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Article

Evaluation of the Effects of Nationwide Conservation Voltage Reduction on Peak-Load Shaving Using SOMAS Data

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Abstract: In this paper we propose a new method to evaluate the effects of nationwide conservation voltage reduction (CVR) on peak-load shaving, using substation operating results management system (SOMAS) data. Its evaluation is based on a national CVR factor, which is defined as the weighted average of CVR factors associated with all transformer banks and weighting coefficients are determined by the reconstructed loads corresponding to each transformer bank. To make use of the data resulting from nationwide CVR without installing additional measuring devices, we adopt a linearized static-load model with a linearizing parameter. SOMAS data are used to evaluate the effects of nationwide CVR on peak-load shaving in the Korean power system. Evaluation results show that the national CVR factor of the Korean power system has small values in the summer season and large values in the winter season. This means that the effect of nationwide CVR on peak-load shaving in the Korean power system presents stronger benefits during winter months.

Keywords: linearized static-load model; linearizing parameter; nationwide conservation voltage reduction (CVR); national CVR factor; peak-load shaving; substation operating results management system (SOMAS)

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1. Introduction

Smart grids provide significant opportunities for utilities to control their distribution voltages effectively. With the additions of communication and smart controllers to voltage regulators and transformer load tap changers, utilities could take finer control of distribution voltage levels [1–3]. Particularly, conservation voltage reduction (CVR) could be an easy win for smart grids [4–6]. CVR is a well-known technique of controlling distribution voltage levels to reduce energy consumption [7,8]. It is widely used for two main reasons: peak-load shaving and reducing the total annual energy consumption. CVR is also directly linked to a reduction in carbon emissions. Moreover, with reduced voltages, transformer life is extended because iron losses are a function of operating voltage levels [9]. Especially during periods of peak demand, when there is a significant amount of stress on the transformer, and CVR may be a way to reduce this stress and potentially help prevent outages. The first wide-scale implementation of CVR ocurred during the oil embargo in 1973, when the Public Service Commission of New York ordered its utilities to implement a voltage reduction of 3.0%–5.0% in order to reduce annual energy consumption [7]. Since then, many electric utilities have tried to implement CVR in their power systems using different strategies [10–17]. In particular, CVR is a practice employed by modern electric utilities as an emergency measure for peak-load shaving with a voltage reduction in the range of 2.0%–5.0% [18–20]. For example, Korea Electric Power Corporation (KEPCO) has implemented CVR with two-step voltage reductions of 2.5% and 5.0% to reduce peak load in the short term. One key characteristic that determines the effects of CVR is the nature of the load [14]. Its effect differs from utility to utility and circuit to circuit because load characteristics vary.

Owing to the complexities and uncertainties of power systems [21], decision makers and planners are facing increased pressure to respond more effectively to a number of the associated issues and conflicts. In particular, the effects of nationwide CVR, *i.e.*, CVR implemented at a national level, should be evaluated in advance to aid power-system operators in making proper emergency plans related to peak-load shaving. Since the first wide-scale implementation of CVR in 1973, considerable research has been done evaluating the effects of CVR implemented at regional levels [10–17,22–29]. However, there have been relatively few reports of evaluations of the effects of CVR at a national level [30,31]. In contrast to other methods, our method allows evaluation of the effects of nationwide CVR without installing additional measuring devices. In this paper, substation operating results management system (SOMAS) were used to evaluate the effects of nationwide CVR; however energy management system (EMS) data can also be used following suitable processing.

The purpose of this paper is to propose a new method for evaluating the effects of nationwide CVR on peak-load shaving using SOMAS data. The paper is divided into four sections, including the Introduction. Section 2 describes a linearized static-load model with a linearizing parameter and proposes the definition of a national CVR factor as a metric for evaluating the effects of nationwide CVR. In Section 3, the national CVR factors for the Korean power system are estimated from nationwide CVR implemented in different seasons. Our conclusions are given in Section 4.

2. National CVR Factor

2.1. Linearized Load Modeling Based on SOMAS Data Resulting from Nationwide CVR

In the Korean power system, there are two readily available sources of data that do not require the installation of additional measuring devices: EMS data and SOMAS data. The Korean EMS records its data every 4 s from all substations across the country. Due to its complex data structure and some data errors caused by its fast communication requirements, it is difficult to use EMS data for providing accurate load modeling at a national level. In the case of SOMAS, data are sent every 2 min from every transformer bank across the country and are used to analyze load status. This analysis allows KEPCO to monitor power usage and take any necessary preemptive action to avoid outages. Because SOMAS collects 2-minute averaged data, it is not appropriate to use SOMAS data for estimating the parameters of dynamic-load modeling. Dynamic-load modeling can accurately reflect the load characteristics; however, it requires high time-resolution data. On the other hand, the parameters of static-load modeling can be estimated using SOMAS data because relatively low time-resolution data are sufficient for static-load modeling [32–34]. In particular, ZIP (constant impedance, current, and power) load modeling has a simple structure, and its parameters can be derived from just a few data samples. Moreover, because ZIP load modeling can represent the physical meaning of loads and it is used by many electrical companies including KEPCO to manage their power systems, it is one of the most appropriate modeling techniques for estimating parameters based on SOMAS data.

Assuming that the total number of operating transformer banks is N_T and n denotes the discrete-time index of SOMAS data, a ZIP model of the load measured at the k^{th} transformer bank is given by:

$$P_{M_k}(n) = P_{R_k}(n) \cdot \{p_{Z_k} \cdot V_{B_k}^2(n) + p_{I_k} \cdot V_{B_k}(n) + p_{P_k}\} \tag{1}$$

where:

$p_{Z_k} + p_{I_k} + p_{P_k} = 1$;

n_{I_k} : Inception time when a voltage reduction is implemented at the k^{th} transformer bank;

$P_{M_k}(n)$: Measured load including the effect of the voltage reduction;

$P_{R_k}(n)$: Reconstructed load after removing the effect of the voltage reduction;

$V_{M_k}(n)$: Bank voltage measured at the k^{th} transformer bank;

$V_{S_k} = V_{M_k}(n_{I_k} - 1)$: Steady-state bank voltage just before the inception time;

$V_{B_k}(n) = \dfrac{V_{M_k}(n)}{V_{S_k}}$: Normalized bank voltage based on V_{S_k};

p_{Z_k} : Constant-impedance fraction of the reconstructed load;

p_{I_k} : Constant-current fraction of the reconstructed load;

p_{P_k} : Constant-power fraction of the reconstructed load.

Although the ZIP load model is one of the most appropriate non-linear load models due to its simple structure and practicality, it cannot be used with SOMAS data resulting from nationwide CVR. Given that nationwide CVR is usually in the range 2.0%–5.0%, it is difficult to accurately determine ZIP parameters using SOMAS data obtained from nationwide CVR [34]. Therefore, instead of the ZIP load model, this paper uses a linearized load model, which was proposed in [34] and is described briefly below.

If $\Delta V_{B_k}(n)$ denotes the voltage variation due to nationwide CVR, Equation (1) can be modified to:

$$P_{M_k}(n) = P_{R_k}(n) \cdot \{p_{Z_k} \cdot (1+\Delta V_{B_k}(n))^2 + p_{I_k} \cdot (1+\Delta V_{B_k}(n)) + p_{P_k}\} \tag{2}$$

where $\Delta V_{B_k}(n) = \dfrac{\Delta V_{S_k}(n)}{V_{S_k}} = \dfrac{V_{M_k}(n) - V_{S_k}}{V_{S_k}}$.

This can be rearranged as follows:

$$\begin{aligned} P_{M_k}(n) &= P_{R_k}(n) \cdot \{p_{Z_k} \cdot (1 + 2\Delta V_{B_k}(n) + \Delta V_{B_k}^2(n)) + p_{I_k} \cdot (1+\Delta V_{B_k}(n)) + p_{P_k}\} \\ &= P_{R_k}(n) \cdot \{(p_{Z_k} + p_{I_k} + p_{P_k}) + (2p_{Z_k} + p_{I_k}) \cdot \Delta V_{B_k}(n) + p_{Z_k} \cdot \Delta V_{B_k}^2(n)\} \\ &= P_{R_k}(n) \cdot \{1 + (2p_{Z_k} + p_{I_k}) \cdot \Delta V_{B_k}(n) + p_{Z_k} \cdot \Delta V_{B_k}^2(n)\} \end{aligned} \tag{3}$$

Assuming that the voltage variation is small compared with the nominal voltage, Equation (3) can be simplified to the basic form of the linearized load model with a linearizing parameter p_{C_k}:

$$P_{M_k}(n) \cong P_{R_k}(n) \cdot \{1 + (2p_{Z_k} + p_{I_k}) \cdot \Delta V_{B_k}(n)\} = P_{R_k}(n) \cdot \{1 + p_{C_k} \cdot \Delta V_{B_k}(n)\} \tag{4}$$

Given that the values of $P_{M_k}(n)$ and $\Delta V_{B_k}(n)$ are obtained from SOMAS data, $P_{R_k}(n)$ is required to estimate the linearizing parameter. In this paper, $P_{R_k}(n)$ is assumed to be in the form of a quadratic polynomial. This assumption is possible because nationwide CVR is usually implemented near peak-load time, and its time period is short enough to consider the load profile as a quadratic polynomial curve. Therefore, the reconstructed load can be expressed with polynomial coefficient a_{m_k}:

$$P_{R_k}(n) \cong a_{2_k} \cdot n^2 + a_{1k} \cdot n + a_{0_k} \tag{5}$$

Finally, to estimate the linearizing parameter and polynomial coefficients, an objective function is defined as:

$$\min \quad \sum_n [(a_{2_k} \cdot n^2 + a_{1_k} \cdot n + a_{0_k})\{1 + p_{C_k} \cdot \Delta V_{B_k}(n)\} - P_{M_k}(n)]^2 \tag{6}$$

subject to $0 \le p_{C_k} \le 2$.

