Conservation voltage regulation (CVR) applied to energy savings by voltage-adjusting equipment through AMI

B-R Lan[1], C-A Chang[2,3,4], P-Y Huang[3], C-H Kuo[3], Z-J Ye[3], B-C Shen[3] and B-K Chen[3]

[1]Industrial Technology Research Institute, Hsinchu, Taiwan
[2]Department of Electrical Engineering, Tatung University, Taipei, Taiwan
[3]Institute of Nuclear Energy Research, Taoyuan City, Taiwan

E-mail: d10302001@ms.ttu.edu.tw

Abstract. Conservation voltage reduction (CVR) includes peak demand reduction, energy conservation, carbon emission reduction, and electricity bill reduction. This paper analyzes the energy-reduction of Siwei Feeders with applying CVR, which are situated in Penghu region and equipped with smart meters. Furthermore, the applicable voltage reduction range for the feeders will be explored. This study will also investigate how the CVR effect and energy conservation are improved with the voltage control devices integrated. The results of this study can serve as a reference for the Taiwan Power Company to promote and implement voltage reduction and energy conservation techniques. This study is expected to enhance the energy-reduction performance of the Penghu Low Carbon Island Project.

1. Introduction

Conservation voltage reduction (CVR) is energy-saving measure that, in accordance with the voltage regulated standards at the users' end (e.g. ANSI C84.1 for the United States of America; article 36 of the Electricity Act of Taiwan) and by lowering the operating voltage of distribution feeder, allows reduction of the system's demand for electricity [1,2]. This approach is known to have the following advantages: to hinder the peak load; to reduce electrical energy loss; to defer investment on new equipment, and to lower operating cost of electrical power generation, and eventually to save energy and reduce carbon emission.

Power companies can reduce the electricity demand through the application of CVR. However, voltage drop occurs during the power transmission process, as shown in figure 1. To avert overly low of voltage at the feeder's end, the power company must boost the voltage at the feeder's end as shown in figure 2. If the operator may lower the voltage at the end of the feeder, along with voltage-adjusting equipment located at the middle and downstream of the feeder, then it will allow the voltage at the users' end to fall within a reasonable range, and this will expand the scope for managing the voltage.

Some studies also point out that the application of CVR does appear effective in terms of energy savings. Table 1 compiles results of tests run by power companies from different geographical zones, on applications of CVR on residential and commercial electrical loads: This study have observed from these test results that every 1% of reduction in voltage, it will also reduce the demand of power consumption by 0.8 to 1.38% [3]. This study can therefore determine that CVR does enhance energy-saving effectiveness; however, the aforementioned studies and documents did not discuss the impact of CVR on either loss from transmission line or transformer.

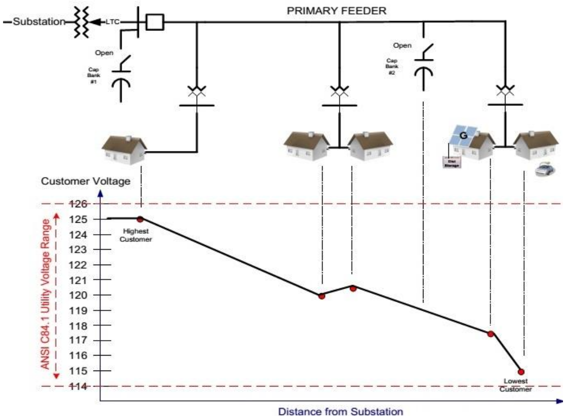

Figure 1. Feeder voltage drop without voltage-adjusting equipment.

