Conservation Voltage Reduction Technology Yields Sustainable Electrifications: An Exploratory Study on Implementation Capability

*M. Spertip [a], F. Karbalaei [b], A. Yazdaninejadi [c, *]*
[a] *Electrical Engineering Department, Shahid Rajaee Teacher Training University, Tehran, Iran, Address:*
Lavizan, Tehran, Iran, P. O. Box: 16785-163, Phone: +98 21 22970060-9, Mobile:09305330568
Email: miad.student.74@gmail.com,
[b] *Electrical Engineering Department, Shahid Rajaee Teacher Training University, Tehran, Iran, Address:*
Lavizan, Tehran, Iran, P. O. Box: 16785-163, Phone: +98 21 22970060-9, Mobile:09124445325
Email:f_karbalaei@sru.ac.ir,
[c, *] *Electrical Engineering Department, Shahid Rajaee Teacher Training University, Tehran, Iran, Address:*
Lavizan, Tehran, Iran, P. O. Box: 16785-163, Phone: +98 21 22970060-9, Mobile:09141404389
Email:a.yazdaninejadi@sru.ac.ir (Correspondence Author),

Abstract- Conservation voltage reduction (CVR) as a readily available technology can easily tackle line congestion and peak load issues besides meeting the energy conservation by a marginal reduction in voltages of user-end nodes. However, the application of this technology is limited owing to some unclear technical aspects such as its response to industrial loads, load modeling type, and load estimation error. Therefore, this paper aims at presenting a comprehensive analysis of the CVR process to shed light on the various aspects of this technology for operators who seek to implement it. To this end, CVR process is explored based on load composition on a typical feeder with three zones. Different sizes for active and reactive powers in consumers of those zones are taken into consideration. By doing so, not only CVR process with different load arrangements is explored but also effect of the dominant loads on feeders is unveiled. This study also deals with identifying which load modeling type show better robustness to modeling errors. In this manner, CVR process in the pointed cases are performed with a considerable error on the parameters of load models. The obtained results show that in spite of expectations, CVR may have different outputs.

Keywords: Conservation voltage reduction technology; Clean and sustainable electrification; Sustainable grids; Load modeling errors; Energy conservation;

1. Introduction

Sustainable electrification renders the need for employing efficient technologies [1]-[2]. In this manner, conservation voltage reduction (CVR) has been well-recognized as a key idea which paves the way to provide sustainable electricity energy. By a marginal reduction in the voltages of user-end nodes in a controlled manner, CVR helps to tackle line congestion, peak load, and network loss problems by electric distribution utilities without impacting customers [3]-[4].

Meeting these issues in critical conditions by CVR helps to yield sustainable electrification [5]. Therefore, a suitable study on the application of this technology in electrical grids is of the essence [6].

How to design pathways towards sustainable energy transition has attracted worldwide concerns [7]. The CVR implemented as a pilot project in America [8] and Australia [9] has proven to provide impressive energy savings. Energy savings from US feeders have been estimated at 3.04% [8]. The considerable effects of CVR on reducing energy use have been investigated suitably in [10]. CVR advantages have been proven in adverse energy system challenging issues, such as the power loss reduction that is explored in [11]. Making decisions by utilities to perform voltage reduction, identify candidate CVR feeders, and undertake cost and revenue analysis renders the need for extensive and comprehensive studies [9]. A number of studies have been conducted to identify barriers associated with CVR and also propose more effective assessment methods. In this manner, different comparison-based methods are presented in [12]-[14]. The comparison-based method follows a straightforward methodology to calculate the CVR factors. In these methods, vulnerability to weather noise and lack of a reliable control group are frequently underlined as the main shortcomings [12]. Methods based on regression [15]-[16] offer load consumptions as a function of voltages and temperature. The factors associated with CVR are extracted from the determined load-to-voltage sensitivities. In these methods, a real-time calculation is used to find out CVR factors directly from measurements [8], [16]. However, inaccurate data and impulsive noises can easily degrade the performance [17]. Likewise, synthesis-based method [18] assesses the performance of CVR on individual electrical appliances

The electricity stands as a key input for socioeconomic development [19]. Deployment of CVR along with recent flexible technologies underscores how crucial this process is [20]-[22]. In [20], CVR is developed as well as optimal placement of battery energy storage in distribution facilities. A CVR study is also conducted for the optimal integration of distributed generation in an active distribution network in [21]. Another study is presented for an unbalanced network in [22]. In similar fashion, optimal power flow-based CVR operation is studied in photovoltaic-rich distribution networks in [23]. In [24], the importance of energy conservation and environmental protection is highlighted.

Despite sequel of advantages, decision-making about implementing the CVR process needs more extensive studies. Therefore, in this paper, a comprehensive analysis of CVR process is carried out for operators of distribution networks who seek to implement it. At the outset, this study aims at exploring load compositions with residential, industrial, and commercial loads. To this end, CVR process is followed based on a typical feeder with three zones and the load compositions are perfumed by these zones. The pointed load compositions can help to explore the effect of loads arrangements on CVR. This is while; the assigned load size to the different load types in different arrangements and active to reactive power ratio can easily affect the obtained results from CVR process. Therefore, to provide a comprehensive study, different sizes for active and reactive powers in consumers of those zones are taken into consideration. By doing so, not only CVR process with different load arrangements can be explored but also effect of the dominant loads on feeders would be unveiled. Moreover, based on the mentioned exploration, this paper investigates that whether the CVR process can be implemented in all load arrangements of systems or not. The load modeling types is the next important issue to be discussed. Thus, suitable comparison is preformed between load modeling types in performing CVR technology. To assess the robustness of the employed load modeling type, the effect of load modeling error on CVR process should be also explored thoroughly. To this end, a considerable error for each parameter of load model is considered and the CVR process is performed. Finally, a suitable discussion is taken into consideration for drawing new insights on different aspects of CVR process which can paves the way for future researches in this area. In brief, the main contributions could be listed as follows:

- A comprehensive analysis of CVR process is carried out for operators of distribution networks who seek to implement it;
- Not only CVR process with different load arrangements is explored but also effect of the dominant loads on feeders is unveiled. To this end, a proper load composition is considered in different scenarios which are associated with the size of active and reactive;
- Suitable comparison is preformed between load modeling types in performing CVR;
- A considerable error for each parameter of load model is considered and the CVR process is performed to assess the robustness of different load modeling types;
- The new insights on different aspects of CVR process are drawn and discussed which paves the way for future researches in this area;

- Finally, the obtained results show that in spite of expectations, CVR may have different outputs.

2. The outline of the conducted analysis on CVR process

Herein, at the outset, to establish a suitable framework, a typical feeder is taken into consideration which is divided into different zones. Based on the distance from the upstream connection point, these zones are named “near-zone”, “middle-zone”, and “far-zone”. These zones create the classification opportunity for considering different load compositions in feeders. Residential, commercial, and industrial loads are the types which are considered in the load compositions. In this manner, the load type of feeder is presented as “type of load 1-type of load 2-type of load-3”. In this expression, “type of load 1”, “type of load 2”, and “type of load 3” are associated with the load type in the near-zone, middle-zone, and far-zone, respectively.