2.2. Estimation of a National CVR Factor

The CVR factor, which is defined as the ratio of the normalized load reduction to the normalized voltage reduction, is the metric most often used to estimate the effectiveness of CVR as a peak-load shaving or energy-saving measure. To estimate the CVR factor of the k^{th} transformer bank, its normalized load reduction is expressed as:

$$\Delta P_{B_k}(n) = \frac{\Delta P_{R_k}(n)}{P_{R_k}(n)} = \frac{P_{M_k}(n) - P_{R_k}(n)}{P_{R_k}(n)} \tag{7}$$

The reconstructed load in Equation (7) can then be obtained from Equation (4) with the linearizing parameter that minimizes the objective function of Equation (6):

$$P_{R_k}(n) = \frac{P_{M_k}(n)}{1 + p_{C_k} \cdot \Delta V_{B_k}(n)} \tag{8}$$

Substitution of Equation (8) into Equation (7) yields:

$$\Delta P_{B_k}(n) = p_{C_k} \cdot \Delta V_{B_k}(n) \tag{9}$$

Therefore, the CVR factor of the k^{th} transformer bank is given by:

$$CVRF_{B_k} = \frac{\Delta P_{B_k}(n)}{\Delta V_{B_k}(n)} = p_{C_k} \tag{10}$$

In this paper, a national CVR factor is defined as the weighted average of CVR factors of all transformer banks considered:

$$CVRF_N = \sum_{k=1}^{N_C} \{\frac{P_{R_k}(n_F)}{P_N(n_F)} \times CVRF_{B_k}\} = \sum_{k=1}^{N_C} \{w_k \times CVRF_{B_k}\} \tag{11}$$

where $P_N(n) = \sum_{l=1}^{N_C} P_{R_l}(n)$: National load corresponding to the sum of transformer-bank loads.

In Equation (11), N_C represents the number of transformer banks considered and n_F indicates the time when the effect of nationwide CVR on peak-load shaving is maximized during the period of its first-step voltage reduction. As shown in Equation (11), the weighting coefficient w_k is based on the reconstructed load of the corresponding transformer bank. Substitution of Equation (10) into Equation (11) yields:

$$CVRF_N = \sum_{k=1}^{N_C} \{w_k \times p_{C_k}\} = \sum_{k=1}^{N_C} \{w_k \times (2 \cdot p_{Z_k} + p_{I_k})\} \tag{12}$$

This can be rearranged as follows:

$$CVRF_N = 2 \cdot \sum_{k=1}^{N_C} \{w_k \times p_{Z_k}\} + \sum_{k=1}^{N_C} \{w_k \times p_{Z_k}\} = 2 \cdot p_{Z_N} + p_{I_N} = p_{C_N} \tag{13}$$

where p_{Z_N} and p_{I_N} represent the constant-impedance fraction and the constant-current fraction of the national load, respectively, and p_{C_N} becomes the linearizing parameter of the national load.

3. Evaluating the Effects of Nationwide CVR on Peak-Load Shaving

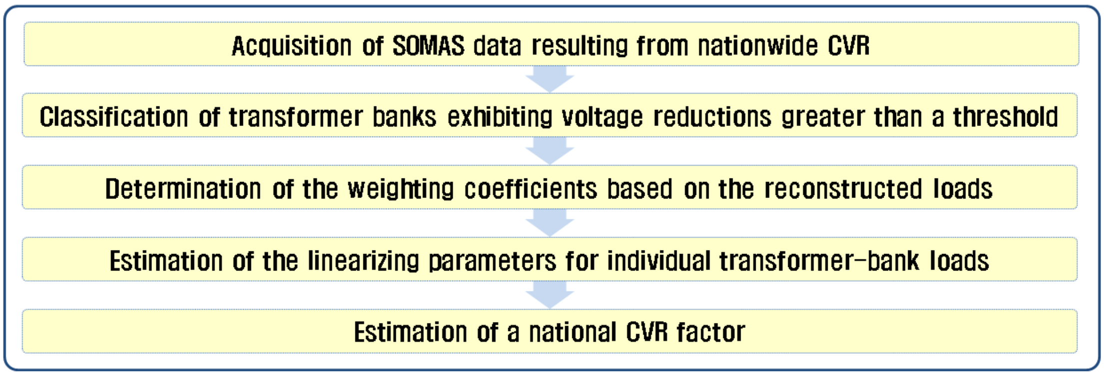
Bank voltages are controlled to maintain a minimum voltage to customers at the ends of distribution lines. Due to this operational constraint, the voltage reduction of some transformer banks was too small to be detected as a result of nationwide CVR. In this paper, only the transformer banks exhibiting voltage reductions greater than a threshold were considered when evaluating the effects of nationwide CVR. In addition, the inception time is defined as the time when the voltage variation becomes greater than the threshold, which was set to 0.8% based on the analysis of SOMAS data resulting from nationwide CVR. Figure 1 shows a flowchart for evaluating the effects of nationwide CVR.

