The Effects of Air Conditioner Load on Voltage Stability of Urban Power System

BEI WU, YAN ZHANG, MINJIANG CHEN
School of Electrical Engineering
Shanghai JiaoTong University
No.800, Dongchuan Rd., Shanghai 200240
CHINA

Abstract: - Based on reactive power-voltage characteristics analysis of air conditioners, the effects of air conditioner load on voltage stability of an urban power system are investigated in this paper. Indexes for evaluating bus voltage security are proposed, and static voltage stability analysis method is adopted. The computational analysis of a real urban power system in East China shows that air conditioner load has a bad impact on voltage stability of an urban power system. With an increase in air conditioner load, bus voltage security and voltage stability of the system decrease. So measures should be taken to prevent voltage instability, especially for the system which has small loading margin and poor reactive sources.

Key-words: - Air conditioner load, voltage stability, bus voltage security, V-Q curve, load model, loading margin

1 Introduction

With the continuing increase in the demand for electric power, the voltage stability problem becomes more complex and serious. Cases of voltage instability leading to system collapse have been observed in Japan, the United States, Canada and so on [1-3]. These events generally took place in heavily loaded power systems, and had a strong impact on social economy. Since voltage instability is today considered as the main threat to stability, security and reliability of power systems, increasing attention has been contributed to voltage instability phenomena and great efforts have been made on it [4-7].

Among the factors influencing system voltage stability, load characteristic is the most key and direct one. In the summer of 1987, the power system failure occurred in the service area of the Tokyo Electric Power Company, Inc [3]. When this failure occurred, there are no abnormal operating conditions and other faults. One of the considerable causes is the continued growth of air conditioner load. Accident analysis considered that air conditioners, with the characteristics of voltage down causing current rise, played an adverse role in the incident. Large numbers of air conditioning equipments hastened voltage collapse of the system, since they presented high reactive power consumption during depressed voltage conditions.

In these days, with the torrid economic growth and the development of the living standard of the people, an increasing percentage of the load is air conditioners for summertime conditions. In some cities of China, air conditioners account for more than 40% of the total loads. The especial reactive power-voltage (V-Q) characteristic of air conditioner load threats voltage stability of urban power system. Researching on the effect of air conditioner load on voltage stability of urban power system is useful for operators to take preventive measures, which is significant for power system to operate safely and stably.

In this paper, an air conditioner load model based on test data is presented. On the basis of reactive power-voltage characteristics analysis of air conditioner load, the effects of air conditioner load on the voltage stability are investigated for a real urban power system in East China, including the effects of air conditioners on bus voltage security as well as the effects of the loads with different composition on voltage stability of the whole power system.

2 V-Q Characteristics Analysis of Air Conditioner

Induction motor provides the motive power for air conditioner. Although there are fan electromotor, thermostat and other electrical and machine elements besides induction motor in air conditioner, they present low power consumption. Thus, air conditioner has the similar load characteristics to induction motor. The steady-state active power drawn by air conditioners is fairly independent of voltage. Air conditioner reactive power is more sensitive to voltage levels. As voltage drops, the reactive power will fist decrease as a result of reduction of excitation power drawn by motor core accordingly, but then increase as the voltage drops further because of the rapid increasing of the reactive loss in leakage reactance of motor.

Fig. 1 illustrates the V-Q characteristic of an air conditioner (KFR-32GW/B) with rating power/current: 1220W/5.8A. The curve was obtained by testing the air conditioner under standard cooling condition and under-voltage protection was released in the experiment. From Fig.1, as expected, the V-Q curve of the air conditioner has a distinct shape "U". In the vicinity of rating voltage, an increase or decrease in the reactive power consumed by the air conditioner is accompanied by an increase or decrease in voltage. But as voltage drops to a certain extent (0.83 per unit or so, i.e. "knee"), the reactive demand of air conditioner is observed to have an upward tendency. That is, when the air conditioner voltage is well below rating voltage, the reactive power drawn by air conditioner increases noticeably with decreased voltage.