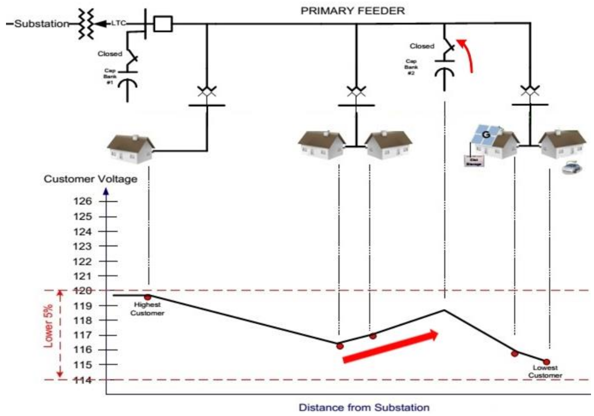

Figure 2. Feeder voltage drop with voltage-adjusting equipment.

Table 1. Test Results of CVR in the US.

Utility	Percent Demand Reduction for 1% Voltage Reduction	
	Residential	**Commercial**
American Electric Power 1	0.80 %	0.78 %
American Electric Power 2	0.90 %	0.86 %
Consumers Power Company	0.83 %	1.38 %
San Diego Gas & Electric Co.	1.14 %	0.08 %

In 2013, Bureau of Energy, Ministry of Economic Affairs of Taiwan began to promote and implement the “Penghu Smart Grid Demo Site” project, with the Siwei Feeder as one of the automated feeders of the project. In line with of the development of “Low-Carbon Island Project”, the authority aims to install smart meters and build Smart Homes within the zones covered by the Siwei Feeder; the infrastructure will work together with Distribution Management System (DMS), Meter Data Management System (MDMS), and Demand Response Management System (DRMS), etc. [4]. The monitoring, management and control functions over grid catered by the smart grid do not only provide real-time data on power consumption, support demand response, accelerate detection and repair of failures [5], but also help power companies to carry out CVR in a more effective manner in order to achieve a better energy savings.

This study has chosen the Siwei Feeder for a simulation of CVR in order to analyze the losses of transmission lines and distribution transformers at different levels of voltage reduction, then further studies the changes on energy-saving performance after adding up voltage-adjusting equipment. Through the application of CVR, this study will enhance the outcome in terms of energy savings and carbon emission reduction of the Low-Carbon Island Project and the installation of smart grid, and eventually promote the power company’s performance.

2. CVR in combination with smart grid and voltage-adjusting equipment

Before implementation of CVR, the power company needs to understand the voltage allocation on the feeders in order to assure that the voltage at the users’ end complies to the voltage regulated standards. Generally, there are two ways to find out the voltage of the electrical power distribution system: the first is to measure the voltage at the feeder’s end with a meter, and send the data back to the power company with communication systems. The second way is to measure the voltage and current output at the substation, then in collocation with the circuit model to come up with the estimation of voltage at every end of the feeder. However, neither of the above methods allows power companies to gain a precise and accurate observation of the voltage at the users’ end of the feeder, thus in order to prevent adverse effects on electrical devices’ lifecycle and efficiency brought by overly low voltage. Thus, power companies are often reluctant to carry out measures of significant voltage reduction, resulting in limited energy-saving performance of CVR [6].

With the Advanced Metering Infrastructure (AMI) of smart grid and the Distribution Automation System (shown in figure 3), one may measure and collect voltages at users' ends along the feeder with the AMI system, then transfer the data collected back to the internal data base of the power company. When the voltage at user's end disrespects the voltage-regulated standards, the user's meter will send an alarm message. Then the Distribution Management System (DMS) will analyze the collected data for decision-making purpose, and send the commands to the voltage-adjusting equipment of the power distribution system, allowing the company to monitor and control simultaneously the voltage at the users' end, and increase the voltage when it is too low [4]. In this case, the power company, in compliance with the voltage-regulated standards at the users' end, reduces the system voltage as much as possible to maximize the energy-saving performance. The integrated volt/var control for CVR should rely on the distribution system state estimation to provide the on-line model for effective VCR control and monitoring. And the utility should consider the feeder load variations would lead to uncertain effects on CVR controls.