3.1. Estimation of Linearizing Parameters for Transformer-Bank Loads in the Korean Power System

SOMAS data were used to estimate the linearizing parameters for the transformer-bank loads found in the Korean power system. On 9 August 2012, nationwide CVR was implemented in the Korean power system with the aim of performing peak-load shaving. It was reported that KEPCO ordered a

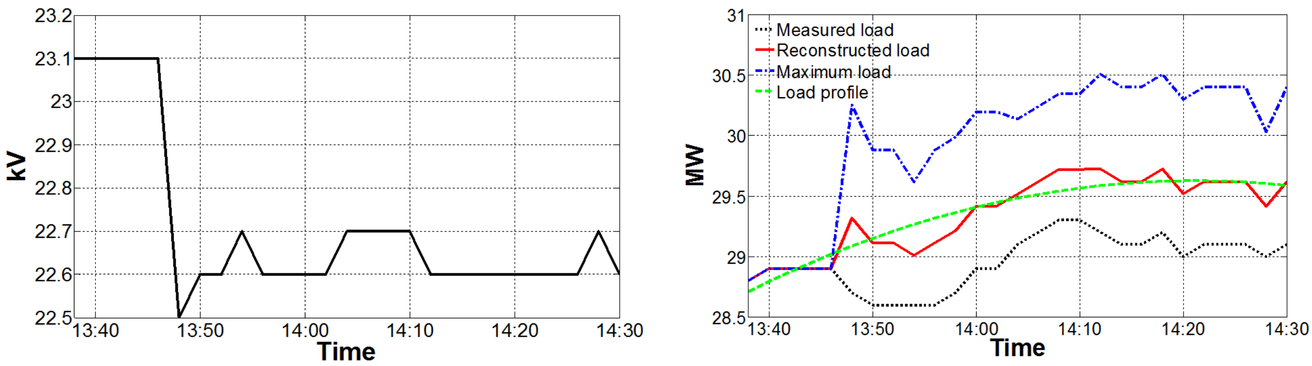
2.5% voltage reduction to all substation operators at 14:43, with the total number of operating transformer banks set at 2093.

Figure 1. Flowchart for evaluating the effects of nationwide CVR.



In the case of the 108th transformer bank, the inception time was 13:46 and its actual voltage reduction was about 2.17%, dropping from 23.1 kV to 22.6 kV, as shown in Figure 2a. In this case, the objective function of (6) reaches its minimum value when $p_{C_{108}} = 0.82$, $a_{2_{108}} = -0.00049$, $a_{1_{108}} = 0.04244$, and $a_{0_{108}} = 28.7105$. Therefore, the CVR factor of the 108th transformer bank becomes 0.82, equal to the linearizing parameter [see Equation (10)]. In Figure 2b, the red solid line indicates the reconstructed load after removing the effect of the voltage reduction and the green dashed line indicates the load profile in the form of a quadratic polynomial curve. It can be seen that the reconstructed load exhibits a similar trend to the load profile.

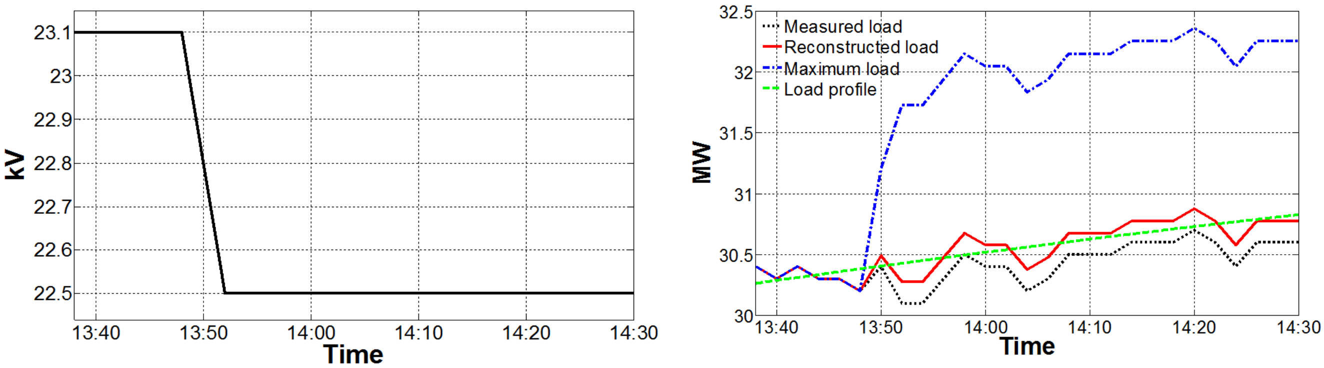
Figure 2. Results of the nationwide CVR implemented at the 108th transformer bank on 9 August 2012: (**a**) measured bank voltage; and (**b**) transformer-bank load.



