power through 24 hours.
- DGs are connected to single node and two nodes on a same feeder.

4.2 Estimation of two pairs of LDC parameters

MaxC_DG is decided while the one or more available tap positions exist in TS_LDC method. Fig. 9 illustrates the ranges of feasible LDC parameters in LDC method, DG (0.06662 (p.u.)) is connected to node 1. (1) is the range of LDC parameters without both bandwidth and DG, (2) is the range with bandwidth and without DG, (3) is the range without bandwidth and with DG and (4) is the range with both bandwidth and DG. We can find that the feasible LDC parameters with bandwidth become small. Therefore, in LDC method, MaxC_DG (0.06662 (p.u.)) at node 1 is decided while intersection of (2) and (4) exists; the intersection point is only one.

Meanwhile, Fig. 10 illustrates the range of feasible LDC parameters in TS_LDC method. Because of no considering bandwidth, the range (2) and (4) in Fig. 10 are not needed. We can find that the feasible LDC parameters become larger than LDC method. More specifically, (3) is the range of LDC parameters without bandwidth when DG 0.06662 (p.u.) is connected to node 1 and (5) is the range of LDC parameters without bandwidth when DG 0.09657 (p.u.) is connected to node 1. For MaxC_DG 0.09657 (p.u.)

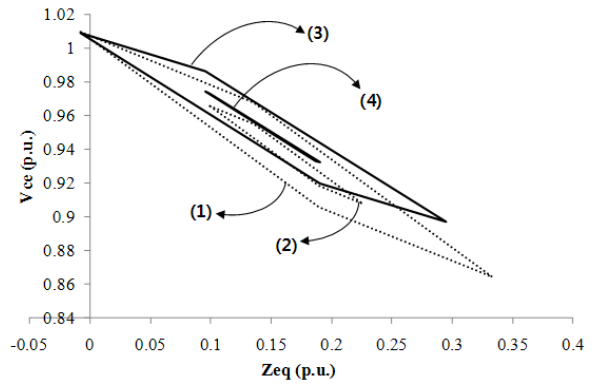


Fig. 9. Ranges of feasible LDC parameters in LDC method

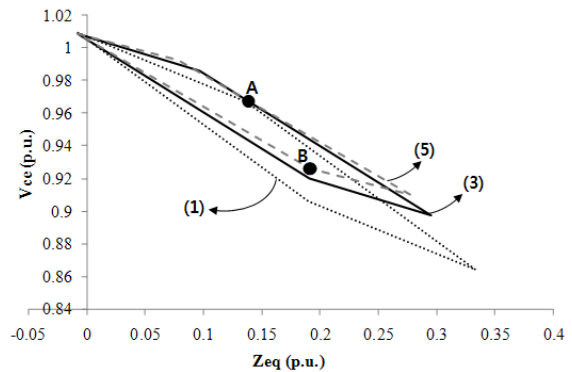


Fig. 10. Ranges of feasible LDC parameters in TS-LDC method

estimated by Eq. (6), two pairs of LDC parameters are used; the upper LDC parameters is A and the lower LDC parameters is B (dots (•) in Fig. 10). The difference of both sending voltages estimated by A and B is more than tap step at peak time.

4.3 Estimation of MaxC_DG for single node

Fig. 11 shows MaxC_DG that can be connected to each node, which is calculated by Eq. (8). The white bar graph (1) means MaxC_DG when ULTC is operated continuously, not discretely. The gray bar graph (2) means MaxC_DG when ULTC is operated by LDC method. The black bar graph (3) means MaxC_DG when ULTC is operated by TS_LDC method. It's natural that (2) is smaller than (1), because (1) is calculated by loadflow analysis and (2) is calculated by considering discreteness. Most importantly, (3) is larger than (2), because (3) is achieved by more