Load compositions by changing load types cannot stand as a comprehensive study. For employing a suitable comparison platform, these load compositions are performed in three different simulation scenarios for presenting a comprehensive analysis which helps show the importance of the consumers places in different zones. The load compositions besides these scenarios are illustrated in Fig. 1. At the outset, the active and reactive powers in consumers’ buses are considered to be constant at the nominal voltage regardless of the load types in zones. Then, the active and reactive powers of the buses at nominal voltage are the function of the load type. Finally, the sum of active and reactive powers of different zones in the different load models are assumed equal to each other. These scenarios besides the presented load compositions can offer higher reliability and sustainability in a decision-making process. To make the conducted study comprehensive and for generating different load compositions in simulation studies, the zoning issue is preformed based on the impedance of the feeder. In the way, the shorter branches may have one or two zones. For example, consider a feeder with Residential-Commercial-Industrial loads which is depicted in Fig. 2. Besides this feeder, there is another feeder with a short length. The second feeder has two zones with industrial and commercial loads. Both the polynomial load model and the exponential load model are also taken into consideration in the conducted study.

They are two common load models in the load modeling distribution networks. Both of them are approximate methods which aim at modeling the load behavior of the network [25]-[29].

In the polynomial load model, the active and reactive powers are as follow:

$$P = P_n \left(P_1 \left(\frac{V}{V_n} \right)^2 + P_2 \left(\frac{V}{V_n} \right) + P_3 \right) \tag{1}$$

$$Q = Q_n \left(Q_1 \left(\frac{V}{V_n} \right)^2 + Q_2 \left(\frac{V}{V_n} \right) + Q_3 \right) \tag{2}$$

In these equations, P_1 and Q_1 are the weighting factors associated with constant impedance loads, P_2 and Q_2 are the weighting factors associated with constant current loads, and P_3 and Q_3 are the weighting factors associated with constant power loads. Moreover, P_n and Q_n are the active and reactive powers in nominal voltage V_n and nominal frequency f_n. The polynomial load model has a feature that can combine the models of these three loads in order to simulate residential, industrial, and commercial loads. Likewise, in the exponential load model, the active and reactive powers are governed as follow:

$$P = P_n \left(\frac{V}{V_n} \right)^{k_{pv}} \left(\frac{f}{f_n} \right)^{k_{pf}} \tag{3}$$

$$Q = Q_n \left(\frac{V}{V_n} \right)^{k_{qv}} \left(\frac{f}{f_n} \right)^{k_{qf}} \tag{4}$$

here, P and Q are the active and reactive powers in voltage V and frequency f. Furthermore, k_{pv}, k_{qv}, k_{pf} , and k_{qf} are constant parameters. In the exponential load model, frequency dependence is often ignored because the voltage changes are greater than the frequency changes and the simplified exponential model (voltage dependent only) is expressed as follows:

$$P = P_n \left(\frac{V}{V_n} \right)^{k_{pv}} \tag{5}$$

$$Q = Q_n \left(\frac{V}{V_n} \right)^{k_{qv}} \tag{6}$$

Load modeling error stands as a challenging issue which imperils the accuracy of CVR. This issue originated from different reasons including changes in regional texture and lack of up-to-date load modeling coefficients in proportion to network load changes. Therefore, in order to obtain the effect of this issue on the process of reducing the conservation voltage, 20% upward change and 20% downward change are considered in the values of load modeling parameters. Reducing the network power consumption stands as one of the main goals of CVR process in distribution networks. The network power consumption is equal to the power of loads besides the network losses. Therefore,

$$P_g = P_d + P_{loss} \tag{7}$$

here, P_{loss} is loss power, P_g is the network power consumption, and P_d is the power of loads. It should be emphasized that the CVR results are assessed by the network power consumption, power losses, and voltage drops. Simulation cases are as follow:

- Explore possibility of implementing CVR on feeders with different load arrangements as described in Fig. 1;
- Explore the effect of the nominated load of the feeder on CVR process;
- Provide suitable comparison between load modeling types in performing CVR technology;
- Assess the robustness of different load modeling types by contemplating considerable error for each parameter of the employed load model in the CVR process.

3. Testbed, simulation studies, and results

3.1 The testbed

CVR process is simulated based on the IEEE 33-bus test system [30] which is presented in Fig. 3.

More detailed data can be founded in [31]. Based on pervious explanations, the zones on this testbed are considered as shown in Fig. 3. Constant parameters associated with the polynomial and the exponential models [32]-[33] are also reported in Table 1.

3.2 Simulation studies and numerical results

Herein, CVR simulation studies are classified into six scenarios. In the first scenario, the load model is considered polynomial. The active and reactive powers in consumers' buses are assumed to be constant at the nominal voltage. In the second scenario, the active and reactive powers in consumers' buses are the same as in the first scenario and the load model is exponential. In the third and fourth scenarios, the active and reactive powers of the buses at nominal voltage are the function of the load type. The load models are polynomial and exponential, respectively. In the fifth and sixth scenarios, the sum of active and reactive powers of different zones in the different load models are assumed equal to each other. Likewise, the load models are polynomial and exponential, respectively. Simulations are performed with different load compositions, and CVR process is assessed with three terms of voltage, line losses, and the supplied power. The typical voltage reductions are considered in the simulation process which are 2.25%, 4%, 6%, and 8%.

A. Scenario-1: CVR process by considering polynomial load model: the active and reactive powers in consumers' buses are considered to be constant

Herein, the polynomial is considered for modeling the loads. The active and reactive powers in consumers' buses are constant. The CVR process is conducted with different load compositions and with these voltage reductions. One of the places that always has the highest voltage drop is the end bus of each area. The bus number of these points in this test system are 6, 12, 19, 22, and 25. Table 2 deals with the ranking of bus voltages that have the lowest voltage in different load arrangements in the CVR process with 8% voltage reduction. As expected, the Industrial-Industrial-Industrial arrangement results in the greatest voltage reduction owing to the constant power characteristic of these loads. In the loads with the constant power characteristic, voltage reduction increases the current and consequently, increases the voltage drop in the feeder.

Table 3 shows the effect CVR process on system line losses. It can be seen that any increment in the percentage of voltage reduction increases losses. In different load configurations, there are loads with constant power characteristics. Therefore, reducing voltage increases the current. In different load arrangements, the increment in currents of loads is not the same. Consequently, the reflected losses in this table are also not the same. In this table, the highest reported loss is associated with Commercial-Residential-Industrial load. The lowest reported loss is associated with Industrial-Commercial-Residential load.

Moreover, Table 4 shows the changes in injected power by the source for different load arrangements during CVR process. By applying higher percentages of voltage drop, the output power of the source decreases. The minimum amount of power output between different load arrangements in a specific voltage drop (e.g. 8%) is associated with Commercial-Industrial-Residential load. The maximum one is related to Industrial-Residential-Commercial load.

Here, results are different from those typical and simple predictions. The injected powers by the source in Commercial-Residential-Industrial and Residential-Commercial-Industrial loads arrangements are expected to be the highest one. It was also predicted that Industrial-Residential-Commercial and Industrial-Commercial-Residential loads arrangements would be the lowest in injected power by the source. Since the active and reactive power consumption of the buses remains constant at the rating voltage regardless of their load type, none of these expectations are met.