(**a**) (**b**)

In the case of the 480th transformer bank, the inception time was 13:48 and its actual voltage reduction was about 2.59%, declining from 23.1 kV to 22.5 kV, as shown in Figure 3a. In this case, the objective function of Equation (6) reaches its minimum value when $p_{C480} = 0.22$, $a_{2_{480}} = -0.00002$, $a_{1_{480}} = 0.01208$, and $a_{0_{480}} = 30.2622$.

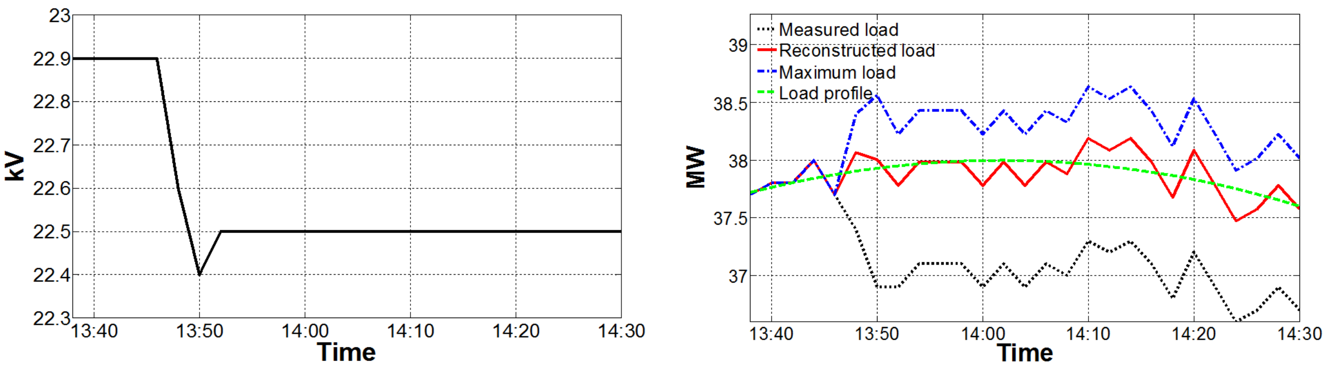
Figure 3. Results of the nationwide CVR implemented at the 480th transformer bank on 9 August 2012: (**a**) measured bank voltage; and (**b**) transformer-bank load.



(**a**) (**b**)

In the case of the 705th transformer bank, the inception time was 13:46 and its actual voltage reduction was about 1.75%, dropping from 22.9 kV to 22.5 kV, as shown in Figure 4a. In this case, the objective function of Equation (6) reaches its minimum value when $p_{C705} = 1.34$, $a_{2_{705}} = -0.00049$, $a_{1_{705}} = 0.02345$, and $a_{0_{705}} = 37.7200$.

Figure 4. Results of the nationwide CVR implemented at the 705th transformer bank on 9 August 2012: (**a**) measured bank voltage; and (**b**) transformer-bank load.



(**a**) (**b**)

From the above three results, it can be seen that the linearizing parameters are different according to each transformer bank.

