Impact of Distributed Generation on Voltage Regulation by ULTC Transformer using Various Existing Methods

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Abstract: - Even in a system with voltage regulation, distributed generation (DG) can cause over-voltage as well as under-voltage. This paper focuses on the impacts of DG on voltage regulation by under-load-tap-changer (ULTC) transformer using various existing methods. The considered methods include: lookup-table method, voltage-based method, line drop compensator (LDC), and a practical method, called reactive power device control (RPDC) that is a software function currently used by Taiwan Power Company (Taipower). First of all, a software package Matlab/simulink was used to build a sample system, a simplified model of a typical distribution system, and form control blocks for the four above methods of voltage regulation. Then, the sample system was simulated and analyzed by taking into account the DG size, location, and power factor. The study is illustrated by a numerical example with various operating conditions to confirm the impact of DG on the validity of voltage regulation by ULTC transformer utilitizing four existing methods.

Key-Words: - Distributed generation, grid interconnection, ULTC, voltage regulation, LDC, voltage deviation.

1 Introduction

With rapid increasing installed capacity for wind generation, the validity of voltage regulation, using traditional methods is doubted due to the high penetration of wind generation. Most distribution feeders are radial arrangements with one-way power flow from substation to end users. In general, voltage regulation for simple radial feeders is easy and straightforward. ULTC transformers and switched capacitor banks are the most common facilities for voltage regulation. The size, interconnection location, and operating power factor of DG are the major factors that may distort the validity of existing voltage regulation methods. In this paper, the impact of DG on voltage regulation by ULTC transformer, employing four existing methods commonly used in distribution networks is investigated and feasible strategies for maintaining feeder voltage quality after DG installation are also discussed.

2 Interconnection Rules for Distributed Generations

Table 1 outlines the requirements for the steady-state voltage deviation caused by DG grid-connection in the US, Germany, and Denmark. IEEE Std. 1547 states that the DR (distributed resource) unit shall parallel with the area electrical power system (Area EPS) without causing a voltage fluctuation at the point of common coupling (PCC) greater than ±5% of the prevailing voltage level of the Area EPS at the PCC, and meet the flicker requirements. Although the system characteristics, voltage levels and considerations are different from country to country, the requirements of maximum permissible steady-state voltage deviation caused by DG grid-connection are commonly bounded within 1 to 5% [1]-[5].

Table 1 Overview of common requirements for voltage deviation

	Area, Regulation and Scope		Voltage Deviation
US	IEEE Std. 1547		± 5 %
Germany	VDEW	Medium Voltage Network	< 2 %
	VDN	Individual generating unit (wind turbine)	≤ 0.5 %
	VDN	Entire plant (wind farm)	≤ 2 %
	VDN	System faults	≤ 5 %
Denmark	DEFU	10 ~ 20kV grid	≤ 1 %
	Eltra Transmission grid	General constraint (wind farm)	< 3 %
		Until a freaquency of 10 per hour (wind farm)	< 2.5 %
		Until a freauency of 100 per hour (wind farm)	< 1.5 %
	Eltra Distribution grid	10 ~ 20kV grid (wind turbine)	≤ 4 %
		50 ~ 60kV grid (wind turbine)	≤ 3 %

3 Existing Voltage Regulation Methods

The ULTC transformer and switched capacitor banks are the most common voltage-regulation facilities to maintain the voltage profile along a radial feeder. Generally, for better voltage regulation, both ULTC and switched capacitor banks are applied. The practical system conditions, such as network configuration, system operating schemes, load characteristics, existing reactive power, voltage control devices and local regulation, etc. should be considered and coordinated in the determination of voltage regulation strategy. Four voltage regulation methods: lookup-table, voltage-base, line-drop compensation (LDC) and RPDC methods are examined as follows.

3.1 Lookup-table method

The proper tap position of a ULTC transformer is basically determined by loading conditions and load characteristics of the ULTC transformer or a typical feeder fed by this transformer. Hence, a prearranged table for the ULTC tap positions is required to follow the change of loads without measuring equipment. The table is usually made up by engineers with plentiful operating experience with the concerned transformer. Because the daily load curves are different from season to season and from weekday to holiday, the lookup-table method can only be applied to a very limited situation with almost constant daily load curves.

3.2 Voltage-based method

If the voltage at the "regulating point" can be obtained, the tap positions for ULTC can therefore be determined by the measured voltage obtained from potential transformer (PT) or other voltage measurement devices. The regulating point is usually the secondary bus of the ULTC transformer at the substation. Compared with the Look-up table method, the advantage of this method is that unplanned load changes can be responded to.

