# Influence of Load Characteristics on System Dynamics and Load-Shedding Control Effects in Power Grid

LI Ye, ZHANG Baohui, *Senior Member, IEEE*, TAN Tingyue, GUAN Zhe

School of Electrical Engineering, Xi'an Jiaotong University, Xi'an 710049, China
E-mail: ly.lycc@stu.xjtu.edu.cn

**Abstract:** Diversified load characteristics may cause utterly different system dynamics such as the frequency dynamic and voltage dynamic, thus having different influence on under-voltage and under-frequency load-shedding control effects. This paper analyzes the four load characteristics such as the constant impedance load, the constant current load, the constant power load and the induction motor. These four loads responses differently and have different active/reactive power dynamics during separations in the power grid. Simulations illustrate that the induction motor may lead to severe oscillations and voltage collapses due to the lack of reactive power supply, thus triggering under-voltage load-shedding control. However, the ZIP loads tend to cause frequency drop because of insufficient active power supply, thus triggering under-frequency load-shedding control. In addition, unlike the ZIP loads, the induction motor is more likely to result in system instabilities after executing the same magnitude of load curtailments. Therefore, it is imperative to execute load shedding at the induction motor first in order to guarantee both the frequency stability and voltage stability.

**Key Words:** Load characteristics, Load-shedding control, System dynamics, Frequency stability, Voltage stability

## 1 INTRODUCTION

With the development of the power grid, system stabilities, such as angle stability, voltage stability and frequency stability, have attracted much attention [1-2]. Moreover, the great increment of induction motors in the power grid may increase the risk of system instabilities. Therefore, it is necessary to study the influence of load characteristics on system dynamics and load-shedding control effects in the power grid.

Recently, scholars have done much work on load modelling and simulations. Ragu tried to evaluate the influence of induction motor modelling on under-voltage load shedding [3]. Vivaldo analyzed the detailed induction motor model for voltage stability estimation [4]. Wu Shengyu studied the influence of sudden increase of dynamic loads on voltage stability [5]. Xu Taishan, Sun Huadong and Wang Yihong et al. have conducted much work on measuring the degree of transient voltage instability with considerations on the induction motor [6-8]. Zhang Qiang studied the impact of load characteristics on frequency stability [9]. C. X. Ren analyzed the negative control effects of UFLS/UVLS caused by load characteristics [10]. Hou Yuqiang proposed a new method automatic load-shedding control based on frequency and voltage dynamics interaction [11].

However, few scholars have studied the influence of different load models on system dynamics and load-shedding control effects of conventional UVLS and UFLS when there is severe mismatch power during power system separations.

This paper analyzes the four load characteristics such as the constant impedance load, the constant current load, the constant power load and the induction motor. These four loads response differently and have different active and reactive power dynamics during separation disturbances in the power grid.

Simulations illustrate that the induction motor may lead to severe oscillations and voltage collapses due to the lack of reactive power supply, thus triggering under-voltage load-shedding control. However, the ZIP loads tend to cause frequency drop because of insufficient active power supply, thus triggering under-frequency load-shedding control. In addition, unlike the ZIP loads, the induction motor is more likely to result in system instabilities after executing the same magnitude of load curtailments. Therefore, it is imperative to execute load shedding at the induction motor first in order to guarantee both the frequency stability and voltage stability.

## 2 ANALYSES OF DIFFERENT LOAD CHARACTERISTICS

Different load characteristics will result in different load dynamics such as the active power and reactive power. As for the ZIP load models such as the constant impedance load, the constant current load and the constant power load, their active and reactive power can be expressed as follows:

$$P_Z = P_0 \frac{V^2}{V_0^2} \qquad Q_Z = Q_0 \frac{V^2}{V_0^2} \tag{1}$$

$$P_I = P_0 \frac{V}{V_0} \qquad Q_I = Q_0 \frac{V}{V_0} \tag{2}$$

$$P_P = P_0 \qquad Q_P = Q_0 \tag{3}$$

where $P_z$ and $Q_z$ represent the active and reactive power of the constant impedance load, $P_I$ and $Q_I$ represent the active and reactive power of the constant current load, $P_P$ and $Q_P$

represent the active and reactive power of the constant power load, $V$ denotes the load voltage, $V_0$ is the rated load voltage.