3.2. Evaluation of the Effects of Nationwide CVR in the Korean Power System

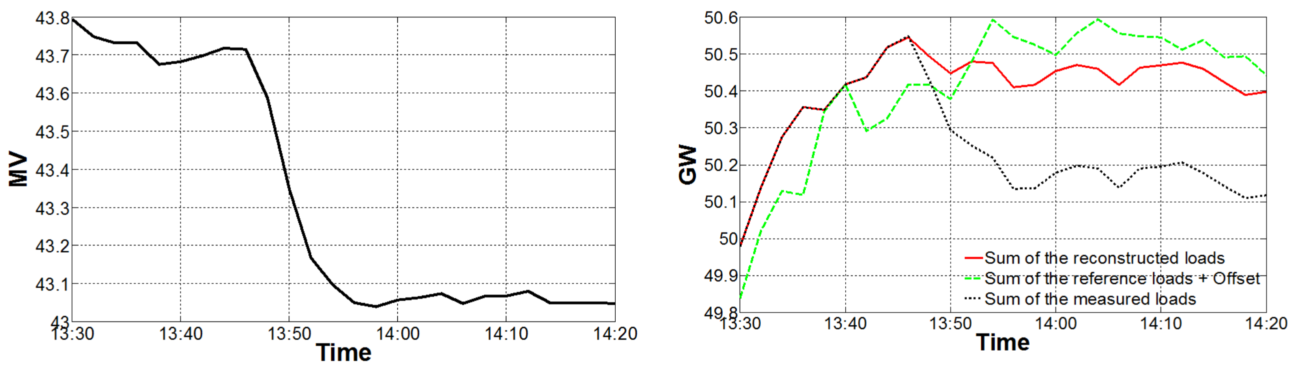
For comparison, this paper used the load data saved on a reference date when neither nationwide CVR nor any abnormal loading event occurred. Additionally, the reference date was chosen to lie near the date when the corresponding nationwide CVR would be implemented.

3.2.1. Case I: Nationwide CVR on 9 August 2012

At 13:43 on 9 August 2012, nationwide CVR was implemented in the Korean power system with the main purpose of peak-load shaving. In this case, voltage reductions greater than 0.8% were detected on 1901 transformer banks from among 2093. The voltage reductions of 1901 transformer banks were also limited due to the operational constraint mentioned before.

As shown in Figure 5a, when the nationwide CVR was implemented with a command of 2.5% voltage reduction, the average voltage reduction at the national level was 1.56%, declining from 43.72 to 43.04 MV. Figure 5b shows that the sum of the reconstructed loads has a similar profile to the sum of reference loads. To compare them more easily, an offset of −1031 MW was added to the sum of reference loads. The reconstructed loads of individual transformer banks were obtained using the linearizing parameters estimated in Section 3.1, and 6 August 2012 was selected as the reference date for the reference loads. Figure 5b also shows that the maximum peak-load shaving appeared at 13:58, with a reduction amount of 280 MW. The difference between the sum of the reconstructed loads and the sum of the measured loads reflects the peak-load shaving results from the voltage reduction.

Figure 5. Results of the nationwide CVR implemented on 9 August 2012: (**a**) sum of 1901 bank voltages; and (**b**) sum of 1901 transformer-bank loads.



(**a**) (**b**)

Following this first evaluation, it was found that the national CVR factor was 36.20% on 9 August 2012.

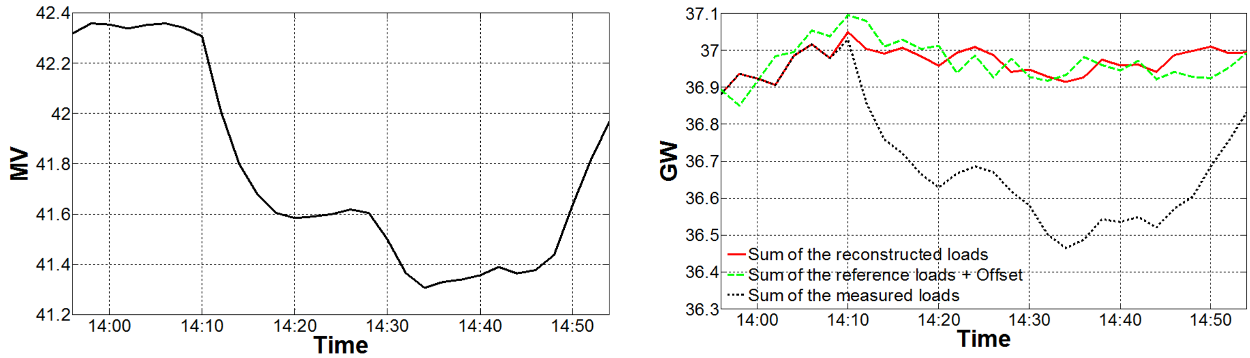
3.2.2. Case II: Nationwide CVR on 16 October 2012

At 14:09 on 16 October 2012, there was another implementation of nationwide CVR in the Korean power system. In this case, voltage reductions greater than 0.8% were detected on 1837 transformer banks from among 2098.

As shown in Figure 6a, when the first-step voltage reduction was implemented with a command of 2.5% voltage reduction, the average nationwide voltage reduction was 1.82%, going from 42.35 to 41.55 MV.

When the second-step voltage reduction was implemented with a command of 5.0% voltage reduction, the average nationwide voltage reduction was 2.47%, declining from 42.35 to 41.31 MV. For comparison, 18 October 2012 was selected as the reference date for the reference loads, and an offset of 595 MW was added to the sum of the reference loads. As shown in Figure 6b, the maximum peak-load shaving for the first-step voltage reduction appeared at 14:20 with a reduction amount of 329 MW. For the second-step voltage reduction, the maximum of peak load shaving appeared at 14:32, with a reduction amount of 450 MW.