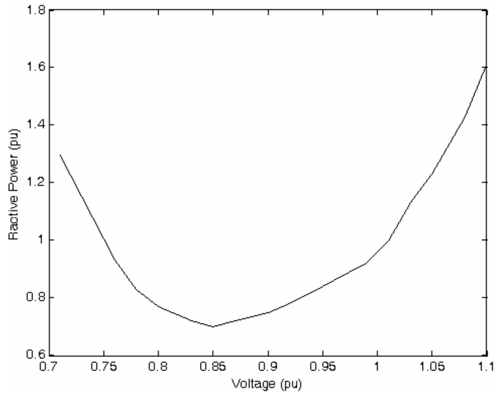

Fig. 1 V-Q characteristic of an air condition under standard cooling condition

The reactive power – voltage characteristic of air conditioner plays a notable adverse role in voltage stability of power system. It is because that in order to maintain voltage at an acceptable level sufficient reactive sources, which are used to meet the reactive demand of loads and to compensate the reactive loss, are necessary. If the system is lack of reactive sources, the reactive power of the system will maintain balance at low voltage level, that is to say, the shortage of reactive sources is covered through low voltage and the reduction of reactive power drawn by loads. However, the characteristics of air conditioners, which draw more reactive power at low voltage level, will bring voltage levels down further and is obviously detrimental to voltage stability of the power system.

3 Problem Formulation

Although voltage stability is a dynamic phenomenon, system dynamics influencing voltage stability are usually slower forms. The system can be assumed in a quasi stable state, and therefore voltage stability can be effectively analyzed by using static methods.

Static analysis technique, which examines the viability of the equilibrium point represented by a specified operating condition of the power system, without taking dynamic effects resulting from other control actions into account, has been successfully used for detailed postmortem analysis of actual system events [8].

Static analysis technique based on power flow simulation methodology is employed to study on the influence of air conditioners on bus voltages and voltage stability of the whole system. In order to give prominence to the influence made by air conditioners, the dynamic characteristics of synchronous generators, on-load tap-changing transformers and reactive compensating devices are neglected in the research.

The research on the effects of air conditioners on bus voltages involves two aspects: (i) taking some 10-KV buses of the system as representative buses to calculate these bus voltages and the secondary voltages of the higher substation that connected to these buses, comparing these values when there is no air conditioners with those bus voltages when air conditioners comprise a much larger share of loads at these 10-KV buses. These comparisons account for the impacts that air conditioners have on bus voltages; (ii) research on effects of air conditioners on bus voltage of the higher substation by changing the percentage that air conditioners account for of the total loads of 10-KV buses.

Then the effects of increasing loads on voltage stability of 220-KV power system with different load class composition are investigated.

3.1 Load model

Load characteristics are among the key factors influencing system voltage stability. Besides air conditioners, load types of urban power system include lighting, electric heating, televisions, computers, equipments, etc. Lighting and heating-type loads have the similar characteristic to constant impedance. Within adjustable voltage limits the characteristics of televisions and computers are similar to air conditioners, but once voltage drops below 0.9 per unit, these loads will drop out under the control of their own protective devices. According to the proportion of each component on the total reactive power of the composite load and their load characteristics, the reactive power of the composite load at bus voltage magnitude U_k can be expressed as:

$$Q_k = \sum_{i=1}^{n} \rho_i Q_{ki} \qquad (1)$$

Where Q_k , Q_{ki} are reactive components of the composite load and the i^{th} load component at U_k respectively, ρ_i defines the proportion of the i^{th} load component at this bus.

In order that the load power variation with voltage could be simulated better, the polynomial model, commonly referred to as the ZIP model, is adopted to describe the reactive characteristics of the load [9]:

$$Q = Q_{\mathrm{b}}(b_2U^2 + b_1U + b_0) \qquad (2)$$

Where Q_b is reactive component of the load when the bus voltage is rating voltage. The V-Q curve of bus load is obtained based on various U_k and corresponding Q_k , and the coefficients of the load polynomials $b_0 \sim b_2$ are computed by curve fitting. Various percentages of air condition result in different V-Q curves, and thereby different load polynomials $b_0 \sim b_2$, and then various ZIP models are obtained.

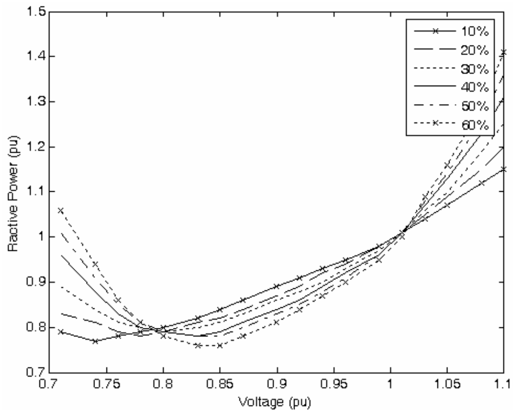

Fig.2 V-Q curves of composite loads

Fig.2 illustrates the V-Q curves of the composite loads with various percentages of air conditioners.

Comparing Fig.2 with Fig.1 shows that, the "knees" of composite loads are lower than that of air conditioner loads. The "knee" voltage increases with an increase in the percentage of air conditioners. The larger the percentage is, the clearer the "U" shape of the characteristic of composite loads is.