Herein, the robustness of the polynomial load model in this scenario is evaluated. Sometimes, the coefficients of the polynomial model are not accurate. These coefficients can be affected when the system information is not available or system data are not updated. In such systems, it is possible to implement the CVR process. In this manner, ranking the robustness of different load arrangements is of importance. To do so, 20% upward changes and 20% downward changes are considered in the values of load modeling coefficients and the obtained results are reported in Table 5. It can be seen that the results in upward and downward changes from the actual value are not always equal and the robustness of different arrangements in positive and negative changes of 20% are different. For example, Residential-Industrial-Commercial load arrangement in -20% and Residential-Residential-Residential load arrangement in +20% have the highest robustness in terms of voltage. Moreover, the minimum robustness in terms of losses is associated with Commercial-Commercial-Commercial load arrangement. In general, a certain load arrangement cannot be introduced as the robust load arrangement against uncertainty because the robustness of different load arrangements is assessed from the three perspectives.

Therefore, the operator should employ this table based on their priority among voltage, losses, and energy saving. Although these arrangements render fewer advantages than other load arrangements but still maintain their efficiency in CVR process.

B. Scenario-2: CVR process by considering exponential load model: the active and reactive powers in consumers' buses are considered to be constant

This scenario deals with CVR process when the active and reactive powers in consumers' buses are considered to be constant at the nominal voltage and the load model is exponential. Table 6 presents the ranking of different load arrangements in the term of voltage drop during the CVR process with 8% voltage reduction. As expected, the Industrial-Industrial-Industrial arrangement results in the greatest voltage drop owing to the constant power characteristic of these loads. The reflected results show that the deviation of voltage values from each other in different load combinations and in the case of using polynomial load model is greater than of the case where exponential load model is used. Table 7 shows the effects CVR on network losses. The reflected losses in this table are lower than those in Table 3. Moreover, the highest loss is associated with Commercial-Residential-Industrial. Likewise, the lowest one is associated with Industrial-Residential-Commercial. Moreover, this table indicates that any increment in the percentage of voltage reduction increases losses.

Table 8 reports the variations in the delivered power by the primary station for different load arrangements during CVR process. By applying higher percentages of voltage drop, the output power of the source decreases. Moreover, the minimum amount of power output between different load arrangements in a specific voltage drop (e.g. 8%) is associated with Residential-Industrial-Commercial load. The maximum is related to Residential-Commercial- industrial load. AS can be seen none of the expectations about the delivered power by the primary station are met. The obtained results regarding robustness of the exponential load model are given in Table 9 in terms of voltage drop, losses, and the output power of the source. The load arrangements Industrial-Residential-Commercial compared to Industrial-Commercial-Residential load combination is more robust in terms of line losses and supplied power. From the viewpoint of voltage, these two combinations are not comparable. Moreover, the percentage of upward and downward changes of the actual value is not always equal, as the polynomial load model.

C. Scenario-3: CVR process by considering polynomial load model: Active and reactive power of buses at nominal voltage are the function of load type

Here, the active and reactive powers of the buses at the nominal voltage are a function of the type of load. The aim is to explore the effect of load types residential, industrial and commercial on CVR process in different load arrangements at different distances from the source. Six fixed buses with active and reactive power are considered for each of the loads. The active and reactive power values of these six buses will not change during the compositions. For allocating the same buses to each area only one to eighteen buses are employed in this scenario as shown in Fig. 4. In this figure, the zone with orange color indicates the near area, purple indicates the far area, and red also indicates the area between the far and near areas.

The highest voltage drop is associated with Commercial-Industrial-Residential arrangement and the lowest one is with Residential-Industrial-Commercial arrangement. It was expected that load arrangements with industrial load at the end of the feeder have the highest voltage drop. Moreover, Industrial-Industrial-Industrial load arrangement was also expected to have the highest voltage drop among different arrangements. Since the powers assigned to the loads are not equal based on the primary data of the testbed [34], none of these expectations are met. Moreover, Table 10 reports the results of losses and Table 11 reflects the supplied powers in different load arrangements.

Commercial-Residential-Industrial and Residential-Commercial-Industrial load combinations were expected to have the highest line losses and production capacity among the load arrangements. It was also predicted that the lowest increase in line losses and power supply would be related to load arrangements Industrial-Residential-Commercial and Industrial-Commercial-Residential. In these arrangements, the industrial load has a constant power characteristic which is placed near the source. By reducing the voltage, the industrial load consumption current flows a shorter path along the feeder. Finally, these expectations are not met because the active and reactive powers assigned to the loads are different. Most of the line losses are for the Commercial-Industrial-Residential arrangement. The reason can find in the active power consumption of the residential load which is bigger than the industrial load.

Simulation results in the state of uncertainty of polynomial load model parameters are given in Table 12. Load arrangement Commercial-Commercial-Commercial compared to the others is more robust in terms of line losses and supplied power while Residential- Residential-Residential arrangement has the lowest robustness. Typically, the operators make a decision based on the network potentials and their priorities. According to this table, the percentage of upward and downward changes of the actual value is not always equal. Moreover, if a load arrangement has the least or most change in one term, it is not necessary to have the least or most change in other terms. Moreover, the CVR process in those combinations with improper robustness can be employed and is still an effective solution to reduce peak load and save energy after evaluating the cost and revenue analysis by operators.

D. Scenario-4: CVR process by considering exponential load model: Active and reactive power of buses at nominal voltage are the function of load type

This scenario follows the purposes of the previous scenario with the exponential model. The highest voltage drop is for Commercial-Industrial-Residential arrangement and the lowest one is for Residential-Industrial-Commercial arrangement. It was expected that load arrangements with industrial load at the end of the feeder have the highest voltage drop. Since the assigned size for industrial load is not greater than the all others in this testbed [35], the expectation is not met. Table 13 gives the results associated with losses. The lowest line losses are for Residential-Industrial-Commercial arrangement. Moreover, Table 14 presents the supplied powers in different load arrangements. The lowest power output is in Industrial-Commercial-Residential arrangement.

Commercial-Residential-Industrial and Residential-Commercial-Industrial load combinations were expected to have the highest line losses and supplied power among the load arrangements. These expectations are not met because the active and reactive powers assigned to the loads are different. Due to the voltage-dependent characteristic of loads in this scenario, by decreasing voltage in all load arrangements, power consumption decreases which can be followed in Table 13. In the exponential load model, the lowest value of the exponent is related to the industrial load. Hence, the highest increment in current and in line losses are related to this load. In the commercial and residential load models, the value of the K_p is equal to 0.9 and and 0.99, respectively. Since in these loads K_p is near to one, voltage reduction results in a smaller current than the industrial load and consequently, have fewer line losses. Simulation results in the state of uncertainty of exponential load model parameters are given in Table 15. The load arrangement Industrial-Industrial-Industrial compared to the others seems to be more robust while Commercial-Commercial-Commercial arrangement has the lowest robustness.

E. Scenario-5: CVR process by considering polynomial load model: The sum of active and reactive powers of different zones are assumed equal to each other

Here, the sum of active and reactive powers of different areas in different load models are equal to each other. By changing the type of load, the sum of the active and reactive powers of the six selected buses of each area do not change and are equal. The process is followed by considering the polynomial load model. The presence of high-consumption and low-consumption areas in previous scenarios would affect the results from the explained perspectives. In this regard, the amount of power in the three areas pointed in Fig. 4 is assumed to be equal.