3.3 LDC method

The objective of LDC is to keep the voltage of a constant voltage point (CVP) at a feeder constant. The tap positions for ULTC with LDC is determined by the load variation. Both bus voltage and feeder current at the substation end of interested feeder are measured. Hence, both PT and current transformer (CT) are required to achieve the goal.

3.4 Taipower's RPDC method

Nowadays, Taipower utilizes RPDC (reactive power device control), a function of EMS (energy management system) to control the voltage profiles of feeders fed by a ULTC transformer. Based on prearranged control criteria, both the ULTC and switched capacitor banks are controlled. First of all, the RPDC controls the switched capacitor banks to compensate for the reactive power required by the feeder loads. In this stage, the feeder voltage can be improved simultaneously. If the voltage is not within the permissible region, the RPDC will change the ULTC tap position to regulate the feeder voltage further. In a few special cases, the switched capacitor banks are mainly used to regulate the feeder voltage rather than correct the power factors of the feeder.

4 Impact of DG on the Validity of Existing Voltage Regulation Methods

4.1 Sample system and parameters

A simplified typical distribution system, shown in Fig. 1, is adopted as a sample system to examine the impact of DG on the validity of existing voltage regulation methods. The system parameters are described as follows:

1. The system short-circuit capacity at the primary side of the substation ULTC transformer is assumed to be 800 MVA.
2. The main transformer ratings are: 25 MVA, 69−11.4 kV and Z% = 9%.
3. The feeder mains of length 10km each and conductor size 477MCM ACSR are overhead lines.
4. To examine the validity of existing voltage regulation methods, annual peak load weekday was selected. Also, Feeders A and B are assumed to be at heavy and light loading conditions, respectively.
5. Feeder A mainly supplies industrial power loads distributed along the feeder. The typical daily load curves on summer weekdays are shown in Fig. 2. The coinciding peak load of feeder A is 2.8 MVA.
6. Feeder B supplies residential loads distributed along the feeder. The typical residential daily load curves for the same summer weekday as Fig. 2 are shown in Fig. 3. The peak load of feeder B is 0.4 MVA.
7. The loads of the other feeders fed by the same ULTC transformer are lumped together and connected to the secondary bus of the transformer. The peak load of the lumped load is assumed 12.17 MVA.
8. The total connected demand of the main transformer is about 60% of its rated capacity.
9. All the discrete loads are assumed uniformly distributed along the feeders.

10. The DG is assumed to be installed at Bus A3, the first tapping-off point of feeder A from the substation, or Bus A12, the end of feeder A. Also, the maximum DG sizes at the particular locations that will not result in under-voltage or over-voltage at the feeder end are applied. Hence, the installed DG size is 6MW at Bus A3 or 0.9MW at Bus A12, respectively. The DG is modeled as a constant PQ device.

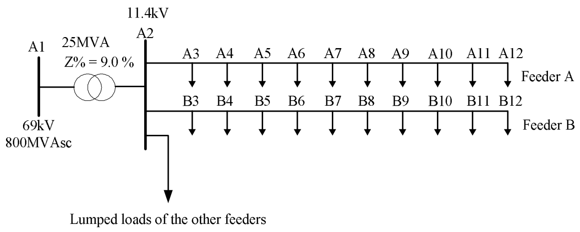

Fig. 1 Sample system

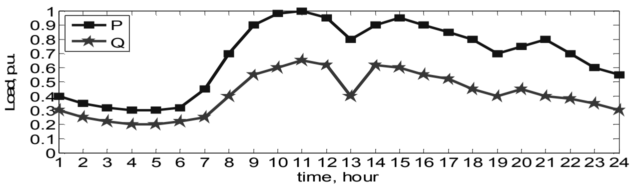

Fig. 2 Typical industrial daily load curves

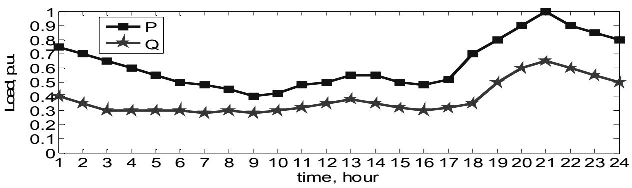

Fig. 3 Typical residential daily load curves

4.2 Without voltage regulation

The tap position for this case is fixed. Fig. 4 shows the daily voltage profiles of Bus A2, the substation ends of feeders, Bus A12, the end of feeder A, and B12, the end of feeder B.