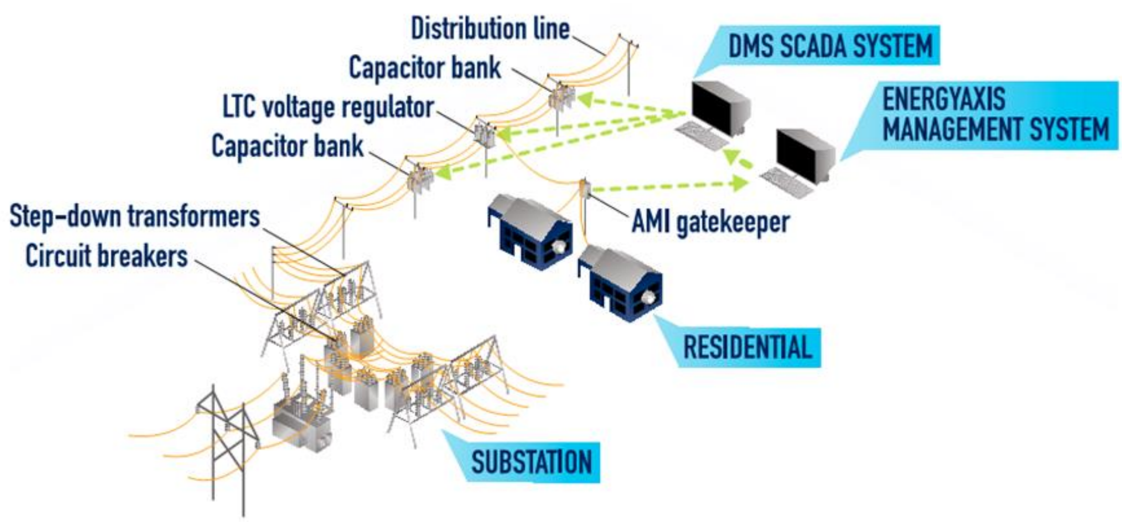

Figure 3. CVR with smart grid and voltage-adjusting equipment.

3. Presentation of simulation system

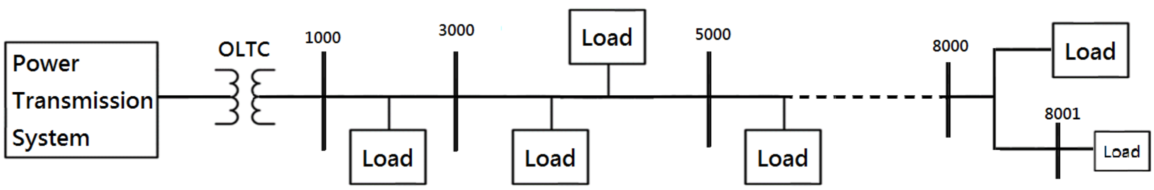

Figure 4. Siwei feeder of Penghu.

This study has chosen the Siwei Feeder as sample system, with the estimated peak and off-peak loads on 2018 as base for further analysis. Figure 4 shows the single-line diagram of Siwei Feeder, alimented by Penghu Magong S/S, it is an underground electrical power distribution system of 11.4 kV. In order to study the impact of CVR on transformer loss, this study adopted the data and typical characteristics collected from the handbook, "Underground Distribution System of Taiwan Power Company" to calculate the series reactance via equation (1) [7]. This study then came up with impedance parameters of transformers with different capacities (table 2), and entered the data into the transformer model (figure 5).

Equation of voltage regulation rate is expressed as follows:

$$VR\%(pf) \approx Rs\%\cos\theta + Xs\%\sin\theta \quad (1)$$

Table 2. Taipower-impedance data of typical transformers used in underground distribution system.