The highest voltage drop should be for Commercial-Residential-Industrial and Residential-Commercial-Industrial load arrangements among those arrangements with mixed load types. Industrial-Industrial-Industrial load has the highest voltage drop among all arrangements. Because all three load types are industrial. Moreover, the Commercial-Residential-Industrial arrangement should have the highest line losses and supplied power among the arrangements with mixed load type owing to the presence of industrial load at the end of the line. By decreasing voltage, the required current by the industrial load is increased. Then, this current passes through the entire length of the feeder. Therefore, it brings more line losses. Tables 16 & 17 confirm these statements. These tables report line losses and supplied power in different cases. On the other hand, the lowest rate of increment in line losses and supplied power is for Industrial-Residential-Commercial load arrangement. In this load arrangement, the industrial load is located near the source. In this situation, by reducing the voltage, the required current flows a shorter path along the feeder. Therefore, it has the least line losses and consequently, needs the lowest supplied power. The combination of Industrial-Industrial-Industrial load would have the highest line losses and supplied power among single-state load arrangements. Likewise, the power consumption of Commercial-Commercial-Commercial arrangement has more dependent on voltage. Thereby, it yields the lowest line loss and supplied power among single-state arrangements.

Here, the robustness of the polynomial load model against the modeling error during the CVR process is evaluated where the sum of active and reactive powers of different areas are considered to be equal to each other. The obtained results are presented in Table 18. The highest robustness is related to the arrangement Industrial-Industrial-Industrial and the lowest strength is related to the arrangement Commercial-Commercial-Commercial load.

F. Scenario-6: CVR process by considering exponential load model: The sum of active and reactive powers of different zones are assumed equal to each other

In scenario-5, CVR process is perused by considering the polynomial load model and the sum of active and reactive powers of different zones are assumed equal to each other. This process is followed by considering the exponential load model. The presence of high-consumption and low-consumption areas would affect the results from the explained perspectives. The amount of power in those areas pointed in Fig. 4 is also contemplated to be equal besides considering the exponential load model. As expected, the highest voltage drop is for Commercial-Residential-Industrial. Also, Industrial-Industrial-Industrial load has the highest voltage drop among all arrangements because all three load types are industrial. Tables 19 & 20 report lines losses and supplied power in different cases. Commercial-Residential-Industrial arrangement has the highest line losses and supplied power among the arrangements with mixed load type. The lowest rate of increment in line losses and supplied power is for Industrial-Residential-Commercial load arrangement. The arrangement Industrial-Industrial-Industrial load would have the highest line losses and supplied power among single-state load arrangements.

As pointed earlier, some systems may not have accurate system information, load modeling may be out of date, and load modeling may not have been updated. Herein, the robustness of the exponential load model against the modeling error during the CVR process is evaluated where the sum of active and reactive powers of different areas are considered to be equal to each other. The obtained results are given in Table 21. The highest robustness is related to the arrangement Residential-Residential-Residential and the lowest strength is related to the arrangement Commercial-Commercial-Commercial load. The obtained results confirm that the CVR process in those combinations with improper robustness can also be employed and is still an effective solution to reduce peak load and save energy after evaluating the cost and revenue analysis by operators. In exponential modeling, load arrangements have less robustness than in the arrangements in polynomial load modeling in a similar condition. That is, the issue of uncertainty has less effect on polynomial load modeling.

3.3 Discussion

CVR technology tackles line congestion and peak load issues besides meeting the energy conservation by a marginal reduction in the voltages of user-end nodes. In order to investigate the effect of CVR process on the network, two models of polynomial and exponential load have been used. Moreover, three different cases are considered based on these load modeling to make the conducted analysis a comprehensive study. In the first case, the active and reactive powers in consumers' buses are assumed to be constant at the nominal voltage regardless of load types in the zones. In the second case, the active and reactive power of the buses in the nominal voltage is a function of the type of load. In the third one, the sum of active and reactive powers of different. Based on the considered load modeling and the abovementioned cases, results in six scenarios show that:

- Exponential modeling has less robustness than polynomial load modeling in similar conditions;
- The simulation studies indicate that although industrial loads require lager current during CVR process and they have adverse effects on CVR process, this process is not restricted for the feeders with these kinds of loads and precise CVR assessment should be conducted;
- In the arrangements where the industrial loads are close to the end of the feeder, the abovementioned issue is exacerbated;
- Not only in industrial loads but also in the residential and commercial loads, the aforementioned issue can be met in CVR process. Therefore, depends on location of the load, length of feeder, and size of the load, voltage reduction may result in increment of power consumption:
- Finally, the obtained results show that in spite of expectations, CVR may have different outputs.

4. Concluding remarks

Conservation voltage reduction (CVR) technology can stand as suitable solutions for tackling line congestion and peak load issues besides meeting energy conservation. This important tool can facilitate sustainable electrifications, especially in critical conditions. This paper presented a comprehensive analysis of CVR process for operators who seek to implement it. This paper explored that whether the CVR process can be implemented in all load arrangements of systems or not. Moreover, in this study, the effect of load modeling error on CVR process and the relationship between the maximum possible CVR in a system and the load combinations of that system was also unveiled. To this end, suitable farmwork is provided and different simulation studies are carried out. The obtained results are interrogated in three terms of voltage, line losses, and supplied power. The following points were noticed as the major conclusions of the conducted study:

- It was seen that exponential modeling shows less robustness than polynomial load modeling in similar conditions. That is, the uncertainty issue has less effect on polynomial load modeling;
- It was shown that presenting a decision-making meter for implementing CVR process seem to be sophisticated tasks owing to the existence of high and low consumption in load arrangements;
- Moreover, there is common sense that CVR process in some load arrangements is impossible. This is while; the conducted study unveiled that the CVR process is possible to implement on different load arrangement with different consumptions. Therefore, CVR assessment was recommended for operators to see whether the CVR process can be implemented in their feeder or not;
- The obtained results show that in spite of expectations, CVR may have different outputs;
- Furthermore, it was seen that the modeling error has not the same effect on the mentioned assessment terms which calls the need for CVR assessment based on the operator's priority.

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Biography

Miad Spertip received the B.Sc. degree in electrical engineering from Shahid Rajaee Teacher Training University, Tehran, Iran, in 2019, the M.Sc. degrees in electrical engineering from Shahid Rajaee Teacher Training University, Tehran, Iran, in 2022. His research interests include power system analysis, and Conservation voltage reduction technology.

Farid Karbalaei received the B. Sc. degree in power engineering from K. N. Toosi University of Technology, Tehran, Iran, in 1997, and the M.Sc. and Ph.D. degrees in power engineering from Iran

University of Science and Technology, Tehran, Iran, in 2000 and 2009, respectively. Currently, he is a associate professor in Shahid Rajaee Teacher Training University, Tehran, Iran. His research interests include power system dynamics and control, voltage stability and col- lapse and reactive power control.