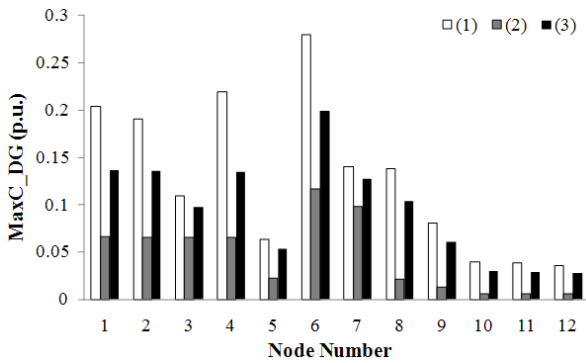
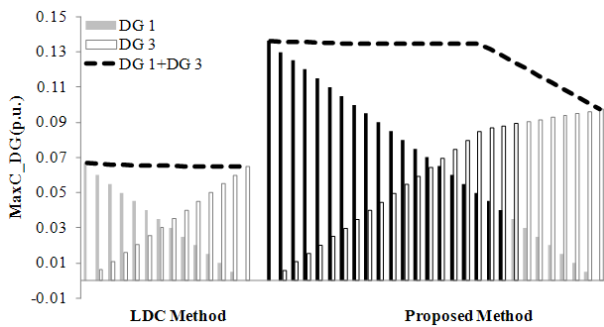
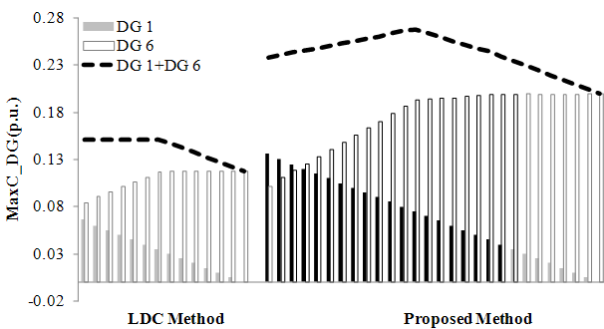


Fig. 11. MaxC_DG for single node



(a) DGs are connected to node 1 and node 3



(b) DGs are connected to node 1 and node 6

Fig. 12. MaxC_DG for two nodes

feasible LDC parameters. Therefore, compared with LDC method, the superiority of the proposed TS_LDC method is ascertained.

4.4 Estimation of MaxC_DG for two nodes

Two pairs of the predesigned LDC parameters are used unchanged for a period when DGs are connected to multiple nodes. Fig. 12 (a) shows MaxC_DG when DG 1 and DG 3 are connected to node 1 and node 3 at the same time and MaxC_DG of DG 3 according to decrease of DG1.

Fig. 12(a) explains MaxC_DG for two nodes on same feeder, on the other hand, Fig. 12(b) explains MaxC_DG for two nodes on individual feeders. That is, Fig. 12(b) shows MaxC_DG when DG 1 and DG 6 are connected to node 1 and node 6. The gray filled bar graphs means MaxC_DG at node 1 and the gray blanked bar graphs means MaxC_DG at node 3 in LDC method. The black filled bar graphs means MaxC_DG at node 1 and the black blanked bar graphs means MaxC_DG at node 3 in TS_LDC method. For DG 1 plus DG 3 and DG 1 plus DG 6, the proposed method increases MaxC_DG.

Meanwhile, When DGs are connected to every node, the range of feasible LDC parameter in the proposed TS_LDC method becomes large, and MaxC_DG can be interconnected to distribution systems over LDC method.

5. Conclusions

DGs are connected to utility systems, and the positive actions of the utilities are core. However, the utilities nowadays have been concerned about grid stabilization because of intermittent DG output. In order to reduce the utility's burdens and increase DG introduction, the advanced operation algorithm is absolutely indispensable to existing distribution systems. Especially, for ULTC, the voltage regulation method is very important since the maximum installable DG capacity (MaxC_DG) depends on the sending voltage. The existing LDC voltage regulation method with bandwidth constricts MaxC_DG. Therefore, this paper proposed the advanced voltage regulation method for ULTC, TS_LDC, which uses two pairs of LDC parameters without bandwidth. Thereby, the studies that DG is connected to single node and DGs are connected to two nodes are performed under TS_LDC method. Compared with LDC method, MaxC_DG can be increased in TS_LDC method. The superiority of the proposed method was certified.

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