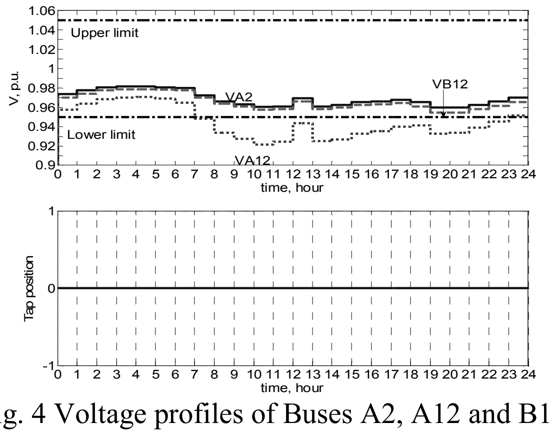

Fig. 4 Voltage profiles of Buses A2, A12 and B12, and tap position of ULTC (without voltage regulation)

This Figure indicates that without voltage regulation the voltage at Bus A12 will drop down below the lower limit (0.95 p.u.) during the 8 a.m. to 11 p.m. period. That is not permissible according to Taiwan's regulation. The notations of bus voltage are as follows: VA2 denotes the voltage at Bus A2 and VB12 means the bus voltage at Bus B12, etc.

4.3 By existing voltage regulation methods

4.3.1 Lookup-table method

The prechosen tap positions for the ULTC are shown in Table 2.

Table 2 Predestinated tap positions of ULTC

Time (h)	1	2	3	4	5	6
Tap position	6	6	6	5	5	5
Time (h)	7	8	9	10	11	12
Tap position	5	6	7	8	9	9
Time (h)	13	14	15	16	17	18
Tap position	9	9	9	9	9	9
Time (h)	19	20	21	22	23	24
Tap position	9	9	10	10	9	8

The sample system under given load conditions, the bus voltages at Buses A2, A12 and B12 can be regulated in the desired voltage region (±2.5% as a percentage of the nominal voltage) if the Lookup-table method is applied and prechosen tap positions for ULTC are suitable.

Fig. 5 shows the daily voltage profiles of Buses A2, A12 and B12 while a DG of 6 MW is connected to Bus A3 and operated at full load with a power factor of 0.85 lagging. The voltages along feeders A and B are all increased because a DG operated at lagging power factor will supply both real and reactive powers to the system. Fig. 5 demonstrates that the DG does affect the voltage profiles along the feeders significantly. In this case, the voltages at Bus A2, the substation ends of feeders, and Bus B12, the end of the light-loading feeder, Feeder B, almost hit the upper limit of 1.05pu. If the transformer loading is further reduced from the given condition, the voltages at the ends of feeders, especially the lightest load feeder, should hit the upper limit. On the other hand, if a DG connection location is moved to the substation, Bus A2, then more DG capacity can be installed without exceeding the permissible maximum voltage deviation of ±2.5%. The over-voltage will occur in some time interval. Hence, the lookup table needs to be modified after a DG is installed to consider the combination effect of DGs and loads on the voltage regulation.

If a DG of 0.9MW is connected to Bus A12 and operated at full generation capacity with 0.95 leading power factor, the voltage profiles along the feeders will be decreased, as shown in Fig. 6. A DG operated at a leading power factor does not generate sufficient kilovars to supply their own needs and consequently must take additional kilovars from the system. Under this operating condition, the voltage at Bus A12, the connection point of the DG, is close to the lower limit of 0.95 p.u., the permissible minimum service voltage according to the Electrical Law in Taiwan. Hence, the distribution system does have a risk of under-voltage in some severe operating conditions.

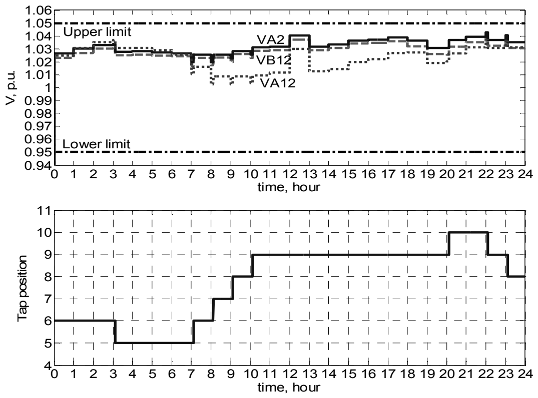

Fig. 5 Voltage profiles for Buses A2, A12 and B12, and tap positions of ULTC by Lookup-table method (DG of 6MW, P.F.=0.85 lagging @ Bus A3)