Amin Yazdaninejadi received the B.Sc. degree in electrical engineering from Urmia University, Urmia, Iran, in 2012, the M.Sc. degrees in electrical engineering from Amirkabir University of Technology (AUT), Tehran, Iran, in 2014, and Ph.D. degree in the School of Electrical Engineering, University of Urmia, Urmia, Iran in 2018. He is currently an Assistant Professor in the Department of Electrical Engineering, Shahid Rajaee Teacher Training University, Tehran, Iran. His research interests include power system protection, power system automation, and smart grid technologies.

Fig. 1. Load compositions.

Fig. 2. A simple feeder.

Fig. 3. IEEE 33-Bus test system.

Fig. 4. The zones in Scenario-3

Table 1. Coefficients of polynomial and exponential modeling [32]-[33].

Table 2. CVR ranking among different arrangements based on voltage drop at the last bus in scenario-1.

Table 3. The effect CVR process on system line losses in different arrangements

Table 4. The changes in injected power by the source for different load arrangements during CVR process.

Table 5. Results of 20% upward and 20% downward changes in the modeling coefficients: Scenario-1

Table 6. CVR ranking among different arrangements based on voltage drop at the last bus in scenario-2.

Table 7. The effect CVR process on system line losses in different arrangements in scenario-2

Table 8. The changes in injected power by the source for different load arrangements during CVR processes in scenario-2

Table 9. Results of 20% upward and 20% downward changes in the modeling coefficients: Scenario-2

Table 10. The effect CVR process on system line losses in different arrangements in scenario-3

Table 11. The changes in injected power by the source for different load arrangements during CVR processes in scenario-3

Table 12. Results of 20% upward and 20% downward changes in the modeling coefficients: Scenario-3

Table 13. The effect CVR process on system line losses in different arrangements in scenario-4

Table 14. The changes in injected power by the source for different load arrangements during CVR processes in scenario-4

Table 15. Results of 20% upward and 20% downward changes in the modeling coefficients: Scenario-4

Table 16. The effect CVR process on system line losses in different arrangements in scenario-5

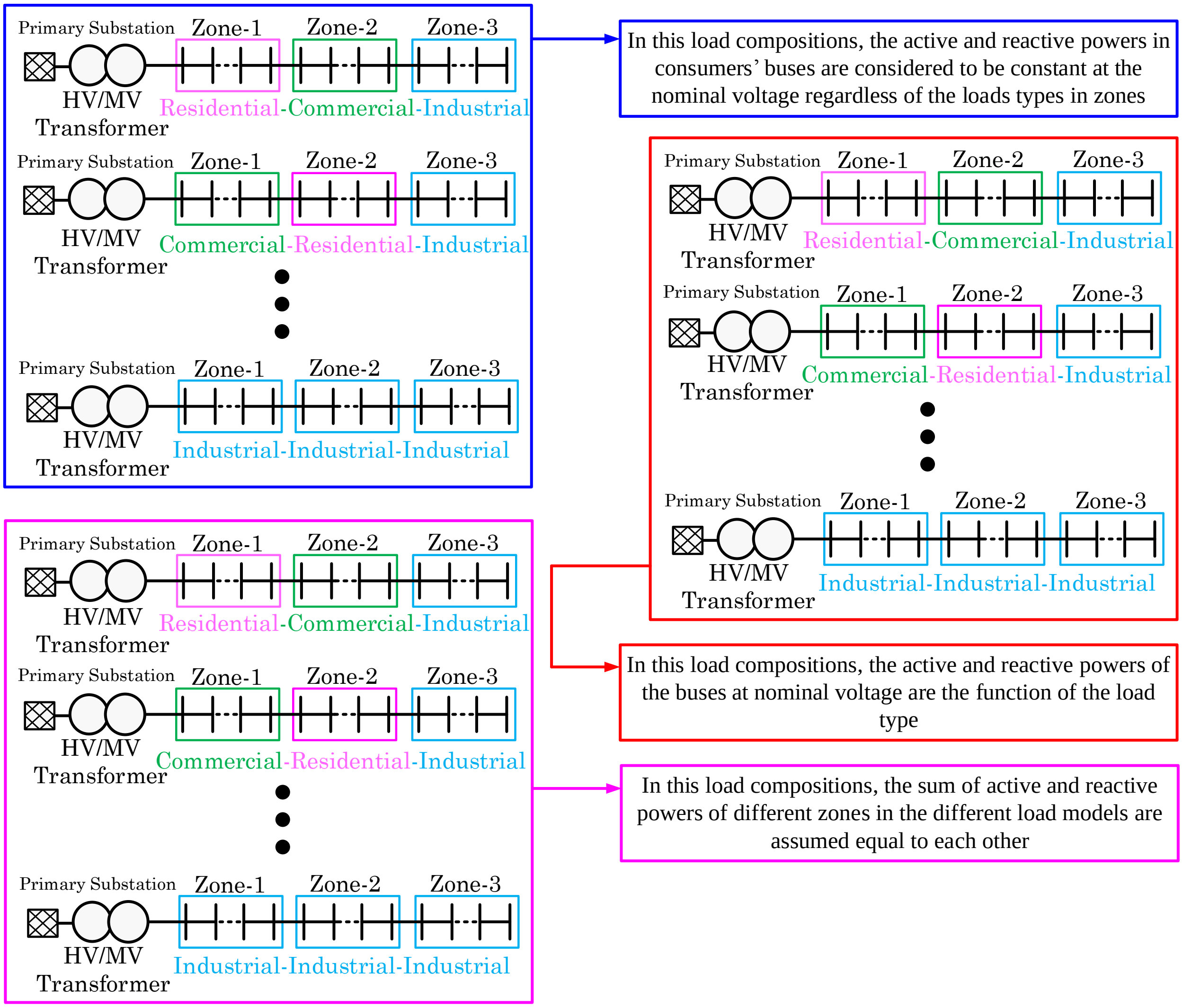
Table 17. The changes in injected power by the source for different load arrangements during CVR processes in scenario-5

Table 18. Results of 20% upward and 20% downward changes in the modeling coefficients: Scenario-5

Table 19. The effect CVR process on system line losses in different arrangements in scenario-6

Table 20. The changes in injected power by the source for different load arrangements during CVR processes in scenario-6

Table 21. Results of 20% upward and 20% downward changes in the modeling coefficients: Scenario-5



In this load compositions, the active and reactive powers in consumers' buses are considered to be constant at the nominal voltage regardless of the loads types in zones

In this load compositions, the active and reactive powers of the buses at nominal voltage are the function of the load type

In this load compositions, the sum of active and reactive powers of different zones in the different load models are assumed equal to each other

Fig. 1. Load compositions.

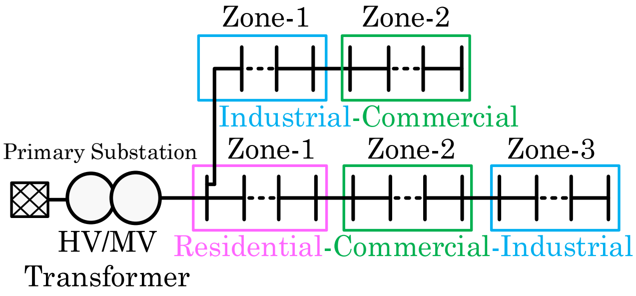


Fig. 2. A simple feeder.