Figure 6. Results of the nationwide CVR implemented on 16 October 2012: (**a**) sum of 1837 bank voltages; and (**b**) sum of 1837 transformer-bank loads.



(**a**) (**b**)

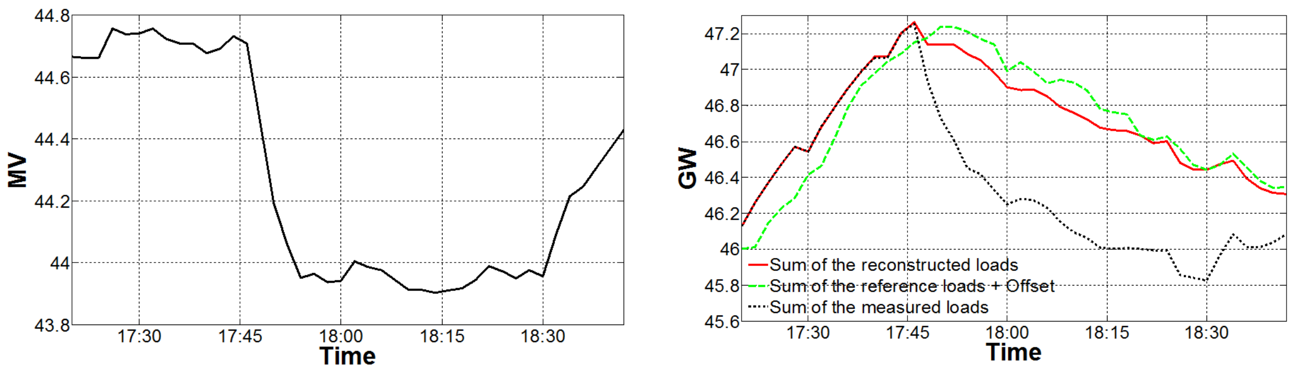
Following this second evaluation, it was found that the national CVR factor was 49.89% on 16 October 2012.

3.2.3. Case III: Nationwide CVR on 20 November 2012

At 17:32 on 20 November 2012, there was a third implementation of nationwide CVR in the Korean power system. In this case, voltage reductions greater than 0.8% were detected on 1936 transformer banks from among 2104.

As shown in Figure 7a, when the nationwide CVR was implemented with a command of 2.5% voltage reduction, the average voltage reduction at the national level was 1.83%, going from 44.72 to 43.90 MV. For comparison, 19 November 2012 was selected as the reference date for the reference loads, and an offset of 810 MW was added to the sum of reference loads. As shown in Figure 7b, the maximum peak-load shaving occurred at 18:14, with a reduction amount of 668 MW.

Figure 7. Results of the nationwide CVR implemented on 20 November 2012: (**a**) sum of 1936 bank voltages; and (**b**) sum of 1936 transformer-bank loads.



(**a**) (**b**)

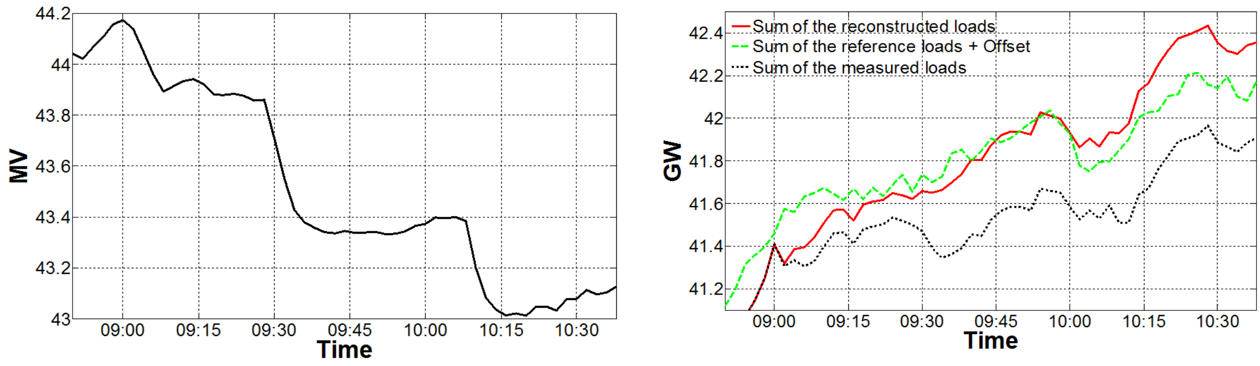
Following this third evaluation, it was found that the national CVR factor was 79.50% on 20 November 2012. It should be noted that these two values are much larger than those for the previous two cases.

