# VOLTAGE STABILITY INVESTIGATION OF GRID CONNECTED WIND POWER PLANT

KHẢO SÁT ỔN ĐỊNH ĐIỆN ÁP TRONG LƯỚI ĐIỆN CÓ KẾT NỐI NHÀ MÁY ĐIỆN GIÓ

***Trinh Trong Chuong***
*Hanoi University of Industry*

***Pham Van Hoa***
*Electric Power University*

***Dao Quang Thach***
*Hanoi University of Technology*

**ABSTRACT**

*At present, it is very common to find renewable energy resources, especially wind power which is connected to distribution systems. The impact of this wind power on voltage distribution levels has been addressed in the literatures. The majority of this work deals with the determination of the maximum active and reactive power that is possible to be connected on a system load bus, until the voltage at that bus reaches the voltage collapse point. It is done by the traditional methods of PU curves reported in many references. Theoretical expression of maximum power limited by voltage stability transfer through a grid is formulated using an exact representation of distribution line with ABCD parameters. The expression is used to plot PU curves at various power factors of a radial system. Limited values of reactive power can be obtained. This paper presents a method to study the relationship between the active power and voltage at the load bus to identify the voltage stability limit. It is a foundation to build a permitted working operation region in complying with the voltage stability limit at the Point of common coupling (PCC) connected wind power plant.*

**TÓM TẮT**

*Hiện nay, các nguồn năng lượng tái tạo, đặc biệt là nguồn điện gió đang phát triển mạnh mẽ được kết nối với các hệ thống điện phân phối. Khi mức gia tăng công suất điện gió vào Hệ thống điện càng lớn thì việc phân tích ảnh hưởng của chúng đến chế độ vận hành của hệ thống điện càng trở nên quan trọng. Khi kết nối với lưới điện phân phối, một trong những vấn đề được quan tâm nhất là tính vận hành ổn định của chúng, cụ thể là giới hạn ổn định điện áp của nhà máy điện gió trong các hệ thống cung cấp điện. Để đánh giá vấn đề đó có thể xây dựng một đặc tính công suất - điện áp nhờ việc giải bài toán phân bố công suất thông thường. Bài báo này sẽ giới thiệu một phương pháp tính toán giới hạn ổn định điện áp trong mạng điện có kết nối nhà máy điện gió bằng việc sử dụng sơ đồ mạng 2 cửa có thông số ABCD. Giá trị điện áp và công suất giới hạn được xác định nhờ xây dựng một biểu thức mô tả quan hệ giữa công suất và điện áp tại nút kết nối trang trại gió với hệ thống thông qua biểu đồ pha điện áp và thông số của đường dây trong sơ đồ Thevenin.*

## I. INTRODUCTION

Recently Wind Generator (WG) has been experiencing a rapid development in a global scale. The size of wind turbines and WPPs are increasing quickly; a large amount of wind power is integrated into the power system. As the wind power penetration into the grid increases quickly, the influence of wind turbines (WT) on the power quality and voltage stability is becoming more and more important. It is well known that a huge penetration of wind energy in a power system may cause important problems due to the random nature of the wind and the characteristics of the WG.

In large WPP connected to the transmission network the main technical constraint to take into account is the power system transient stability that could be lost when, for example, a voltage dip causes the switch off of a large number of WGs. In the case of smaller installations connected to weak electric grids, power quality problems may became a serious concern because of the proximity of the generators to the loads. The existence of voltage dips is one of the main disturbances related to power quality in distribution networks. In developed countries, it is known that from 75% up to 95% of the industrial sector claims to the electric distribution companies are related to problems originated by this disturbance type [4,5]. These problems arise from the fact that many electrical loads are not designed to maintain their normal use behaviour during a voltage dip. The aim of this paper is to conduct a voltage stability analysis using exact representation of distribution line with ABCD parameters, to evaluate the impact of strategically placed wind generators on distribution systems with respect to the critical voltage variations and collapse margins. This paper concludes with the discussion of wind generators excellent options for voltage stability.

## II. INDUCTION MACHINES

Induction machines are use extensively in the power system as induction motors but are not widely used as generators. Despite of their simplicity in construction, they are not preferred as much as synchronous generators, since they cannot generate and regulate the reactive power. However, induction generators have the benefits of providing large damping torque in the prime mover, which makes it suitable for the application in fixed speed WTs. The fixed speed WT uses a squirrel cage induction generator that is coupled to the power system through a connecting transformer as shown in Fig 1 [1]. Due to different operating speeds of the WT rotor and generator, a gearbox is used to match these speeds. The generator slip slightly varies with the amount of generated power and is therefore not entirely constant [2], [4].

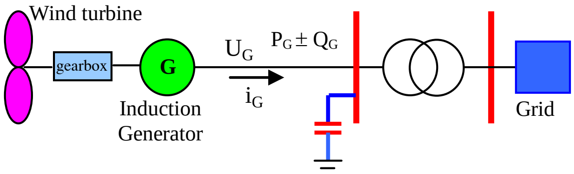


*Fig. 1 Modelling wind turbine connected grid [1]*

However, the speed variations are in the order of 1%, this wind turbine is normally referred to as constant speed. Todays, this type of wind turbine is nearly always combined with stall control of the aerodynamic power, although pitch-controlled ones were built before. Induction machines consume reactive power and consequently, capacitors at each WT are embedded to correct the power factor. These are typically rated at around 30 percent of the WPP capacity. As the operating voltage of most wind generators is 690V, a step-up transformer are needed to connect to the medium voltage systems.

## III. VOLTAGE STABILTY

A system experiences a state of voltage instability when there is a progressive or uncontrollable drop in voltage magnitude after a disturbance such as increase of demand or changes in operating condition. The main factor, which causes these unacceptable voltage profiles, is the inability of the distribution system to meet the demand for reactive power. Under normal operating conditions, the bus voltage magnitude (U) increases as Q injected at the same bus is increased [3]. However, when U of any bus of the system decreases with the increase of Q at the same bus, the system is said to be unstable. Although the voltage instability is a local problem, its impact on the system can be wide spread as it depends on the relationship between transmitted P, injected Q and receiving end U. These relationships play an important role in the stability analysis, can be displayed graphically.

### *A. PU Curves*

When considering voltage stability, the relationship between transmitted P and receiving end U is of interest. The voltage stability analysis process involves the transfer of P from one region of a system to another, and monitoring the effects to the system voltages, U. This type of analysis is commonly referred to as a PU study.

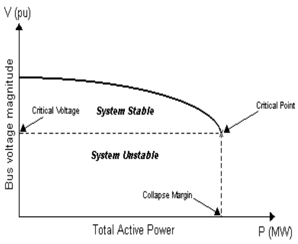


*Fig. 2 Typical PU curve*

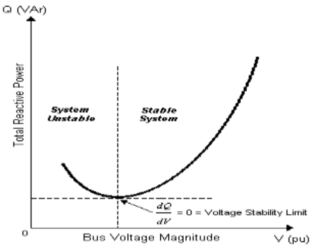


*Fig 3. Typical QU curve*

The Fig 2 shows a typical PU curve. It represents the variation in voltage at a particular bus as a function of the total active power supplied to loads or sinking areas. It can be seen that at the “knee” of the PU curve, the voltage drops rapidly when there is an increase in the load demand. Load flow solutions do not converge beyond this point, which indicates that the system has become unstable. This point is called the Critical point. Hence, the curve can be used to determine the system's critical operating voltage and collapse margin. Generally, operating points above the critical point signifies a stable system. If the operating points are below the critical point, the system is diagnosed to be in an unstable condition.

### *B. QU curves*

Voltage stability depends on how the variations in Q and P affect the voltages at the load buses. The influence of reactive power characteristics of devices at the receiving end is more apparent in a QU relationship. It shows the sensitivity and variation of bus voltages with respect to reactive power injections or absorptions. Fig 3 shows a typical QU curve, which is usually generated by a series of load flow solutions. Figure 3 shows a voltage stability limit at the point where the derivative dQ/dU is zero. This point also defines the minimum reactive power requirement for a stable operation. An increase in Q will result an increase in voltage during normal operating conditions. Hence, if the operating point is on the right side of the curve, the system is said to be stable. Conversely, operating points in the left side of the graph are deemed to be unstable [4, 5].

## IV. VOLTAGE STABILITY BOUNDARY

If the WPP produces $P_{WP} + jQ_{WP}$ ; local load is $P_L + jQ_L$, the complex power delivered to the line shown in Fig 4 is:

$$S_{line} = (P_{WP} - P_L) + j(Q_{WP} - Q_L) \qquad (1)$$

From the phasor diagram in Fig 5 the per-unit voltage rise at the local busbar may be estimated as:

$$\Delta U = \frac{R.P_{grid} + X.Q_{grid}}{U_{grid}} + j\frac{X.P_{grid} - R.Q_{grid}}{U_{grid}} \qquad (2)$$

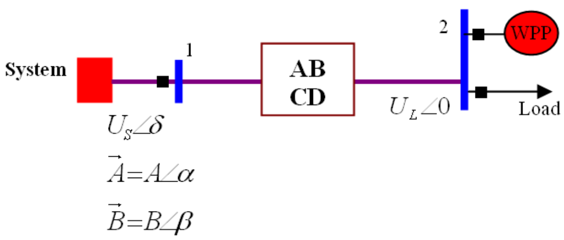


*Fig. 4 Radial feeder with connected WPP*

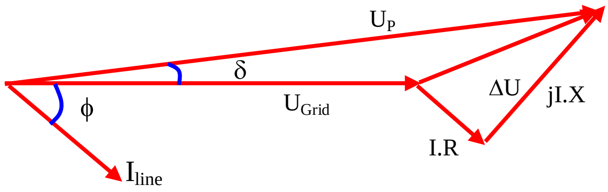


*Fig. 5 Voltage Phasor Diagram*

Equations 1 and 2 show that, where line power flow is dominated by WG production, operating synchronous WGs at a constant power factor will result in voltage excursion as the plant tries to export reactive power in constant proportion to active power. Line impedance directly increases voltage rise. Line X/R ratio skews the effects of real and reactive power. A clearer appreciation of these may be obtained by considering the Universal Power Circle Diagram (UPCD) for a short distribution line shown in Fig 6 [10]. A radial transmission line is shown in Fig. 4 in which a generator with a constant voltage $U_S\angle\delta$ supplying complex power $S_L$ to a load with a terminal voltage $U_L\angle 0$ through a transmission line represented by its ABCD parameters. $S_L$ at the receiving end of a transmission line shown in Fig. 4 is given as [4]:

$$S_L = \frac{-AU_L^2}{B}\angle\beta - \alpha + \frac{U_S U_L}{B}\angle\beta - \delta \qquad (3)$$

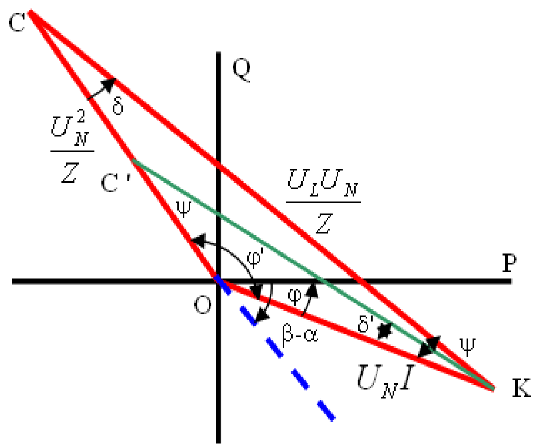


*Fig. 6 UPCD for short distribution line*

The above equation (3) represents a circle for varying value of δ with position of centre indicated by $\frac{-AU_L^2}{B}\angle\beta-\alpha$ and radius by $\frac{U_S U_L}{B}$ where A = A ∠α and B = B ∠β are the line constants and δ is power angle. From Fig. 6:

$$OC = \frac{AU_L^2}{B};\ \ OP = S_L;\ CP = \frac{U_S U_L}{B} \quad (4)$$

$$\phi' = 180^0 - (\beta - \alpha) + \phi;\ \ \delta' = \delta - \alpha \quad (5)$$

ϕ is the power factor angle and is positive for lagging power factor and negative for leading power factor. In ΔOCK:

$$\frac{OP}{\sin\delta'} = \frac{CP}{\sin\phi'} = \frac{OC}{\sin\theta} \quad (6)$$

From (3) to (6): $S_L = \frac{U_S^2 \sin\theta \sin\delta'}{AB\sin^2\phi'}$ (7)

Also from ΔOCP: $\theta = 180^0 - (\phi' + \delta')$ (8)

Therefore: $S_L = \frac{U_S^2 \sin(\phi' + \delta')\sin\delta'}{AB\sin^2\phi'}$ (9)

For $S_L$ to be maximum: $\frac{dS_L}{d\delta} = \frac{dS_L}{d\delta'} = 0$ (10)

Solution of (9) provides critical value of power angle δ, critical value of voltage and maximum value of complex power:

$$S_{L-\max} = \frac{U_S^2}{4A.B.\sin^2\phi'/2} \quad (11)$$

$$\delta'_{th} = 90^0 - \frac{\phi'}{2} \text{ and } \delta_{th} = 90^0 - \frac{\phi}{2} + \alpha; \quad (12)$$

Therefore : $U_L^{th} = \frac{U_S}{2A.\sin\phi'/2}$

Equation (9), (11) and (12) relate complex power with maximum complex power:

$$S_L = \frac{S_{L-\max}\left[\sin(\phi' + \delta')\sin\delta'\right]}{\cos^2\phi'/2} \quad (13)$$

The maximum value of active power and limiting value of reactive power:

$$\begin{aligned} P_{L-\max} &= S_{L-\max}.\cos\phi \\ Q_{L-\lim} &= S_{L-\max}.\sin\phi \end{aligned} \quad (14)$$

Receiving end voltage is obtained as:

$$U_L = \frac{U_S.\sin(\phi' + \delta')}{A.\sin\phi'} \quad (15)$$

This limits dispatch of complex power. While these diagrams are based on complex power flow in the line, they are useful to visualise the effects of network changes on the limits of operation and dispatch of asynchronous WGs connected to the local busbar, particularly where the capacity of the WG is dominant. They also enable computation and examination of loci of busbar voltage as the WG is loaded or as local demand varies, while the plant is in constant power factor or constant voltage control, the flow chart is shown in Fig. 7.

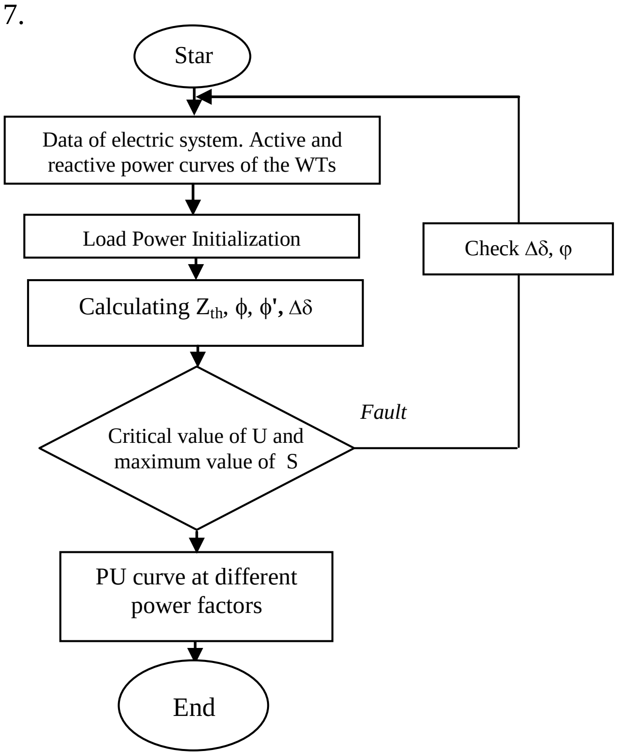


*Fig. 7 Flow chart*

## V. TEST SYSTEM

The studied model represents an equivalent of a distribution segment in Phuoc Ninh, Ninh Thuan, Where large potential of wind energy is located (Fig. 8) [9], Figure 8 shows the proposed location of the WPP (identified as WIND P.P). The existing 110kV line is in solid pink and the planned one is the dashed pink line. The model represents a 20 MW wind power station consisting 10 turbines with Doubly Fed Induction Generator (DFIG) connected to the grid. Extend one of the 110kV lines to the WPP and connect at 110kV. The turbines are stall regulated types, with a rating of 2.0 MW each. Fig 9 shows the equivalent model of the system. $Z_{th}$ = (0,00125 +j0.005), with $S_{base}$ = 100 MVA [10]. Sending end voltage is constant.

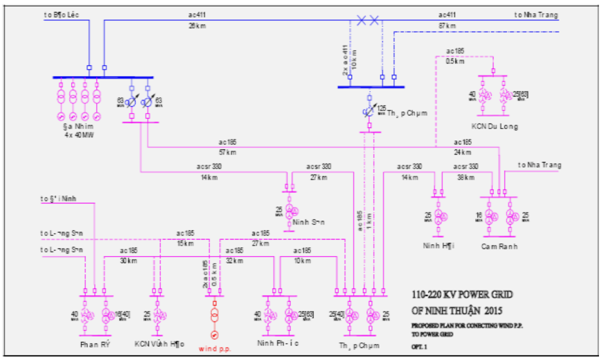

*Fig. 8 The electricity grid where the proposed Phuoc Ninh WP is connected (2015)*

This first option investigates the possibility of using this transformer to handle the WPP power. This layout is shown below. Note that, for the purposes of this type of analysis, the WPP is modelled by combining all the wind turbines into one. The transformer that is normally located at the base of each machine is, therefore, also combined into one item. For this option the voltage profile at the generator terminals is required and therefore all the impedances need to be reflected to the voltage level at the generator, i.e. 690V. This calculation is worked through in the sections that follow. In order to investigate the impact of the injection of active power by the WP the system is approximated to a series of impedances as indicated below.

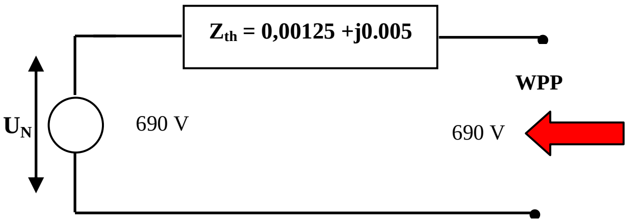


*Fig. 9 Equivalent grid and connection system impedance as seen from the low voltage (690V)*

In Fig 9, $Z_{th}$ is the Thevenin equivalent impedance of the grid up to the PCC and the connection equipment up and until the point being considered. The impedance is composed of both resistance ($R_{th}$) and reactance ($X_{th}$). In mathematical terms, the resistance is a real number and the reactance an imaginary number, hence it is "$jX_{th}$". This is the impedance that represents the WPP. The resistive (real, $R_{WF}$) component is negative so that current and hence active power is produced. If there is anything but full power factor compensation, the reactive (imaginary, $jX_{WF}$) component is positive such that the current through and voltage across the impedance are out of phase and reactive power is consumed. For this option the voltage profile at the generator terminals is required and therefore all the impedances need to be reflected to the voltage level at the generator. Fundamentally, it simulates the injection of current from the WPP in steps and calculates the voltage dropped across the Thevenin impedance at each step. This builds up number of points for the voltage at the generator terminals as the power injected increases.

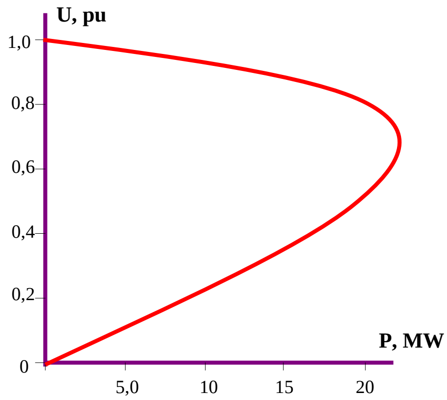


*Fig. 10 PU curve at $\phi = 0^0$*

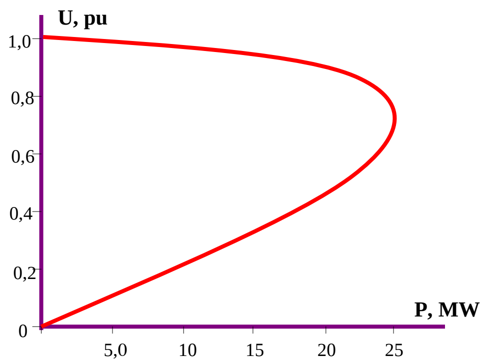


*Fig. 11 PU curve at $\phi = 10^0$ lead*

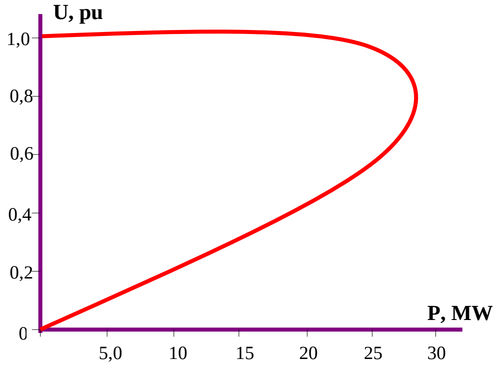


*Fig. 12 PU curve at $\phi = 20^0$ lead*

The PU curves for the above problem has been drawn for 0°,10° leading and 20° leading power factor angle. From the curve we obtain that value of $P_L$ increases from lagging to leading power factor. We also obtain that there are two values of $U_L$ for a given $P_L$ except at $P_{Lmax}$. The curves is shown in Fig. 9. This graph shows that, following the pf =1 from left to right, the voltage rises as the current injected increases and the power increases to about 21,3 MW. Then after 21,3 MW the voltage starts to drop until the critical point where the rate of decrease in voltage is faster than the rate of increase in the current injected and the power actually drops. This (the nose point) is the onset of voltage instability. From this it can be seen that i) approximately a maximum of 21,3 MW power can be injected without instability, and ii) reactive power control is necessary so that the WPP can be operated at, or very close to, unity power factor. If the power factor drops, it can be seen that operation is much too close to the point of voltage instability. Furthermore, the basic compensation known as "no-load" compensation is insufficient. What all this means, in practice, is that if the power factor compensation units fail then WPP production must be stopped.

## VI. CONCLUSIONS

There is a need for WGs to be able to operate within a voltage envelope to maximise dispatch of active power. Additionally, at times when network voltage is depressed the same system could export controlled reactive power for system voltage support. Some Distribution Network Operator are now prepared to consider and integrate WGs that can operate to provide voltage support. Network reinforcement costs may be deferred and loss of generation due to over-voltage shutdown may be reduced. Busbar, generator and excitation system protection settings and timings will require to be applied carefully, within statutory and manufacturers' limits to ensure that WPP operates within accepted network voltages and machine ratings. Simple analytical expression for real power critical voltage has been formulated and had been used to draw PU curve of a radial transmission line. It is observed that real power increases from lagging to leading power factor. We also obtain that there are two values of receiving end voltage $U_L$ for a given $P_L$ except at $P_{Lmax}$. QU curves for fixed $P_L$ and different $U_L$ can also be plotted using the derived relationship and devised algorithm by varying reactive power.

## REFERENCES


1. *Trinh Trong Chuong*; Voltage stability analysis of grid connected wind generators; International Conference on Electrical Engineering; Japan, 2008.
2. *Ake Anderson*; Power quality of wind turbines; Thesis Degree of Doctor of Philosophi, Chalmers Unversity of Technology, Goteborg Swedent 2000.
3. *Johannes Gerlof Slootweg*; Wind Power: Modelling and Impact on Power System Dynamics; PhD thesis, Delft, October 2003.
4. *Vu Van Thong*; Impact of distributed generation on power system operation and control; PhD thesis, University of Leuven, Belgium, May 2006.
5. Feasibility Assessment and Capacity Building for Wind Energy Development in Cambodia, