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Virtual smoothing load duration curve in distribution system operation using IDVR

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ABSTRACT

Improving distribution systems performance has become a significant issue as a result of large increase in electrical power consumption during recent years. The system operators aim to enhance efficiency of the distribution system in both dynamic and static modes. While DFACTS has commonly been employed to promote distribution systems capability in dynamic mode, this paper proposes a new static technique based on using interline dynamic voltage restorer (IDVR) to make a virtual smooth load duration curve for the adjacent loads having different load curves. Such a technique can be used for peak shaving and help the operator postpones the system expansion necessity. Furthermore, as a result of virtual smoothing load duration curve, voltage security margin and system reliability which are two important topics in static performance of the distribution systems will be enhanced. The simulation results demonstrate the suitability of the proposed technique.

Introduction

Due to the large increase of electrical power consumption during recent years, it is required to expand the distribution networks. Almost in all networks, there are some challenges for system expansion such as economical, technical and environmental ones. Therefore, improving performance of the distribution systems has attracted more attention especially after power system restructuring. The system performance can be divided into two modes: dynamic and static [1].

The dynamic mode is concerned with the system state which is investigated based on time domain equations [1]. Different methods and equipments have been presented to enhance the efficiency of the distribution systems at the dynamic mode [1, 2]. FACTS devices are among the best equipments which are utilized by the system operators. They can be used for voltage sag mitigation [3-6] and dynamic stability improvement [7, 8], which are two important issues in dynamic studies.

The static mode studies are based on steady-state model of the system equations [1]. FACTS devices are able to enhance the power system efficiency at the static mode [9-11], such as congestion management and system stability enhancement [12, 13].

In the distribution systems, the distribution lines are responsible to transfer electrical power from transmission networks to the customers. System expansion cannot easily be performed due to aforementioned challenges. Accordingly, at the steady-state situation, the existing distribution feeders should operate at heavy load condition due to the large increase of electrical power consumption. Consequently, the system loadability decreases and the operating point moves toward the voltage instability point [1, 14-16]. Moreover, during this condition, the feeders may trip more often than before which increases the load interruption and causing reduction of the system reliability [17-19].

In the power system, if the operator is able to manage utilization of existing system equipments, it can improve the system performance. For example, the operator can utilize unstressed distribution feeders to control and decrease the electrical power which is transferred through the stressed feeders. It can be achieved by load shifting between different distribution feeders. This load shifting can manage electrical power which is transferred by the distribution feeders. It is noticeable that in this study, the loads are assumed to be constant PQ and the shifting is between electrical power which is transferred through the distribution feeders. Studying about the Microgrids which includes shiftable loads will be focused on the future paper.

In this paper based on using interline dynamic voltage restorer (IDVR) a new technique is proposed to virtually smooth the load duration curves of adjacent customers and reduce their peak load demand. This method improves static performance of the distribution networks and also enables the system operator to manage and control the load of feeders by load shifting. It results in decreasing maximum amount of the electrical power which the distribution lines should transmit to feed the loads. The suggested method is, therefore, able to postpone necessity of the system expansion due to the increase of electrical power consumption.

Also the proposed technique increases the system voltage stability margin and enhances reliability indices of the distribution networks. The suitability of the method is tested on a typical distribution network.

Basic concept of IDVR:

Dynamic voltage restorer (DVR)

Dynamic voltage restore (DVR) is a kind of FACTS device which is used for series compensation in distribution networks. The DVR can mitigate voltage sag and improve power quality of the system [5,6].

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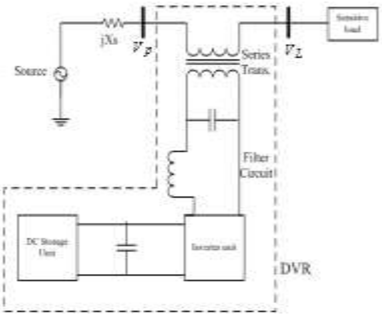
Fig.1 Shows the schematic diagram of a DVR



When a fault takes place in an upstream feeder, voltage at the load side decreases. Therefore, the DVR should inject voltage to the system through its series transformer to maintain voltage of the load side. Fig.2 (a) depicts the system under voltage sag condition. The DVR is modeled with a voltage source and the series reactance of transformer is ignored [5]. The series injected voltage of DVR can be calculated by Equation (1):

$$\overline{V}_{se} = \overline{V}_L - \overline{V}_{sag} + jX_S\overline{I_L} \qquad (1)$$

Voltage swell condition is opposite of voltage sag. Fig.2 (b) shows the system under voltage swell condition. Equation (2) can compute the series injected voltage of DVR:

$$\overline{V}_{se} = \overline{V}_L - \overline{V}_{swell} + jX_S\overline{I_L} \qquad (2)$$

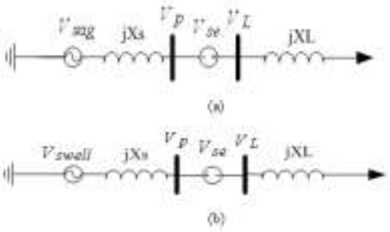


Figure 2- Equivalent circuit for the system under voltage sag (a), and voltage swell (b) conditions

The DVR is able to produce and absorb reactive power by controlling the series injected voltage (Vse). But to exchange active power with the system, the DVR needs the DC storage unit. The DC storage unit saves finite amount of energy, so it cannot support the critical load at the faulty condition for long period of time. It is one of the worst deficiencies of DVR.

Interline dynamic voltage restorer (IDVR)

To solve the limitation of storage unit of DVR, interline dynamic voltage restorer (IDVR) has been proposed. The IDVR consists of at least two DVRs inserted in different distribution feeders which are connected via a common DC link [4]. The feeders can be of the same or different voltage level. During voltage sag condition in one of the feeders, instead of using the storage unit, the IDVR feeds the faulty line by absorbing active power from the common DC link which is supported with the healthy lines. Therefore, IDVR can feed the interrupted loads during long time of voltage sag condition. A model of an IDVR for two compensated lines is depicted in Fig.3

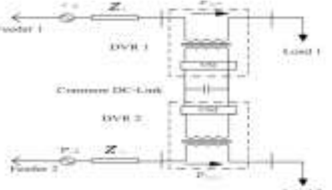


Figure 3- A simple IDVR system with two DVRs connected to a common DC-Link.

Steady-state model of IDVR:

Section 2 implies that the performance of IDVR is similar to interline power flow controller (IPFC) which uses the inverters with a common DC link for series compensation in transmission systems [4]. Hence, in this section, a steady-state power injection model is presented for the IDVR.

Consider in Fig.3 both feeders 1 and 2 originate from a single grid substation. Here, the electrical loss of IDVR is ignored and so the summation of injected active power of all inverters to the distribution feeders is equal to zero. Therefore, the IDVR can be modeled as illustrated in Fig.4 (a). V_a, V_b and V_c are voltage phasors, respectively, at buses a, b and c which can be defined as $V_m \angle \theta_m$ (m=a, b, c). $Vse_{an} \angle \theta se_{an}$ (n=b, c) is the controllable voltage phasor which the IDVR injects to the lines through the series transformers. The power injection model of IDVR is depicted in Fig.4 (b). Equations (3) to (6) present the injected power at buses a, b and c, respectively [20, 21]:

$$P_{inj,a} = \sum_{m=b,c} V_a V_{seam} Y_{am} \sin(\theta_a - \theta_{seam}) \qquad (3)$$

$$Q_{inj,a} = -\sum_{m=b,c} V_a V_{seam} Y_{am} \cos(\theta_a - \theta_{seam}) \qquad (4)$$

$$P_{inj,m} = -V_m V_{seam} Y_{am} \sin(\theta_m - \theta_{seam}) \ , m = b,c \qquad (5)$$

$$Q_{inj,m} = -V_m V_{seam} Y_{am} \cos(\theta_m - \theta_{seam}) \ , m = b,c \qquad (6)$$

Voltage security assessment:

The voltage security is an important issue in the distribution systems and should be considered in many programming and planning problems. There are different methods to assess system voltage security. Using voltage stability indices is one usual method to assess system voltage security. A number of voltage stability indices are proposed in literature to evaluate the voltage security condition in the distribution networks [14-16]. Ref. [16] presents one of the usual indices which can be calculated for all buses of the distribution network. The index is formulated by Equation (7) for the simple two buses system of Fig. 5.

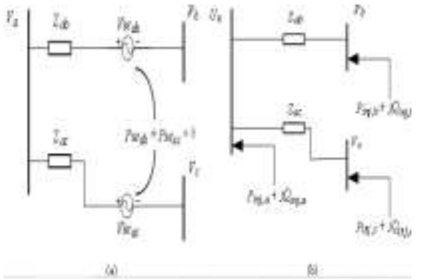


Figure 4- Equivalent circuit (a), and power injection model (b) of IDVR.

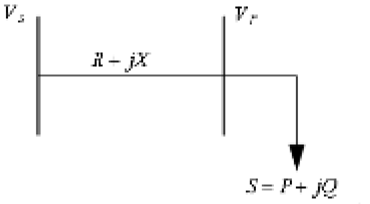


Figure 5- A simple two-bus system

$$SI_r = V_S^4 - 4V_S^2(RP+XQ) - 4(XP-RQ)^2 \qquad (7)$$

Where:

Vs: Amplitude of voltage of the sending bus;

P: Active power demand at the receiving bus (r);

Q: Reactive power demand at the receiving bus;
R: Resistance of the line;
X: Reactance of the line.

By increasing the electrical power consumption at bus r, the network moves toward the collapse point and the SIr index decreases. In the other words, the SIr index far from zero indicates that the node and consequently the system have more voltage security margin. The node with the least value of stability index is known the weakest node and is highly sensitive to voltage collapse.

Virtual smoothing load duration curve:

System expansion requirement

Load duration curve is a diagram showing the amount of electrical energy that each customer uses over the course of time. For almost all customers, the load curve is not smooth and varies at any given time in a day. The lines which are responsible for transferring the electrical power to the customers should be designed so as to satisfy the maximum power demand of loads. In other words, by the load increase, the transfer capability of lines requires to be promoted. However, due to several challenges such as technical, economic and environmental problems, there are limitations on the power system expansion. Such issues make the existing transmission and distribution lines suffer from operating at heavy load conditions. This may cause undesirable effects on the power system such as:

- Voltage instability: While the lines of network are heavy loaded, operating point of the system moves toward the voltage instability point and the voltage stability margin will be reduced.
- Reliability decline: Under the mentioned condition, network lines may trip more often than before. It then leads to an increase in the loss of load expectation.

Proposed method

Consider two adjacent customers having uneven load duration curves whose peak demands do not occur simultaneously. The loads are connected to a substation bus through a separate feeder. When one of the loads is at the peak demand, the feeder which is connected to that is heavy loaded. At the same time, the second load is not at its peak demand and so its related feeder is not heavy loaded.

By means of IDVR, the system operator can transfer electrical power from one feeder to another. Actually, IDVRs can be employed to adjust distributed power between feeders based on the load demands. By controlling transmitted power during different hours of the day, it is then possible to have a smooth virtual load distribution curve for both feeders. Accordingly, no feeder becomes heavy loaded and the carried load decreases. Such an approach helps the system operators to postpone the systems expansion since decreasing the maximum transmitted power defers the present need for the required extension to a later time. The system eigen values also become far from jw axis pushing the system away from the instability point as long as the feeders carry fewer loads than before. The fewer the carried load becomes, the fewer the voltage collapsibility potential would be. Furthermore, the fewer the transmitted load is, the less times the feeder trip. In this technique, IDVR plays the role of an additional line, therefore the system reliability indices can as well be enhanced. To demonstrate application of the proposed technique, a case study is presented which shows, in details, how IDVRs can be employed to provide the aforementioned benefits in the static mode.

Case study

The proposed technique has been tested on a distribution system which is shown in Fig.6. The system has three loads and two feeders. An uninterruptible infinite bus supplies electrical power demand of the system through a 138/33 KV transformer. The system data are given in Appendices A and B. The following abbreviations are used in this section:

SIi: Voltage stability index of bus i
ASI: Average system voltage stability index (,n=number of PQ nodes × number of load levels)
LLi: Load level i
CB: Circuit breaker

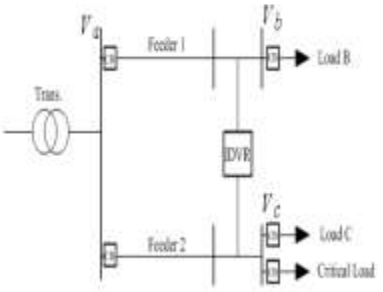
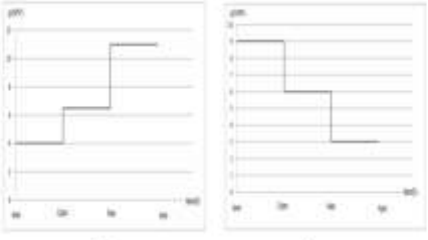


Figure 6- Simplified diagram of the study system

Fig.7 depicts the load duration curves of the customers of buses b and c which have three levels: light load, intermediate load and peak load. Note that Fig.7 (b) is the load duration curve of the summation of the load c and the critical load which are located at bus c. The load curves are not smooth and their peak demands do not occur simultaneously.

It is assumed that customer's electrical power demand increases 5% per year. Table 1 indicates that the system can support the loads until one additional year (2011) while there is not any IDVR in the system. By installing IDVR, the system operator is able to adjust the electrical power which is transmitted by each of feeders and decreases the maximum amount of that. Fig.8 depicts the virtual load curve of each feeder. Column 3 of Table 1 demonstrates that the IDVR postpones the system expansion requirement for 7 years.



(a) (b)

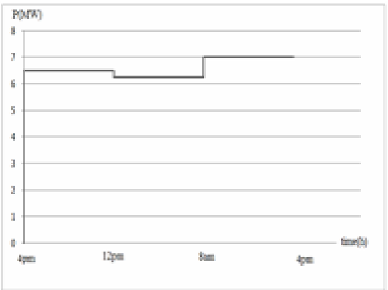


Table 2 represents the load flow results for three load levels before IDVR installation in the system. Columns 2 and 3, Pnet, t and Qnet, t, are the total active and reactive power injected to the system by the infinite bus. The total active and reactive power loss of the system, Ploss, t and Qloss, t, are depicted in columns 4 and 5, respectively. Finally, the voltage of power of PQ buses, b and c, are shown in columns 6 and 7.

After IDVR installation and using its power injection model, the load flow analysis is carried out. The results are shown in Table 3. In this simulation, the amount of reactive power which the inverters inject to each bus of the system is according to the second and third columns of Table 3.

The comparison of Tables 2 and 3 shows that, the total active and reactive power loss for three load levels are decreased by using IDVR. It also improves the voltage profile of the system PQ buses.

The system data and load flow analysis results, Tables 2 and 3, were utilized to investigate system voltage stability at three load levels. The results are displayed in Fig. 9 (a) and (b) for both buses b and c, respectively. As it is shown in Fig. 9, application of IDVR results in an increase in all voltage stability indices. This happens, especially, for bus b at load level three which is the weakest bus, i.e., the most sensitive node for voltage collapse.

The average amounts of voltage stability index for all buses of the system (ASI=) without and with IDVR are 0.778 and 0.848, respectively. The percentage of average voltage stability improvement after IDVR installation is about 10% which is very desirable. As these data and Fig.9 reveal, as long as IDVR is used, the operating point of system is more far from the critical point, accordingly, the probability of voltage collapse is reduced.

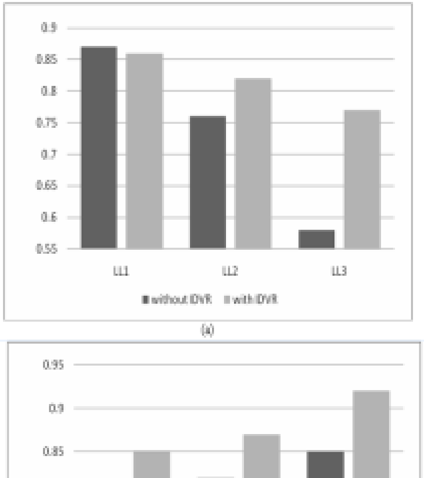


Figure 9- Voltage stability indexes for buses b (a) and c (b)

The system reliability analysis before IDVR installation indicates that the loads B, C and critical load reliability is equal to 0.8664, 0.8754 and 0.8754, respectively. It is clear that the results are equal for three load levels.

Assume that the system operator installs the IDVR. Table 4 depicts the results of reliability analysis in this case. Application of IDVR is similar to a virtual auxiliary feeder added to the system and making an interconnection between feeders 1 and 2. If a fault occurs at one of the lines, the virtual feeder uses the free capacity of the healthy feeder to support the interrupted loads. Therefore, the system reliability is increased. There are some reliability indices in the distribution networks which are very important for the system operators and customers. The previously described system with reliability parameters and average load data, as presented in Appendix B, are employed to evaluate the effect of the proposed method on these indices.

Fig.10 (a) and (b) represent five of the most important reliability indices with and without IDVR, respectively. From this figure, it is clear that IDVR noticeably improves all of these indices. For example, the amount of SAIDI in Fig.10 (b) is reduced about %66 in comparison to Fig.10 (b) which is remarkable.

Also, the system operator is able to decrease the amount of expected energy not supply (ENS) from 12.8 MWh/yr (before the IDVR installation) to 4.4 MWh/yr by utilizing IDVR. The reduction is about %65.

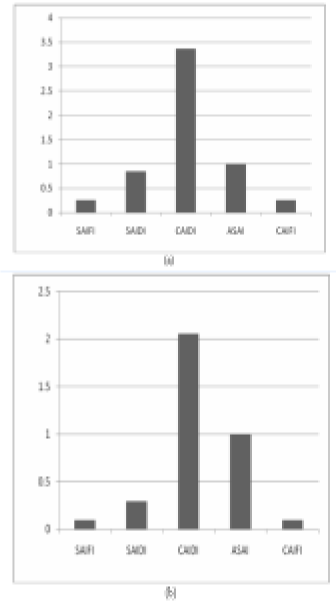


Figure 10- Distribution system reliability indices without (a) and with (b) IDVR

Conclusion

In this study, virtual smoothing of load duration curves has been utilized to enable system operators to increase system loadability. It accordingly could improve the system performance and decrease the necessity of system expansion. The method enhanced the static voltage stability and increased the reliability of the distribution networks. When it comes to the system operation and planning, these two indices are highly important.

Though, IDVRs have commonly been recommended for enhancement of the dynamic performance of distribution networks, this paper employed the IDVR to improve static performance of distribution networks. IDVRs were used to make virtual smooth load duration curves for the feeders. Besides, IDVRs acted as an auxiliary line resulted in promotion of system reliability indices.

The proposed technique was tested on a typical distribution network. It was demonstrated that the virtual load curve smoothing is an appropriate technique in enhancement of static performance of distribution network. For an instance, application of IDVRs yielded in 65 percent decrease in ENS which is one of the most important reliability indices.

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Appendix A

Transformer data:

138/33 KV, 30 MVA, 0.09 pu

Distribution feeder data:

Length of feeder 1= 16 km
Length of feeder 2= 15km
Reactance= 0.25 Ω/km
Resistance= 0.45 Ω/km
Total transfer capability of feeder 1 = 14 MVA
Total transfer capability of feeder 1 = 11 MVA

Load B data:

Power factor= 0.85
Light load level (LL1)= 4 MW
Intermediate load level (LL2)= 6.5 MW
Peak load level (LL3)= 11 MW

Load C data:

Power factor= 0.93
Light load level (LL3)= 2.7 MW
Intermediate load level (LL2)= 5.5 MW
Peak load level (LL1)= 8 MW

Critical load data:

Power factor= 0.97
Light load level (LL1)= 0.3 MW
Intermediate load level (LL2)= 0.5 MW
Peak load level (LL1)= 1 MW

Reliability data:

Reliability of feeder 1 = 0.96
Reliability of feeder 2 = 0.97
Reliability of the IDVR = 0.98
Reliability of the circuit breakers = 0.95

Appendix B

Load B:

Power factor = 1
Number of customers = 8
Average demand of each customer = 1MW

Load C:

Power factor = 1
Number of customers = 6
Average demand of each customer = 1MW

Critical load:

Power factor = 1
Number of customers = 1
Average demand of each customer = 1MW

Average failure rate λ (f/yr):

Feeder 1 = 0.3   Feeder 2 = 0.2

Average outage time r (hours):

Feeder 1 = 3   Feeder 2 = 4

Table 1- System expansion necessity due to the load increasing

Year	Without IDVR	With IDVR
2011	No	No
2012	Yes	No
2013	Yes	No
2014	Yes	No
2015	Yes	No
2016	Yes	No
2017	Yes	No
2018	Yes	Yes

Table 2- Load flow results without IDVR

	$P_{net,t}$ (MW)	$Q_{net,t}$ (MVAr)	$P_{loss,t}$ (MW)	$Q_{loss,t}$ (MVAr)	U_b (pu)	U_c (pu)
LL_1	13.432	6.915	0.432	1.435	0.968	0.947
LL_2	12.887	7.330	0.387	1.330	0.945	0.964
LL_3	14.804	10.177	0.804	2.377	0.894	0.974

Table 3- Loads flow results with IDVR

	$Q_{inj,b}$ (MVAr)	$Q_{inj,c}$ (MVAr)	$P_{net,t}$ (MW)	$Q_{net,t}$ (MVAr)	$P_{loss,t}$ (MW)	$Q_{loss,t}$ (MVAr)	U_b (pu)	U_c (pu)
LL_1	2	1.8	13.331	2.833	0.331	1.153	0.963	0.960
LL_2	2	1.8	12.819	3.299	0.319	1.099	0.952	0.965
LL_3	2	1.8	14.474	5.544	0.474	1.544	0.947	0.985

Table 4- Reliability of loads with IDVR

	Load B	Load C	Critical load
LL_1	0.8664	0.9812	0.9812
LL_2	0.9810	0.9812	0.9812
LL_3	0.8664	0.8754	0.9812

Table 5- Average reliability of loads for three load levels

	Load B	Load C	Critical Load
without IDVR	0.8664	0.8754	0.8754
with IDVR	0.9046	0.9460	0.9812
%Δloss of load expectation	-%28.59	-%56.66	-%84.91