It is obvious that the active/reactive power of both the constant impedance load and the constant current load will decrease when the load voltage drops during disturbances, while the active/reactive power of the constant power load will stay the same.

Furthermore, the active and reactive power of the induction motor can be inferred from Fig 1 where $P$ and $Q$ represent the active and reactive power of the induction motor, $V$ represents the load voltage, $R_r/s$ and $X_r$ represent the rotor impedance, $R_s$ and $X_s$ represent the stator impedance, $s$ denotes the slip of the induction motor, $X_m$ is the excitation reactance.

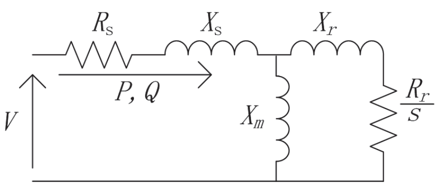

Fig 1. Simplified model of the induction motor.

To simply the analyses, we therefore ignore the effects of both the reactance $X_m$ and the stator resistance $R_s$, then we can obtain the active and reactive power of the induction motor which are given by

$$P = \frac{V^2 R_r}{s((\frac{R_r}{s})^2 + (X_s + X_r)^2)} \tag{4}$$

$$Q = \frac{V^2 (X_s + X_r)}{(\frac{R_r}{s})^2 + (X_s + X_r)^2} \tag{5}$$

Moreover, the differential equation of the slip $s$ of the induction motor is given by

$$2H\dot{s} = T_m - T_e \tag{6}$$

where $T_m$ is the mechanical torque and $T_e$ is the electromagnetic torque which depends on the load voltage level. In addition, $H$ denotes the rotor inertia.

When the load voltage drops, the slip $s$ of the induction motor will increase gradually because the electromagnetic torque decreases with the decrement of load voltage as shown in Eq. (6), thus causing the induction motor to be locked finally. Furthermore, the derivation of active power and reactive power of the induction motor can be derived from Eq. (4) and Eq. (5) as follows:

$$\frac{dP}{dt} = p_v \frac{dV}{dt} + p_s \frac{ds}{dt} \tag{7}$$

$$\frac{dQ}{dt} = q_v \frac{dV}{dt} + q_s \frac{ds}{dt} \tag{8}$$

where $p_v$, $p_s$, $q_v$ and $q_s$ represent the coefficients which are calculable as:

$$p_v = \frac{2R_r V}{\frac{R_r^2}{s} + s(X_r + X_s)} \tag{9}$$

$$p_s = \frac{V^2 R_r [\frac{R_r^2}{s^2} - (X_r + X_s)^2]}{[\frac{R_r^2}{s} + s(X_r + X_s)]^2} \tag{10}$$

$$q_v = \frac{2(X_s + X_r)V}{(\frac{R_r}{s})^2 + (X_r + X_s)^2} \tag{11}$$

$$q_s = \frac{2V^2 \frac{R_r^2}{s^3}(X_r + X_s)}{[(\frac{R_r}{s})^2 + (X_r + X_s)]^2} \tag{12}$$

As shown in Eq. (9) and Eq. (10), $p_v$ is greater than zero and $p_s$ is smaller than zero with a high slip, which means the drop of $V$ and the increase of $s$ will both decrease the active power of the induction motor in Eq. (4). However, as shown in Eq. (11) and Eq. (12), both the $q_v$ and $q_s$ are always greater than zero, which means that the reactive power of the induction motor will decrease with the voltage drop at the beginning of the disturbance, but it will increase rapidly when the slip $s$ reaches to a higher value.

In addition, comparing the active/reactive power of the induction motor with those of the ZIP loads, we can note that the active power of the induction motor will decrease faster than those of the ZIP loads, and the reactive power of the induction motor will increase to a high value finally while those of the ZIP loads will decrease or stay the same during the disturbances in the power grid.