Transformer Capacity (kVA)	Resistance in Series (%)	Reactance in Series (%)	Core Loss (W)	Exciting Current (%)
25	1.03	2.29	65	0.75
50	0.93	2.52	110	0.68
100	0.78	3.03	170	0.64
167	0.75	3.17	153	0.60

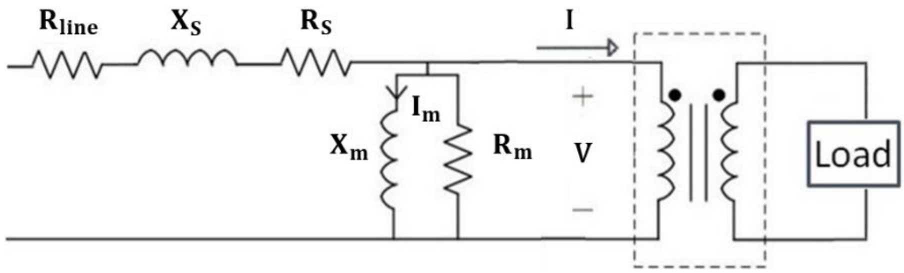

Figure 5. Transformer model.

In terms of the power load model, given the fact that there are mostly residential and commercial users in Penghu, this study has consulted the ZIP model for typical residential and commercial loads from the analysis report of power load models by General Electric (USA). This study selected load model data of ZIP which can present performances of Penghu's load, and the load characteristic varies with the voltage are shown as equations (2) and (3) [8,9].

$$P = P_0\left[0.1934\left(\frac{V_i}{V_0}\right)^2 + 0.6897\frac{V_i}{V_0} + 0.1169\right] \quad (2)$$

$$Q = Q_0\left[3.3383\left(\frac{V_i}{V_0}\right)^2 - 3.1939\frac{V_i}{V_0} + 0.8556\right] \quad (3)$$

where P, Q: Demand for active and reactive power at operation voltage, V_i and P_0, Q_0: Demand for active and reactive power at nominal voltage, V_0.

4. Case study-energy saving performance and permissible range for voltage reduction

First, this study established a simulation system of the Siwei Feeder to analyze the power demands of each component of the feeder under different operating voltages, including the load power, the line loss, the core and copper loss of transformers, with data of minimum load voltage recorded and analysis results shown in table 3.

The results from table 3 indicate that, when the measure of CVR is taken at the Siwei Feeder, the peak load is higher than off-peak and makes the lowest voltage of peak load pattern less than off-peak pattern's; thus the power demand decreases along with the lowered voltage (equation (2)) while system loss also decreases. Hence, the measure of CVR may reduce power load and system loss, and enhance the energy savings.

Table 3. Siwei Feeder-power demands, load power, losses, and minimum load voltage at different operating voltage.

Load	**Annual peak**					**Annual off-peak**				
Voltage at Feeder's Sending End (p.u.)	**0.96**	**0.97**	**0.98**	**0.99**	**1**	**0.96**	**0.97**	**0.98**	**0.99**	**1**
Total Demand of Feeder (kW)	3771	3813	3855	3897	3939	1113	1125	1138	1150	1163
Load Power (kW)	3721	3762	3804	3845	3887	1095	1107	1119	1132	1144
System Loss (kW)	**50.35**	**50.78**	**51.22**	**51.67**	**52.13**	**17.86**	**18.17**	**18.51**	**18.85**	**19.18**
Line Loss (kW)	21.69	21.77	21.85	21.94	22.02	1.97	1.98	1.99	2.01	2.02
Copper Loss (kW)	14.34	14.39	14.44	14.5	14.56	1.32	1.32	1.33	1.34	1.35
Core Loss (kW)	14.32	14.62	14.93	15.23	15.55	14.57	14.87	15.19	15.5	15.81
Minimum Voltage of feeder (p.u.)	**0.936**	**0.946**	**0.956**	**0.966**	**0.975**	**0.952**	**0.962**	**0.972**	**0.982**	**0.992**

The application of CVR must assure that the voltage at users' end complies to "article 36 of Taiwan's Electricity Act: the voltage regulation factor of electrical power supply shall not exceed 5%." Examining the off-peak data in table 3, if the operating voltage is reduced by 4%, the minimum voltage of the feeder will be higher than 0.95 p.u. However, if the operating voltage is reduced by 3% during peak hours, the minimum load voltage of the feeder will become less than 0.95 p.u., which does not respect the voltage-regulated standards. Without the intervention of voltage-adjusting equipment installed at the middle and down stream of the feeder, the maximum permissible voltage reduction range at the receiving end of the Siwei Feeder will be 2%.