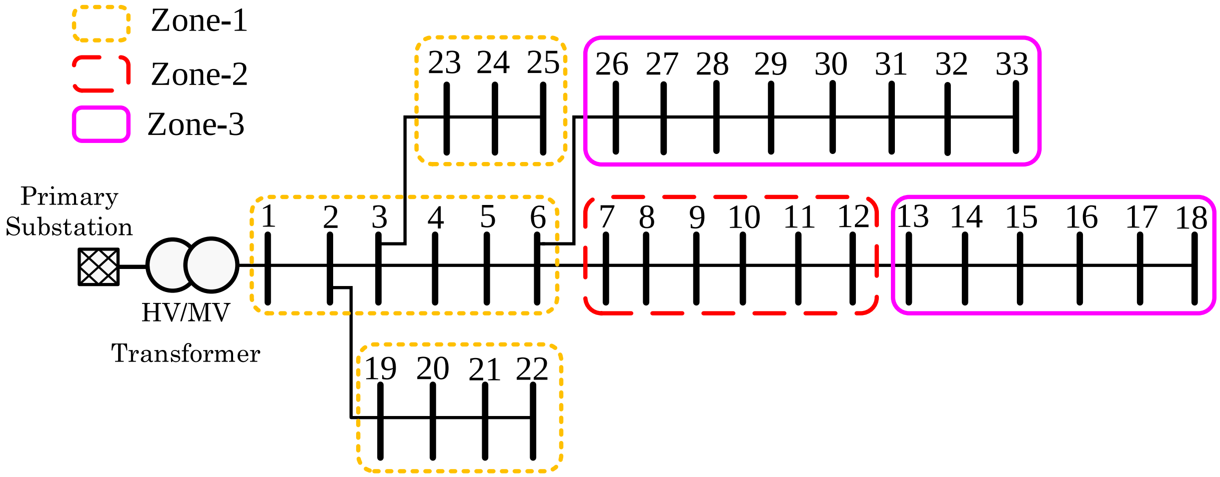


Fig. 3. IEEE 33-Bus test system.

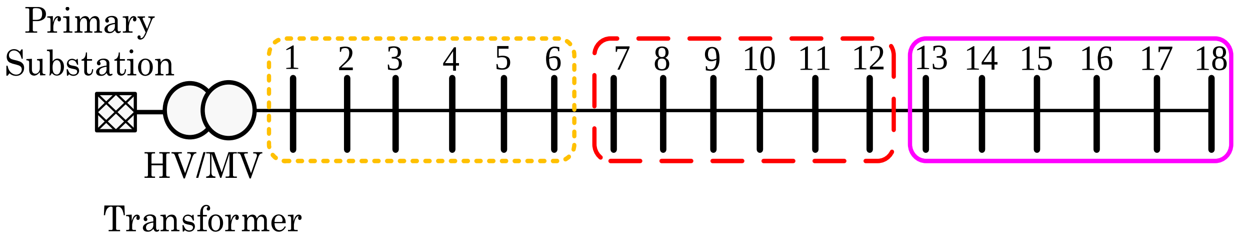


Fig. 4. The zones in Scenario-3

Table 1. Coefficients of polynomial and exponential modeling [32]-[33].

Load type	Modeling parameters at							
	polynomial						exponential	
	p_1	p_2	p_3	q_1	q_2	q_3	K_q	K_p
Commercial	0.43	-0.06	0.63	4.06	-6.65	3.59	6	0.9
Residential	0.85	-1.12	1.27	10.96	-18.73	8.77	1.7	0.99
Industrial	0	0	1	0	0	1	1	0.88

Table 2. CVR ranking among different arrangements based on voltage drop at the last bus in scenario-1.

Ranked	Arrangement	Least bus voltage (pu)
1	Industrial-Industrial-Industrial	0.8310

2	Residential-Commercial-Industrial	0.8341
3	Commercial-Residential-Industrial	0.8341
4	Residential-Industrial-Commercial	0.8382
5	Industrial-Residential-Commercial	0.8384
6	Commercial-Commercial-Commercial	0.8395
7	Commercial-Industrial-Residential	0.8396
8	Industrial-Commercial-Residential	0.8399
9	Residential-Residential-Residential	0.8409

Table 3. The effect CVR process on system line losses in different arrangements

Voltage reduction	Line losses at load arrangement					
	Residential-Commercial-Industrial	Residential-Industrial-Commercial	Industrial-Residential-Commercial	Industrial-Commercial-Residential	Commercial-Industrial-Residential	Commercial-Residential-Industrial
0%	0.174140	0.173380	0.171700	0.172040	0.173590	0.174050
2.25%	0.180270	0.175350	0.173990	0.172250	0.173600	0.180270
4%	0.184360	0.176980	0.175820	0.173110	0.174350	0.184450
6%	0.190320	0.179670	0.178820	0.175150	0.176240	0.190560
8%	0.196940	0.183100	0.182540	0.178240	0.179210	0.197340

Table 4. The changes in injected power by the source for different load arrangements during CVR process.

Supplied Power	The change in injected power at load arrangement					
	Residential-Commercial-Industrial	Residential-Industrial-Commercial	Industrial-Residential-Commercial	Industrial-Commercial-Residential	Commercial-Industrial-Residential	Commercial-Residential-Industrial
0%	4.330200	4.333400	4.33900	4.341800	4.338800	4.333800
2.25%	4.271300	4.246500	4.28200	4.274400	4.243200	4.279100
4%	4.240200	4.199900	4.25600	4.239100	4.192000	4.249500
6%	4.203500	4.143700	4.220700	4.198000	4.130600	4.213400
8%	4.172500	4.095100	4.189700	4.163500	4.077400	4.181200

Table 5. Results of 20% upward and 20% downward changes in the modeling coefficients: Scenario-1

Arrangement	Voltage (%) in coefficients change		Supplied power (%) in coefficients change		Line Losses (%) in coefficients change	
	-20%	+20%	-20%	+20%	-20%	+20%
Commercial-Residential-Industrial	-0.080	0.0818	-0.8069	0.430	-1.2385	0.4104
Commercial-Industrial-Residential	-0.120	0.0535	-1.0749	0.460	-1.0894	0.5600
Industrial-Commercial-Residential	-0.0232	0.0735	-0.3240	0.210	-1.3075	0.6066
Industrial-Residential-Commercial	-0.260	0.2654	-0.9714	0.047	-4.2165	1.7615
Residential-Industrial-Commercial	-0.011	0.230	-1.2484	0.536	-4.3769	2.1200
Residential-Commercial-Industrial	-0.442	0.0818	-0.3497	0.030	-1.1927	0.5412
Commercial-Commercial-Commercial	-0.220	0.2400	-3.0599	1.184	-6.8613	2.9249
Residential-Residential-Residential	-0.034	0.0372	-0.070	0.152	-0.3595	0.7600
Industrial-Industrial-Industrial	-0.0937	0.1170	-1.130	0.067	-2.1618	1.6176

Table 6. CVR ranking among different arrangements based on voltage drop at the last bus in scenario-2.