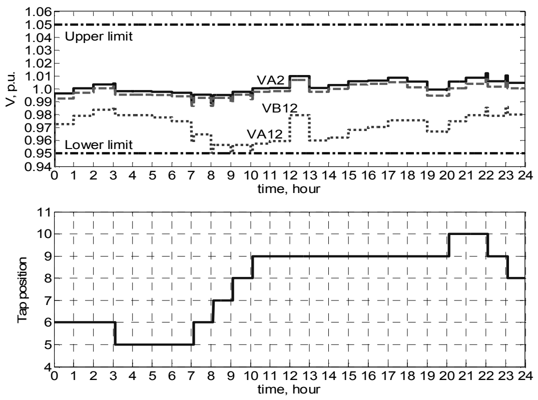

Fig. 6 Voltage profiles for Buses A2, A12 and B12, and tap positions of ULTC by Lookup-table method (DG of 0.9MW, P.F.=0.95 leading @ Bus A12)

4.3.2 Voltage-based method

The resultant bus voltage profiles for Buses A2, A12 and B12, and tap positions of ULTC by Voltage-based method without a DG installed. The tap position is determined based on the voltage at the secondary bus of the substation transformer, Bus A2. Therefore, PT or some other device for measuring voltage is needed. For the sample system under the given load conditions, the bus voltages of Buses A2, A12 and B12 can all be regulated in the desired voltage region if Voltage-based method with a suitable prearranged regulating algorithm is applied.

Fig. 7 presents the resultant bus voltage profiles for Buses A2, A12 and B12, and tap positions of ULTC by Voltage-based method while a DG of 6MW is installed at Bus A3 and operated at full generation capacity with 0.85 lagging power factor. The voltages along the feeders are increased compared to a condition without DG due to the fact that the DG supplies both kilowatts and kilovars to the system. During the operating period, if the voltage at the secondary bus of substation transformer exceeds the dead-band of the upper limit, the tap position of ULTC will be automatically bucked until the voltage returns to the permissible region.

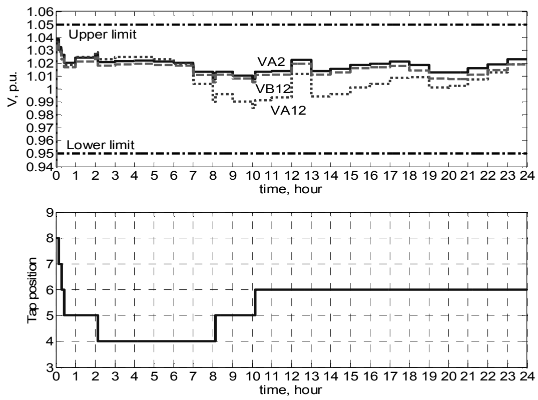

Fig. 7 Voltage profiles for Buses A2, A12 and B12, and tap positions of ULTC by Voltage-based method (DG of 6MW, P.F.=0.85 lagging @ Bus A3)

If a DG of 0.9MW is connected to Bus A12 and operated at full generation capacity with 0.95 leading power factor, the voltage profiles along the feeders will all decrease, as shown in Fig. 8.

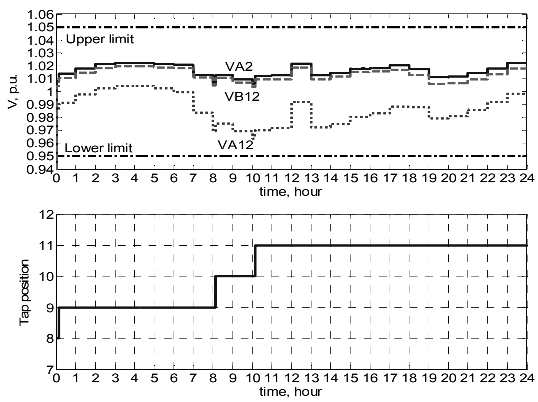

Fig. 8 Voltage profiles for Buses A2, A12 and B12, and tap positions of ULTC by Voltage-based method (DG of 0.9MW, P.F.=0.95 leading @ Bus A12)

The voltage at Bus A2 is decreased under the dead-band of the lower limit due to a DG with leading power factor. Under given conditions, the tap position of ULTC will be boosted to tap position 11. Hence, the sample system does have a risk of under-voltage in some severe operating conditions.

By this method, the effect of DG on the voltage at the point of voltage measured can be taken into account. However, it does not guarantee that the voltages along all feeders in the system are always within the permissible region during the operating period of ULTC. How to locate a suitable measuring point for voltage is an important issue while applying this method.

4.3.3 LDC method

For applying the LDC method both PT and CT are required. The CT is sited at feeder A, the heavy loading feeder with wide voltage spread. If the voltage profiles along feeder A during peak loading can be regulated in the region of desired voltage, the voltage profiles along feeder B shall satisfy the requirements of local rules. The voltages of Buses A2, A12 and B12 can all be regulated in the permissible region by LDC method if there is no DG interconnection. Fig. 9 shows the resultant bus voltage profiles for Buses A7, A2, A12 and B12, and tap positions of ULTC by the LDC method.

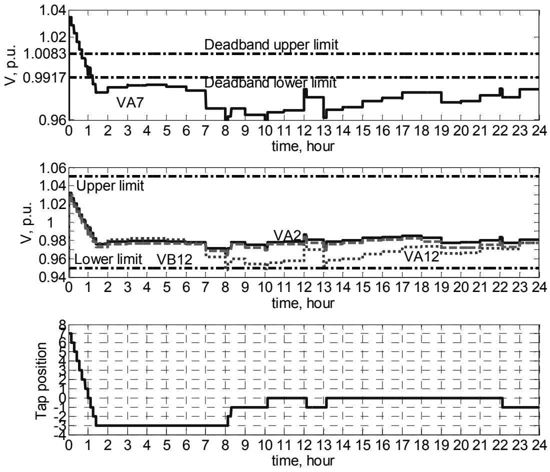

Fig. 9 Voltage profiles of Buses A2, A12, B12 and CVP(A7), and tap positions of ULTC by LDC (DG of 6MW, P.F.=0.85 lagging @ Bus A3)

If a DG of 6MW is installed at Bus A3 and operated at full generation capacity with 0.85 lagging power factor, the measured current of CT will be reduced because the current in the line segment between Buses A2 and A3 is decreased due to the DG supplying kilowatts and kilovars to feeder A at Bus A3. Bus A7 is selected as the CVP (constant voltage point). The LDC will be fooled by the reduced current of Feeder A due to the DG connected at Bus A3. The current flowing through CT may be further reduced or even revised if more power is generated by the DG. The LDC will be fooled and fail to regulate voltage after a DG is installed. That is, the tap position of ULTC will not be regulated correctly.

Fig. 10 illustrates that the voltage of CVP (A7) can not be controlled by LDC method if a DG of 0.9MW with 0.95 leading power factor connected at Bus A12. The tap position of ULTC will be switched from tap 7 to 16, the highest ULTC tap position. An alarm signal will be issued when the tap position of ULTC reaches the limits. In this abnormal circumstance, the settings of LDC have to be modified or switched to manual operation.

In a word, in a distribution system with DG interconnection, CVP voltage may be uncontrollable by LDC because the voltage drop from distribution substation to CVP will be evaluated incorrectly.

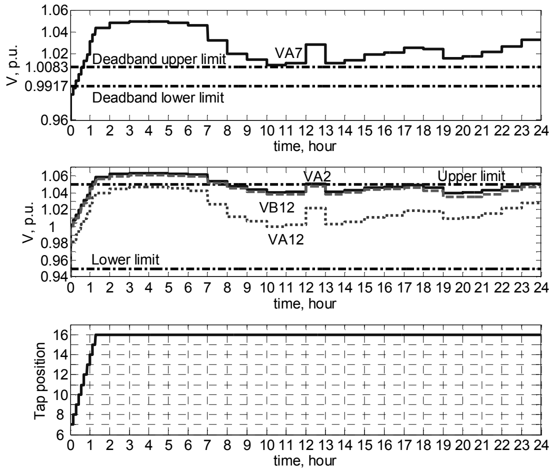

Fig. 10 Voltage profiles of Buses A2, A12, B12 and CVP(A7), and tap positions of ULTC by LDC (DG of 0.9Mw, P.F.=0.95 leading @ Bus A12)

4.3.4 Taipower's RPDC method

In the sample system, two capacitor banks of 3 Mvar each are installed at Bus A2. The switching criteria for the capacitor banks in the sample system are shown in Table 3.

Table 3 switching criteria for capacitor banks

Time / Reactive power	22:00 ~ 06:00	06:00 ~ 08:30	08:30 ~ 11:30	11:30 ~ 12:50	12:50 ~ 17:00	17:00 ~ 22:00
Lagging reactive power (%)	200	70	75	200	200	200
Leading reactive power (%)	300	250	500	100	500	300

Notes: 1. The percentage of reactive power is calculated as a percentage of active power and is switching on or off one bank.
2. The criteria for lagging power factor is switching on a capacitor bank.
3. The criteria for leading power factor is switching off a capacitor bank.

At 6 a.m., the lagging reactive power of Feeder A reaches the setting value (70%) for switching on a capacitor bank. Therefore, the first capacitor bank will be switched on at 6 a.m. That makes the voltage of Bus A2 exceed the allowable upper limit of service voltage. In this circumstance, the tap position of the ULTC transformer will be bucked to reduce the voltage at Bus A2 based on the measured voltage from PT. The feeder load is continually increasing during the 6 a.m. to 11a.m. time slot. At 8 a.m., the lagging reactive power reached another setting value (140%) for switching on the other bank. Therefore, the second bank was switched on. The voltage at Bus A2 will be monitored and regulated continually. Basically, the bus voltages for Bus A2, A12 and B12 can be regulated in the region of desired voltage under normal operating condition if there is no DG interconnection.

Fig. 11 presents the resultant bus voltage profiles for Buses A2, A12 and B12, and tap positions of ULTC by Taipower's RPDC method while a DG of 6MW is installed at Bus A3 and operated at full generation capacity with 0.85 lagging power factor.

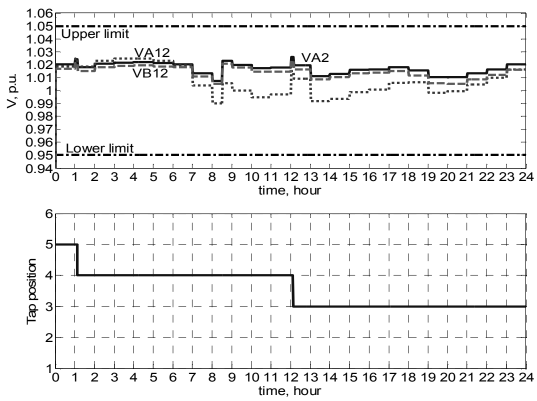

Fig. 11 Voltage profiles of Buses A2, A12 and B12, and tap positions of ULTC by Taipower's RPDC method (DG of 6MW, P.F.=0.85 lagging @ Bus A3)

According to the criteria shown in Table 3, the first switched capacitor bank is switched on at 8:30 a.m. The bus voltages in this system are all regulated within the region of desired voltage under the given conditions of the sample system and operating condition of DG. The DG of 0.9MW with 0.95 leading power factor will take reactive power from the system. In this situation, the first switched capacitor bank will be switched on at 0 a.m., and the second bank will be switched on at 6 a.m. Although the voltage profiles shown in Fig. 12 look quite good they do not guarantee that the voltages along the feeders, especially at the ends of feeders are always within the permissible region by the RPDC method, similar to that of the Voltage-base method.

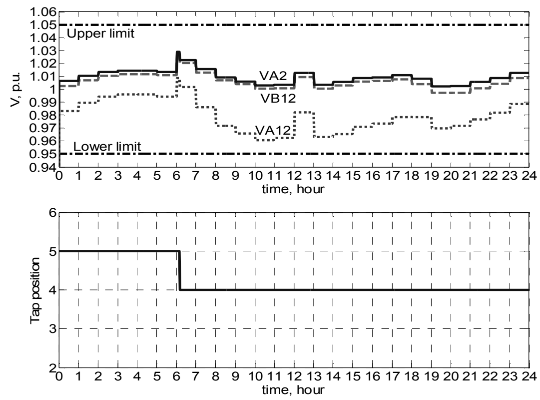

Fig. 12 Voltage profiles of Buses A2, A12 and B12, and tap positions of ULTC by Taipower's RPDC method (DG of 0.9MW, P.F.=0.95 leading @ Bus A12)

5 Conclusion

The simulation results of the sample system have shown that DG interconnection does affect the validity of voltage regulation by all four methods discussed in this paper, especially the Look-up table and LDC methods. All four methods for voltage regulation need to be modified after DG connection. However, it still does not guarantee that the voltages along the feeders, especially at the ends of feeders are always within the permissible region after modification. As a consequence, a novel method needs to be developed to coordinate the distributed generator output and ULTC transformer tap controls to avoid voltage regulation problems.

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