3.2.4. Case IV: Nationwide CVR on 10 April 2013

At 08:57 on 10 April 2013, there was a fourth implementation of nationwide CVR in the Korean power system. In this case, voltage reductions greater than 0.8% were detected on 1913 banks from among 2123.

As shown in Figure 8a, when the first-step voltage reduction was implemented with a command of 2.5% voltage reduction, the average nationwide voltage reduction was 1.92%, declining from 44.18 MV to 43.33 MV. When the second-step voltage reduction was implemented with a command of 5.0% voltage reduction, the average nationwide voltage reduction was 2.65%, dropping from 44.18 MV to 43.01 MV.

Figure 8. Results of the nationwide CVR implemented on 10 April 2013: (**a**) sum of 1913 bank voltages; and (**b**) sum of 1913 transformer-bank loads.



(**a**) (**b**)

For comparison, 11 April 2013 was selected as the reference date for the reference loads, and an offset of 366 MW was added to the sum of reference loads. As shown in Figure 8b, the maximum peak-load shaving for the first-step voltage reduction took place at 9:54, with a reduction amount of 358 MW. For the second-step voltage reduction, the maximum peak-load shaving took place at 10:20, with a reduction amount of 495 MW.

Following these evaluations, it was found that the national CVR factor was 44.22% on 10 April 2013.

3.3. Summary of Evaluation Results in the Korean Power System

Table 1 summarizes the national CVR factors of the Korean power system. The national CVR factor varied between 36.20% and 79.50%, which is slightly different from the typical CVR factors reported previously: field tests showed a CVR factor in the range 50%–150% [27], EPRI's distribution green circuits program found average CVR factors of around 80% [28], and industries have reported CVR factors of 70%–100% [29]. Differences between the national CVR factor and these previously reported CVR factors result from the smoothing effect that occurs when the national CVR factor is estimated based on the weighted average of CVR factors of all transformer banks. In particular, the national CVR factor of the Korean power system was small in the summer season and large in the winter season. This means that the effect of nationwide CVR on peak-load shaving in the Korean power system is substantially greater in the winter season.

Table 1. National CVR factors of the Korean power system.

Time			Number of Transformer Bank		Bank Voltages		Bank Loads		$CVRF_N$
					$\sum_{k=1}^{N_C} V_{S_k}$	$\sum_{k=1}^{N_C} V_{M_k}(n_F)$	$\sum_{k=1}^{N_C} P_{R_k}(n_F)$	$\sum_{k=1}^{N_C} P_{M_k}(n_F)$	
			N_T	N_C	MV	MV	GW	GW	%
2012	08/07	11:20	2093	1889	43.50	42.81	49.97	49.65	39.82
	08/09	13:43	2093	1901	43.72	43.04	50.42	50.14	36.20
	10/16	14:09	2098	1837	42.35	41.58	36.96	36.63	49.89
	10/25	14:10	2098	1932	44.53	43.79	38.68	38.36	52.25
	10/30	18:00	2098	1908	44.03	43.27	41.02	40.60	61.48
	11/06	16:14	2102	1909	44.03	42.95	42.98	42.21	70.42
	11/20	17:32	2104	1936	44.72	43.90	46.68	46.01	79.50
2013	04/02	10:00	2123	1794	41.36	40.58	40.39	39.97	55.26
	04/10	08:57	2123	1913	44.18	43.33	42.03	41.67	44.22
	04/15	09:22	2123	1827	42.16	41.29	38.99	38.66	44.00

4. Conclusions

We have described a new method to evaluate the effects of nationwide CVR on peak-load shaving using SOMAS data. To evaluate these effects, a national CVR factor was proposed as the weighted average of the CVR factors for all transformer-bank loads. To make use of the data resulting from nationwide CVR without installing additional measuring devices, a linearized static-load model was used to represent the transformer-bank loads. In the national CVR factor, the CVR factor for each transformer bank was estimated by finding its linearizing parameter, and the weighting coefficients of the national CVR factor were determined from the reconstructed loads obtained from each transformer bank. Consequently, the national CVR factor represents the linearizing parameter of the national load.

SOMAS data were used for evaluating the effects of nationwide CVR on peak-load shaving in the Korean power system. Because bank voltages are controlled to keep a minimum voltage to end-of-line customers, the voltage reductions of some transformer banks are too small to be detected. In this paper, only transformer banks exhibiting voltage reductions greater than 0.8% were considered when evaluating the effects of nationwide CVR. As a first step in evaluating the effects of nationwide CVR, the linearizing parameters for individual transformer-bank loads were estimated using the SOMAS data obtained from the nationwide CVR. Second, the national CVR factor was estimated as a metric for comparing the effects of the nationwide CVR. Evaluation results showed that the effects of nationwide CVR on peak-load shaving in the Korean power system are greater in the winter season than in summer.

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Conflicts of Interest

The authors declare no conflict of interest.

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