Rate	Arrangement	Least bus voltage (pu)
1	Industrial-Industrial-industrial	0.8419
2&3	Commercial-Residential-Industrial	0.8433
2&3	Residential-Commercial-Industrial	0.8434
4	Commercial-Industrial-Residential	0.8451
5	Residential-Residential-Residential	0.8458
6	Industrial-Commercial-Residential	0.8463
7	Residential-Industrial-Commercial	0.8504
8	Industrial-Residential-Commercial	0.8509
9	Commercial-Commercial-Commercial	0.8528

Table 7. The effect CVR process on system line losses in different arrangements in scenario-2

Voltage reduction	Line losses in load arrangement					
	Residential-Commercial-Industrial	Residential-Industrial-Commercial	Industrial-Residential-Commercial	Industrial-Commercial-Residential	Commercial-Industrial-Residential	Commercial-Residential-Industrial
0%	0.1575	0.1360	0.1371	0.1492	0.1500	0.1580
2.25%	0.1581	0.1391	0.1390	0.1506	0.1517	0.1590
4%	0.1588	0.1415	0.1414	0.1521	0.1533	0.1598
6%	0.1594	0.1436	0.1430	0.1534	0.1546	0.1604
8%	0.1605	0.1475	0.1470	0.1571	0.1570	0.1617

Table 8. The changes in injected power by the source for different load arrangements during CVR processes in scenario-2

Supplied Power	The change in injected power at load arrangement					
	Residential-Commercial-Industrial	Residential-Industrial-Commercial	Industrial-Residential-Commercial	Industrial-Commercial-Residential	Commercial-Industrial-Residential	Commercial-Residential-Industrial
0%	4.2077	4.1210	4.1229	4.1738	4.1682	4.2026
2.25%	4.0861	3.9812	3.9900	4.0530	4.0183	4.0586
4%	4.0140	3.9001	3.9137	3.9820	3.9322	3.9758
6%	3.9196	3.7949	3.8130	3.8800	3.8210	3.8691
8%	3.8200	3.6900	3.7160	3.7970	3.7150	3.7660

Table 9. Results of 20% upward and 20% downward changes in the modeling coefficients: Scenario-2

Arrangement	Voltage (%) in coefficients change		Supplied power (%) in coefficients change		Line Losses (%) in coefficients change	
	-20%	+20%	-20%	+20%	-20%	+20%
Commercial-Residential-Industrial	-0.2447	0.2334	2.6715	-2.5187	5.4917	-5.0814

Commercial-Industrial-Residential	-0.2885	0.2720	2.8687	-2.6875	6.3465	-5.7848
Industrial-Commercial-Residential	-0.2906	0.2731	2.5478	-2.4053	6.3787	-5.7853
Industrial-Residential-Commercial	-0.1951	0.2923	2.1662	-2.3896	3.5544	-5.2500
Residential-Industrial-Commercial	-0.1972	0.2920	2.2783	-2.4846	3.6628	-5.2948
Residential-Commercial-Industrial	-0.2457	0.2334	2.4436	-2.3228	5.5281	-5.0940
Commercial-Commercial-Commercial	-0.3388	0.3041	3.0164	-2.6550	6.0516	-5.0955
Residential-Residential-Residential	-0.2871	0.2719	2.6192	-2.5026	6.3155	-5.8033
Industrial-Industrial-Industrial	-0.2256	0.2171	2.0281	-1.9639	4.8061	-4.5240

Table 10. The effect CVR process on system line losses in different arrangements in scenario-3

Voltage reduction	Line losses in load arrangements					
	Residential-Commercial-Industrial	Residential-Industrial-Commercial	Industrial-Residential-Commercial	Industrial-Commercial-Residential	Commercial-Industrial-Residential	Commercial-Residential-Industrial
0%	0.03610	0.03363	0.04052	0.05098	0.05088	0.0429
2.25%	0.03725	0.03442	0.04096	0.05161	0.05203	0.0442
4%	0.03801	0.03496	0.04133	0.05213	0.05286	0.04512
6%	0.03911	0.03574	0.04194	0.05300	0.05415	0.04642
8%	0.04030	0.0366	0.0421	0.0541	0.0556	0.0478

Table 11. The changes in injected power by the source for different load arrangements during CVR processes in scenario-3

Supplied Power	The change in injected power at load arrangement					
	Residential-Commercial-Industrial	Residential-Industrial-Commercial	Industrial-Residential-Commercial	Industrial-Commercial-Residential	Commercial-Industrial-Residential	Commercial-Residential-Industrial
0%	1.6697	1.6639	1.6496	1.6402	1.6539	1.6668
2.25%	1.6424	1.6368	1.6246	1.6167	1.6295	1.6410
4%	1.6276	1.6222	1.6111	1.6039	1.6163	1.6271
6%	1.6096	1.6041	1.5946	1.5885	1.6004	1.6102

8%	1.5936	1.5884	1.5801	1.5751	1.5800	1.5952

Table 12. Results of 20% upward and 20% downward changes in the modeling coefficients: Scenario-3

Arrangement	Voltage (%) in coefficients change		Supplied power (%) in coefficients change		Line Losses (%) in coefficients change	
	-20%	+20%	-20%	+20%	-20%	+20%
Commercial-Residential-Industrial	-0.0340	0.0340	-0.2298	0.2298	-1.0641	0.6440
Commercial-Industrial-Residential	-0.0970	0.0124	-0.3437	0.2437	-0.8531	0.5595
Industrial-Commercial-Residential	-0.0228	0.0683	-0.3462	0.2770	-0.8697	0.6075
Industrial-Residential-Commercial	-0.0678	0.791	-0.3198	0.2822	-1.9168	0.9965
Residential-Industrial-Commercial	-0.0563	0.1487	-0.3990	0.2955	-1.9026	1.1080
Residential-Commercial-Industrial	-0.0226	0.4655	-0.4349	0.2609	-1.0302	0.6416
Commercial-Commercial-Commercial	-0.0114	0.0011	-0.1027	0.1541	-0.3495	0.4660
Residential-Residential-Residential	-0.0902	0.2367	-2.339	0.9606	-4.7021	2.0655
Industrial-Industrial-Industrial	-0.0679	0.0565	-1.0096	0.8893	-2.0012	1.7979

Table 13. The effect CVR process on system line losses in different arrangements in scenario-4

Voltage reduction	Line losses in load arrangement					
	Residential-Commercial-Industrial	Residential-Industrial-Commercial	Industrial-Residential-Commercial	Industrial-Commercial-Residential	Commercial-Industrial-Residential	Commercial-Residential-Industrial
0%	0.0337	0.0317	0.03868	0.04872	0.048536	0.040703
2.25%	0.03339	0.03132	0.03811	0.04805	0.04822	0.04052
4%	0.3321	0.03110	0.03780	0.04769	0.04805	0.04043
6%	0.03301	0.03085	0.03743	0.04724	0.04782	0.04034
8%	0.03284	0.03063	0.03710	0.04683	0.04761	0.04022

Table 14. The changes in injected power by the source for different load arrangements during CVR processes in scenario-4

Supplied Power	The change in injected power at load arrangement					
	Residential-Commercial-Industrial	Residential-Industrial-Commercial	Industrial-Residential-Commercial	Industrial-Commercial-Residential	Commercial-Industrial-Residential	Commercial-Residential-Industrial
0%	1.6366	1.6341	1.6226	1.6096	1.6210	1.6348
2.25%	1.5866	1.5858	1.5751	1.5611	1.5694	1.5829
4%	1.5574	1.5574	1.5471	1.5327	1.5394	1.5527
6%	1.5192	1.5201	1.5104	1.4955	1.5005	1.5135
8%	1.4819	1.4835	1.4742	1.4591	1.4626	1.4757

Table 15. Results of 20% upward and 20% downward changes in the modeling coefficients: Scenario-4

Arrangement	Voltage (%) in coefficients change		Supplied power (%) in coefficients change		Line Losses (%) in coefficients change	
	-20%	+20%	-20%	+20%	-20%	+20%
Commercial-Residential-Industrial	-0.1290	0.1336	2.1554	-2.0654	2.6086	-2.5285
Commercial-Industrial-Residential	-0.1771	0.1698	2.3239	-2.2182	2.7089	-2.6252
Industrial-Commercial-Residential	-0.2109	0.1978	2.3623	-2.2289	3.1661	-3.0226
Industrial-Residential-Commercial	-0.2077	0.1889	2.1603	-2.0369	3.3910	-3.2016
Residential-Industrial-Commercial	-0.1868	0.1696	2.0108	-1.9033	3.2872	-3.0967
Residential-Commercial-Industrial	-0.1446	0.1363	2.0344	-1.9364	2.9503	-2.8122
Commercial-Commercial-Commercial	-0.2378	0.2127	2.6351	-2.3859	4.0344	-3.7050
Residential-Residential-Residential	-0.1938	0.1857	2.1681	-2.0192	2.8080	-2.7268
Industrial-Industrial-Industrial	-0.1114	0.1082	1.6218	-1.5829	2.1864	-2.1395

Table 16. The effect CVR process on system line losses in different arrangements in scenario-5

Voltage reduction	Line losses in load arrangement					
	Residential-Commercial-Industrial	Residential-Industrial-Commercial	Industrial-Residential-Commercial	Industrial-Commercial-Residential	Commercial-Industrial-Residential	Commercial-Residential-Industrial
0%	0.05859	0.05646	0.05537	0.05556	0.05672	0.05864
2.25%	0.06058	0.05780	0.05595	0.05622	0.05815	0.06064
4%	0.06188	0.05870	0.05642	0.05676	0.05916	0.06198
6%	0.06375	0.06003	0.05720	0.05767	0.06073	0.06396
8%	0.06580	0.06153	0.05818	0.05882	0.06256	0.06618

Table 17. The changes in injected power by the source for different load arrangements during CVR processes in scenario-5

Supplied Power	The change in injected power at load arrangement					
	Residential-Commercial-Industrial	Residential-Industrial-Commercial	Industrial-Residential-Commercial	Industrial-Commercial-Residential	Commercial-Industrial-Residential	Commercial-Residential-Industrial
0%	2.0722	2.0589	2.0430	2.0443	2.0615	2.0731
2.25%	2.0407	2.0280	2.0142	2.0163	2.0327	2.0431
4%	2.235	2.0111	1.9984	2.0010	2.0170	2.0267
6%	2.0024	1.9906	1.9792	1.9823	1.9979	2.0067
8%	1.9836	1.9722	1.9621	1.9657	1.9810	1.9889

Table 18. Results of 20% upward and 20% downward changes in the modeling coefficients: Scenario-5

Arrangement	Voltage (%) in coefficients change		Supplied power (%) in coefficients change		Line Losses (%) in coefficients change	
	-20%	+20%	-20%	+20%	-20%	+20%
Commercial-Residential-Industrial	-0.1680	0.1619	2.2005	-2.1074	2.5199	-2.4488
Commercial-Industrial-Residential	-0.1862	0.1784	2.2244	-2.1260	2.6673	-2.5880

Industrial-Commercial-Residential	-0.2176	0.2042	2.2438	-2.1194	3.1784	-3.0313
Industrial-Residential-Commercial	-0.2593	0.2344	2.2141	-2.0777	3.2446	-3.0606
Residential-Industrial-Commercial	-0.2495	0.2253	2.1837	-2.0533	3.2446	-3.0606
Residential-Commercial-Industrial	-0.1888	0.1782	2.1898	-2.0767	2.8574	-2.7320
Commercial-Commercial-Commercial	-0.1938	0.1857	2.1681	-2.0912	2.8080	-2.7268
Residential-Residential-Residential	-0.2966	0.2644	2.5348	-2.3046	3.8103	-3.5161
Industrial-Industrial-Industrial	-0.1553	0.1504	1.7306	-1.6848	2.1985	-2.1510

Table 19. The effect CVR process on system line losses in different arrangements in scenario-6

Voltage reduction	Line losses in load arrangement					
	Residential-Commercial-Industrial	Residential-Industrial-Commercial	Industrial-Residential-Commercial	Industrial-Commercial-Residential	Commercial-Industrial-Residential	Commercial-Residential-Industrial
0%	0%	0.05397	0.05269	0.05243	0.05320	0.05397
2.25%	2.25%	0.05349	0.05210	0.05170	0.05244	0.05367
4%	4%	0.05325	0.05179	0.05131	0.05203	0.05350
6%	6%	0.05296	0.05143	0.05083	0.05153	0.05329
8%	8%	0.05273	0.05112	0.05041	0.05107	0.05308

Table 20. The changes in injected power by the source for different load arrangements during CVR processes in scenario-6

Supplied Power	The change in injected power at the arrangement					
	Residential-Commercial-Industrial	Residential-Industrial-Commercial	Industrial-Residential-Commercial	Industrial-Commercial-Residential	Commercial-Industrial-Residential	Commercial-Residential-Industrial
0%	2.0193	2.0097	2.0056	2.0118	2.0228	2.0266
2.25%	1.9576	1.9513	1.9479	1.9511	1.9583	1.9614
4%	1.9216	1.9168	1.9138	1.9156	1.9209	1.9238
6%	1.8746	1.8716	1.8690	1.8693	1.8724	1.8751
8%	1.8276	1.8270	1.8248	1.8610	1.8254	1.8279

Table 21. Results of 20% upward and 20% downward changes in the modeling coefficients: Scenario-5

Arrangement	Voltage (%) in coefficients change		Supplied power (%) in coefficients change		Line Losses (%) in coefficients change	
	-20%	+20%	-20%	+20%	-20%	+20%
Commercial-Residential-Industrial	-0.0344	0.0459	-0.3837	0.2292	-1.1549	1.0172
Commercial-Industrial-Residential	-0.1028	0.034	-0.3704	0.2352	-0.9525	0.6685
Industrial-Commercial-Residential	-0.0456	0.0684	-0.3733	0.2724	-0.9190	0.6395
Industrial-Residential-Commercial	-0.0799	0.2099	-0.3385	0.3133	-2.1152	1.1100
Residential-Industrial-Commercial	-0.0914	0.1943	-0.4622	0.3215	-2.0071	1.1493
Residential-Commercial-Industrial	-0.0344	0.0459	-0.4245	0.2795	-1.1230	0.5772
Commercial-Commercial-Commercial	-0.0114	0.001	-0.1027	0.1541	-0.3477	0.4660
Residential-Residential-Residential	-0.1141	0.6897	-1.8890	3.9672	-3.8976	1.8568
Industrial-Industrial-Industrial	-0.0805	0.2852	-1.0049	0.8155	-2.0072	1.7822