3.2 Bus voltage security assessment

The Reactive Power Reserve Coefficient K_Q and Voltage Stability Reserve Coefficient K_U are defined to evaluate voltage stability at operating point:

$$K_Q = \frac{Q_{\max} - Q_0}{Q_{\max}} \quad (3)$$

$$K_U = \frac{U_0 - U_{cr}}{U_{cr}} \quad (4)$$

Where U_0 and Q_0 is bus voltage magnitude and reactive power provided by the system at the operating point respectively, $Q_{\max}$ is the maximum value of reactive power that can be supplied at the bus when the active demand of the bus is P_0 and U_{cr} is corresponding voltage magnitude, i.e. the critical voltage of the V-Q characteristic of the bus. K_Q or K_U indicate how close Q_0 or U_0 is to the maximum reactive power $Q_{\max}$ or critical voltage U_{cr}.

At the operating point, if reactive power Q_0 and bus voltage magnitude U_0 meet $Q_0 < Q_{\max}$ and $U_0 > U_{cr}$, the bus is in a stable state with the reactive load P_0.

From (3) and (4), it is obvious that the higher U_{cr} is, the smaller K_U is, and the smaller $Q_{\max}$ is, the smaller K_Q is. Hence, the increase in U_{cr} or the decrease in $Q_{\max}$ indicates that the bus voltage stability level drops.

3.3 Voltage stability assessment for power system

For a particular operating point, the amount of additional load in a specific pattern of load increase that would cause a voltage collapse is called the loading margin. In this study, we are interested in how the loading margin of a power system varies as the percentage of air conditioner varies.

It is known that conventional power-flow algorithms are prone to encounter convergence problems at operating conditions near the stability limit. The continuation power-flow analysis, which overcomes this problem, is employed in this paper.

4 Practical Applications

The methods described above are applied to a real urban power system in East China for investigating the effects of air conditioner on voltage stability of urban power system. The 2004 summer peak case is used for this study, with expected peak load of 660MW in this city. The highest running voltage level of the urban power system is 220-KV, and MOCH is one of the key 220-KV substations, which located in the thriving commercial area. XINJK, YUNNL and HUJ are substations with two 110/10-KV, 50MVA transformers supplied by MOCH respectively, whose major part of the load on the secondary side are air conditioners.

Due to the close relationship between reactive power and voltage stability, constant impedance load model or ZIP model is applied to reactive load for different purpose of analysis, while constant active power characteristics is assumed for loads of all buses.

4.1 The effects of air conditioners on bus voltage security

(i) The 2004 summer peak case is taken as base case. Increase reactive loads, modeled by constant impedance load model or ZIP load model with 40% air conditioners, on the secondary side of the three representative substations XINJK, YUNNL and HUJ from base case. The critical values of the secondary voltages of the representative substations and MOCH as well as the maximum reactive power supplied from them are calculated. Table.1 lists the results of XINJK and MOCH.

Table 1 Results for different reactive load models

Load Model	XINJK		MOCH	
	U_{cr}	Q_{max} (MVar)	U_{cr}	Q_{max} (MVar)
Constant Impedance	0.5757	40	0.7801	425
ZIP	0.7525	30	0.8824	262

Table 1 shows that when air conditioner is a major part of the load on the secondary side of the representative 110-KV substations, the maximum reactive power that can be supplied from MOCH is lower than that with no air conditioner, with the value decreasing from 425 MVar to 262 MVar, and the corresponding critical voltage rises from 0.7801 per unit to 0.8824 per unit. It is evident that air conditioners are more onerous for bus voltage security.

(ii) Take the 2004 summer peak case as base case. The critical values of the secondary voltages of the representative substations and MOCH as well as the maximum reactive power supplied by them are calculated, with alerted percentage that air conditioners account for of the loads on the secondary side of XINJK, YUNNL and HUJ.

Table 2 Results for alerted percentage of air conditioner load

Percentage of Load Modeled as Air Conditioner	XINJK		MOCH	
	U_{cr}	Q_{max} (MVar)	U_{cr}	Q_{max} (MVar)
10%	0.5883	40	0.7868	416
20%	0.6715	36	0.8356	343
30%	0.7108	33	0.8583	305
40%	0.7525	30	0.8824	262
50%	0.7809	27	0.8989	231
60%	0.8035	25	0.9119	206

Table 2 shows the results of XINJK and MOCH. The critical values of the secondary voltage of 110-KV substations as well as 220-KV substation increase with an increase in air conditioner loads, while the maximum reactive power supplied from them decreases, which make against to voltage stability. Obviously, load composition contributes greatly to bus voltage security.

4.2 The effects of different load composition on voltage stability

Loading margin, which can be obtained by the continuation power flow, is used as index to assess voltage stability for different load composition. The 2004 summer peak case is taken as base case. The active and reactive components of loads of three representative substations are uniformly scaled up. When air conditioners comprise a larger share of the total load of these representative substations, 40% assumed, loading margin of the system is 1886MW. If no air conditioners are included in the loads, the loading margin will be 2038MW, larger than that with lots of air conditioners. Take the secondary side of MOCH as an example, the upper PV curves of the bus are presented in Fig.3:

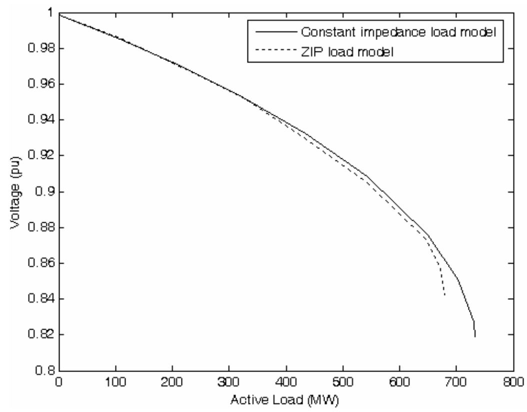

Fig.3 The upper PV curves on the secondary side of MOCH with different load models

As large loading margin indicates the long distance from studied operating point to voltage collapse point, it appears that air conditioner load makes the power system more prone to voltage collapse comparing with constant power load. This may be verified by modal analysis [9]. In base case, when reactive loads on the secondary side of the three representative substations are modeled as ZIP load model with 40% air conditioners, the minimum eigenvalue of reduced Jacobin matrix of power flow is calculated to be 1.2579, while it will be 1.7342 when constant impedance load is considered instead of air conditioner load. As is well known [9], the smaller the magnitude of the minimum eigenvalue, the closer the system voltage is to being unstable.

5 Conclusions

In this paper, the effects of air conditioners steady-state characteristics on voltage stability of an urban power system are investigated. The application to a real urban system in East China shows that (i) a high percentage of air conditioners loads at 10-KV bus will reduce the maximum reactive load supplied from the bus and increase the critical voltage, and therefore push the bus voltage security into danger; (ii) the higher the percentage of air conditioners is, the lower the maximum reactive loads is and the larger the critical bus voltage is. This makes against bus voltage security. A further analysis of loading margin employing continuation power flow shows that air conditioner load will reduce the maximum loadability of the system, and plays an adverse role in voltage stability of power system.

On the basis of the proposed procedure, work is in progress to put forward sound reactive power compensation measure to enhance voltage stability of urban power system.

References:

[1] D. Novosel, M.M. Begovic, V. Madani, Shedding Light on Blackouts, *IEEE Power and Energy Magazine*, Vol.2, No.1, 2003, pp. 3-43.

[2] U.S.-Canada Power System Outage Task Force. *Final report [EB/OL]*, March 31, 2003.

[3] A. Kurita and T. Sakurai, The Power System Failure on July 23, 1987 in Tokyo, *Proceedings of the 27th Conference on Decision and Control*, Austin, Texas, 1988.

[4] H.D. Chiang, A.J. Flueck, K.S. Shah, et al, CPFLOW: A Practical Tool for Tracing Power System Steady State Stationary Behavior Due to Load and Generation Variations, *IEEE Trans. on Power System*, Vol.10, No.2, 1995, pp. 623-634.

[5] Z. Feng, V. Ajjarapu, D.J. Maratukulam, Identification of Voltage Collapse through Direct Equilibrium Tracing. *IEEE Trans. on Power Systems*, Vol.15, No.1, 2000, pp. 342-349.

[6] J. Yang, H.Z. Li, C.M. Wang, et al, A Hybrid Way to Construct Static Voltage Stability Region Based on Combining Loop Current with Node Voltage, *WSEAS Trans. on Circuits and Systems*, Vol.4, No.11, 2005, pp. 1737-1741.

[7] L.A. Zarate, C.A. Castro, J.L.M Ramos, et al. Fast Computation of Voltage Stability Security Margins Using Nonlinear Programming Techniques, *IEEE Trans. on Power System*, Vol.21, No.1, 2006, pp. 19-27.

[8] C.W. Taylor, *Power System Voltage Stability*, New York: McGraw-Hill Inc, 1994.

[9] P. Kundur, *Power System Stability and Control*, New York: McGraw-Hill Inc, 1994.