4.1. Impact of CVR on distribution system losses

Distribution losses include line loss, transformer core loss and copper loss. The line loss and transformer copper loss are dependent on the load current, while transformer core loss is dependent on the operating voltage. Table 3 indicates that since the off-peak load current, hence, the line loss and copper loss on the Siwei Feeder are less than during the peak hours; however, given that the voltage of the feeder is higher during this period, the core loss will be higher than the peak hours. If the data of the losses are further analyzed, core loss is the most recognizable among the losses generated by CVR, which as shown in figures 6 and 7, is visibly better than line and copper loss. Therefore, an effective reduction in transformer core loss will enhance a better energy-saving performance.

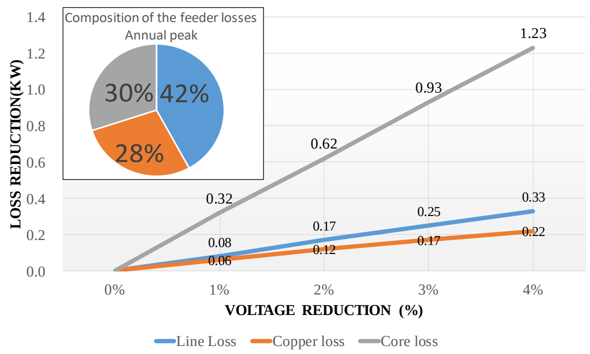

Figure 6. Distribution system losses from CVR – annual peak.

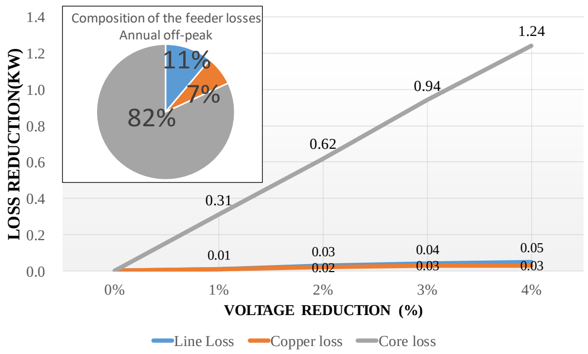

Figure 7. Distribution system losses from CVR – annual off-peak.

4.2. CVR combined with voltage-adjusting equipment

This study brings out measures in order to enhance the energy savings by reducing the operating voltage at the substation, then increase the voltage with control devices (e.g. capacitors or voltage regulator) installed at the middle and lower reaches of the feeder. This allows the voltage at users' end to remain within normal operating range and to increase operating flexibility of CVR. The following sections explain the position of installation of capacitors and voltage regulators and the result analysis.

4.2.1. Capacitor installation. This study consulted the guidelines on capacitor installation described by "Underground Distribution System of Taiwan Power Company" [10] and capacitor standards defined by IEEE (Std. 18) [11], and considered the demand and distribution of system reactive power, then This study decided to install capacitor on Bus #5000 at the Siwei Feeder. Given the fact that TaiPower switch the capacitors off on off-peak, hence this study will not discuss the voltage-regulation performance of capacitors on annual off-peak load. The results of using capacitors to improve the overly low voltage at the Siwei Feeder are shown in table 4.

Table 4. Results of using voltage-adjusting equipment to improve overly low voltage.

Load	Voltage-Adjusting Equipment	Siwei Feeder Operating Voltage 0.97 p.u.
Annual peak	No Device	0.9458 p.u.
	Capacitor	0.9469 p.u.
	Voltage Regulator	0.9504 p.u.
Annual off-peak	No Device	0.9620 p.u.
	Voltage Regulator	0.9620 p.u.

4.2.2. Voltage regulator. This study considered the specification provided by American voltage regulator manufacturers [12] as well as the distribution of overly low voltage throughout the Siwei Feeder, and this study decided to install voltage regulators on the Siwei feeder (as shown in figure 8), with voltage regulators of different phases installed as shown in table 5.

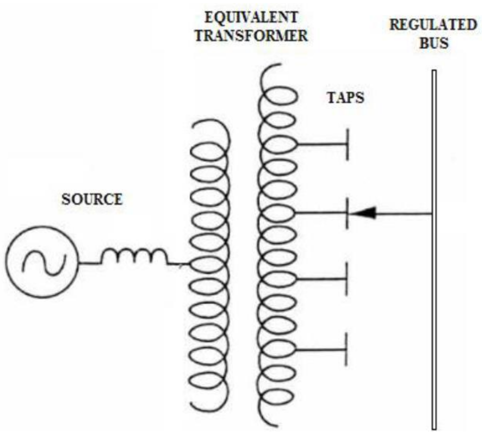

Figure 8. Voltage regulator model.

Table 5. Installation location and installed capacity of voltage regulators on the feeder.

Location	Rated Capacity (KVA)		
	Phase A	Phase B	Phase C
Bus #5000	57	114	57

Table 6 reveals that when the CVR of the Siwei Feeder is done by 3%, it has the terminal voltage without voltage regulators. During off-peak periods, the system does not manifest overly low voltage and the regulator does not carry out any adjustment. However, during peak periods, the measure of

CVR causes the minimum voltage of the feeder to become too low and violates the voltage regulated standards. With the installation of voltage regulators, the equipment detects when the voltage is too low and adjusts the system's minimum voltage to above 0.95 p.u. Therefore, the increment of CVR at the Siwei Feeder could go up to 3% with the voltage regulators installed.

Table 6. Comparative results of different operation at the Siwei Feeder.

Annual peak	**Voltage at the Sending End**	**Load (kW)**	**Minimum Load Voltage (p.u.)**	**Demand Reduced**
	1.00 p.u.	3939.3	0.9754	—
	0.98 p.u.	3855.0	0.9557	84.3 kW (2.14%)
	0.97 p.u. with voltage regulator	3822.7	0.9504	116.6 kW (2.96%)
Annual off-peak	1.00 p.u.	1163.2	0.9920	—
	0.98 p.u.	1137.9	0.9721	25.3 kW (2.18%)
	0.97 p.u.	1125.3	0.9620	37.9 kW (3.26%)

4.3. Comparison of results in energy savings of different operation

Table 6 concludes load demands, minimum voltage under different operation, and the energy savings during peak and off-peak loads of the Siwei Feeder. Without any voltage-adjusting equipment, the permissible range of voltage reduction at the Siwei Feeder is 2%, and it can hinder the peak demand by 2.14%, and decrease peak load capacity correspondingly by 84.3 kW. If voltage regulators at the Siwei Feeder are installed, the permissible voltage reduction range may increase from 2% to 3%, raising the flexibility of voltage reduction measure to enhance better energy savings. The energy-saving performance will increase from 2.14% to 2.96% during peak periods, with peak load reduced from 84.3 kW to 116.6 kW.

This study took the data collected during peak and off-peak loads to evaluate the operating benefits generated by the reduced power consumption derived from CVR. For power companies, the operating deficits reduced from CVR represents the "difference between the fuel cost and the electricity selling price". Hence this study uses the USD: TWD exchange rate in 2017 and the difference between the cost of power generation in Penghu (Cplant, 0.197 USD/kWh) and the selling price of TaiPower (Pselling, 0.098 USD/kWh), as the operating deficit per power consumption unit. The following is the method of the analysis.

Based on the daily power consumption of peak and off-peak days, and proportion of energy savings as shown in "Demand Reduced" of table 6, this study estimated the power consumption that could be reduced on peak and off-peak days. Then, this study used equation (4) to estimate the annual reduced deficit. The results of energy-saving evaluations carried through the aforementioned methods in table 7. If voltage regulators are installed at the Siwei Feeder to reduce the operating voltage by 3%, the energy savings will become more since power company can reduce the annual power consumption of 702,427 kWh, and the corresponding operating deficit is 69,479 USD.

$$\text{Annual reduced deficit } = 8760 \times 0.5 \times \sum_{i=peak,off-peak}(p_i \times \eta_i) \times \left(P_{selling} - C_{plant}\right) \quad (4)$$

Table 7. Operating benefits and power consumption reduced by CVR at the Siwei feeder.

Voltage Reduction	**Load Pattern**	**Daily Power Consumption (p_i)**	**Energy Saving Proportion (η_i)**	**Annually Reduced Consumption**	**Annually Reduced Deficit**
2%	Peak	77,904 kWh	2.1%	482,502 kWh	47,725 USD
	Off-Peak	45,812 kWh	2.2%		
3% with Voltage Regulators	Peak	77,904 kWh	3.0%	702,427 kWh	69,479 USD
	Off-Peak	45,812 kWh	3.3%		

5. Conclusion

CVR is an energy-saving measure through reducing the operating voltage of the feeder, in compliance with the voltage regulated standards, to reduce the system demand. This study adopted sample system with smart meters installed along the Siwei Feeder in Penghu to analyze the impact of CVR. The analysis result indicates that under CVR, there will also be less copper, core, and line losses. Moreover, along with the increment in voltage reduction, the core loss reduction becomes more visible. This study suggested that the utility should use high-efficiency transformers, which have lower transformer losses. Lowering the energy consumption would result in reduced operating costs and less harmful emissions for utility operation. Installation of voltage-adjusting equipment at appropriate locations of the feeder will increase larger range of voltage reduction and enhance better energy savings, and eventually reduce more operating deficits.

Via CVR, lower the load demand is carries out and the power company also can reduce power supply which implies to lower Penghu's operating deficits generated from the relatively high costs of fuel cost. This study reveals that the application of CVR can effectively save energy, and reduce overall system losses so that the power company will not have to make extra investments to upgrade its distribution system to bring up power transmission efficiency, and eventually increase operating performance. In the future, the application of smart grid combined with voltage-adjusting equipment will help power companies to increase the range of voltage reduction.

References

[1] Schneider K P, Tuffner F K, Fuller J C and Singh R 2010 Evaluation of conservation voltage reduction (CVR) on a national level Pacific Northwest National Laboratory
[2] Electricity Delivery & Energy Reliability 2012 Application of automated controls for voltage and reactive power management initial results Department of Energy
[3] Taylor C W 1994 *Power System Voltage Stability* (New York: McGraw Hill)
[4] Sierra Energy Group 2010 AMI and DA convergence: Enabling energy savings through voltage conservation
[5] McLean M 2012 Three DA initiatives that leverage AMI investment Silver Spring Networks
[6] Ellens W, Berry A and West S 2012 A quantification of the energy savings by conservation voltage reduction 2012 IEEE International Conference on Power System Technology (POWERCON) (Auckland) pp 1-6
[7] Underground Distribution System of Taiwan Power Company lesson 4, Taiwan Power Company
[8] Price W W, *et al* 1988 Load modeling for power flow and transient stability computer studies IEEE Trans. on Power Systems **3** 180-7
[9] Zhi Z D 1994 Transient stability studies of the Jen-wuco-generation facility (Tatung University)
[10] Underground Distribution System of Taiwan Power Company lesson 4, Taiwan Power Company, September 2009
[11] IEEE Standard for Shunt Power Capacitors, IEEE Standard 18, 2012
[12] Single-phase pad-mounted step voltage regulator, Cooper Power Systems