## 3 SIMULATION RESULTS

Fig 2 shows the IEEE-39 bus system. As shown in Fig 2, a series of transmission lines marked with $X$ are selected to be tripped, which breaks the whole power grid into two sections. As a result of disconnection, there is a large amount of active power gap in the left section of the power grid.

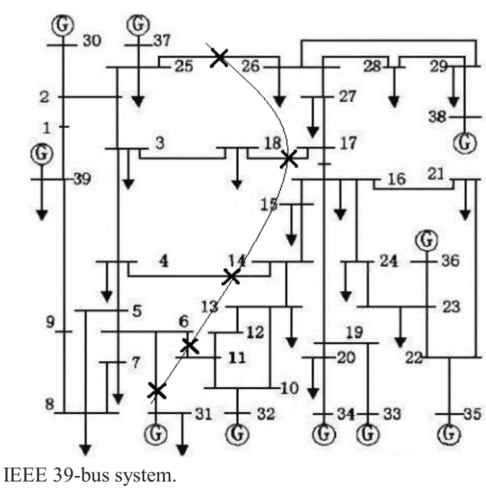

Fig 2. IEEE 39-bus system.

Table 1 and Table 2 show the conventional under-frequency load-shedding scheme and the under-voltage load shedding scheme respectively. The total load-shedding proportion of both the UVLS and the UFLS is 45%.

Table1. Under-frequency Load-shedding Scheme

| Load-shedding Step | Threshold/Hz | Delay/s | Load Curtailments/% |
|---|---|---|---|
| Basic1 | 49.0 | 0.2 | 7 |
| Basic2 | 48.8 | 0.2 | 7 |
| Basic3 | 48.6 | 0.2 | 7 |
| Basic4 | 48.4 | 0.2 | 7 |
| Basic5 | 48.2 | 0.2 | 7 |
| Basic6 | 48.0 | 0.2 | 7 |
| Special 1 | 49.0 | 10 | 3 |

Table2. Under-voltage Load-shedding Scheme

| Load-shedding Step | Threshold/pu | Delay/s | Load Curtailments/% |
|---|---|---|---|
| Basic1 | 0. 90 | 0. 5 | 8 |
| Basic2 | 0. 85 | 0. 5 | 8 |
| Basic3 | 0. 80 | 0. 5 | 8 |
| Basic4 | 0. 75 | 0. 5 | 8 |
| Basic5 | 0. 70 | 0. 5 | 8 |
| Special 1 | 0. 90 | 10 | 5 |

With the drop of frequency and load voltage due to the disconnection of the power grid, the UVLS and UFLS will execute load curtailments at each load bus.

Fig 3 illustrates the dynamic responses when we adopts the induction motor as the load model.

The load voltage of the induction motor will decrease rapidly, which makes the slip increase sharply. As a result, the active power decreases to nearly zero, while the reactive power reaches to a high value. In addition, the dynamics of the induction motor result in severe oscillations in the isolated power grid. Therefore, the induction motor will worsen the system instability status when severe faults occur.

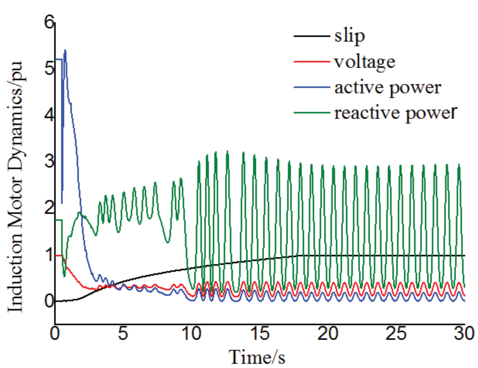


Fig 3. Induction motor dynamics.

Fig 4 illustrates the differences of active power dynamics of the four loads. It can be noted that the active power of the induction motor is much less than those of the ZIP loads during the disturbances, which means the active power gap of the ZIP loads is much greater than that of the induction motor. Therefore, the inertia-center frequency when adopting ZIP loads as the load model drops lower than that when adopting the induction motor. In addition, the inertia-center frequency when using ZIP loads can recover to over 49Hz gradually after load shedding as shown in Fig5.

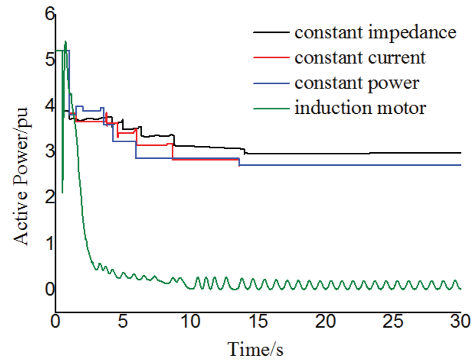


Fig 4. Active power dynamics.

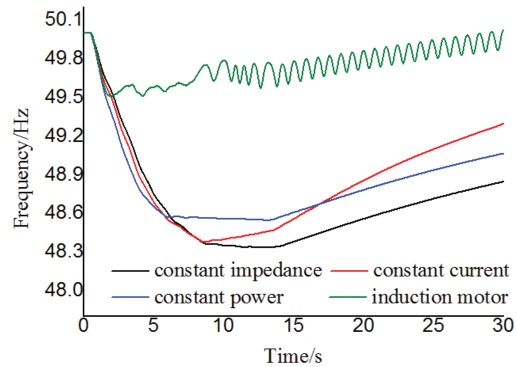


Fig 5. Inertia-center frequency of the isolated grid.

Fig 6 shows the differences of reactive power dynamics of the four loads. It can be seen that the reactive power of the induction motor is much greater than those of the ZIP loads during the disturbances, which means the reactive power gap of the induction motor is much greater than that of the ZIP loads. As we know, load voltage is related to reactive power supply, the load voltage will drop deeper with larger amount of reactive power gap. Therefore, the load voltage of the induction motor drops much deeper than those of the ZIP loads. In addition, the voltage of the induction motor collapses during severe oscillations as shown in Fig 7, meaning that the induction motor will cause voltage collapses.

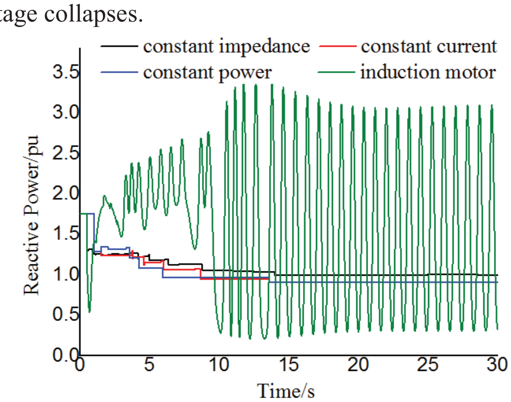


Fig 6. Reactive power dynamics.

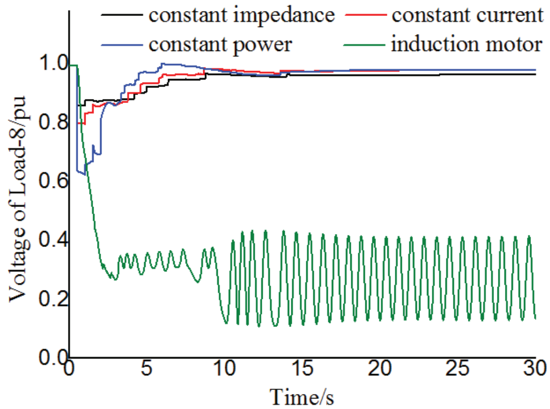

Fig 7. Voltage dynamics of load-8.

Table 3 demonstrates the load-shedding control effects. We can learn from Table 3 that the amounts of under-frequency load shedding with different load characteristics decrease with the order of constant impedance, constant current, constant power and the induction motor. Moreover, the amounts of under-voltage load shedding with different load characteristics increase with the order of constant impedance, constant current, constant power and the induction motor. It means that the characteristic of the ZIP loads tend to trigger UFLS, while the characteristic of the induction motor is more easily to trigger UVLS. As for the total amounts of load shedding, there are little differences among the four loads. Therefore, in order to prevent the power system from system instabilities such as voltage collapses, we should execute load curtailments at the induction motor first when severe faults occur in the power grid.

Table3. Load-shedding Control Results

| Load-shedding / Load Characteristic | UFLS | UVLS | Amount |
|---|---|---|---|
| Constant impedance | 31.00% | 3.28% | 34.28% |
| Constant current | 31.00% | 7.81% | 38.81% |
| Constant power | 24.00% | 14.18% | 38.18% |
| Induction motor | 0.00% | 34.18% | 34.18% |

## 4 CONCLUSIONS

System stabilities are concerned with load characteristics. Different load models have different influence on system dynamics and the load-shedding control effects. And the great increment of induction motors in the power grid may increase the risk of system instabilities such as voltage instability and frequency instability.

This paper analyzes the four load characteristics such as the constant impedance load, the constant current load, the constant power load and the induction motor. These four loads response differently and have different active and [i]reactive power dynamics during separation disturbances in the power grid. The active and reactive power of ZIP loads are only related to the load voltage, while the active and reactive power of the induction motor depend on both the load voltage and the state of motion which is represented by the slip dynamics.

Simulations illustrate that the induction motor may lead to severe oscillations and voltage collapses due to the lack of reactive power supply, thus triggering under-voltage load-shedding control. However, the ZIP loads tend to cause frequency drop because of insufficient active power supply, thus triggering under-frequency load-shedding control. In addition, unlike the ZIP loads, the induction motor is more likely to result in system instabilities after executing the same magnitude of load curtailments. Therefore, it is imperative to execute load shedding at the induction motor first in order to guarantee both the frequency stability and voltage stability.

## REFERENCES

[1] Sun Huadong，Tang Yong，Ma Shiying．A commentary on definition and discussion of power system stability[J]．Power System Technology，2006，30(17)：31-35(in Chinese)．

[2] León Max Vargas, Juri Jatskevich, and José R. Martí. Induction motor loads and voltage stability assessment using PV curves[J]. Power and Energy Society General Meeting, 2009: 1-9.

[3] Ragu Balanathan．Influence of induction motor modeling for undervoltage load shedding studies[J]．Transmission and Distribution Conference and Exhibition，2002，2：1346-1351．

[4] Vivaldo F. da Costa, et al. Voltage stability including detailed induction motor models[J]. Circuits and Systems, 1998: 203-206.

[5] Wu Shengyu, Zhang Xueming, Mei Shengwei. Effect of sudden increase of dynamic loads on voltage stability[J]. Power System Technology and IEEE Power India Conference, 2008: 1-8.

[6] Xu Taishan，Xue Yusheng，Han Zhenxiang．Quantitative analysis of the induction motor transient voltage instability[J]．Automation of Electric Power Systems，1996，20(6)：12-15(in Chinese)．

[7] Wang Yihong, Zhang Xuemin, Sun Yujiao． Transient voltage stability of independent electric power systems with induction motors[J]．Tsinghua Science and Technology，2011，51(1)：36-42(in Chinese)．

[8] Sun Huadong, Zhou Xiaoxin. A quick criterion on judging short-term large-disturbance voltage stability considering dynamic characteristic of induction motor loads[J]. International Conference on Power System Technology, 2006: 1-6.

[9] Zhao Qiang，Zhang Li，Wang Qi，et al．Impact of load frequency characteristics on frequency stability of power systems[J]．Power System Technology，2011，35(3)：69-73(in Chinese)．

[10] C. X. Ren, Y. S. Xue, M. Ding, et al., “Negative Control Effects of UFLS and UVLS,” Automation of Electric Power Systems, Vol. 33, No. 10, 2009, pp. 1-5．

[11] Hou Yuqiang，Fang Yongjie，Yang Weidong，et al．A new method of automatic load shedding control based on the voltage and frequency dynamics interaction[J]．Automation of Electric Power Systems，2010，34(5)：24-28(in Chinese)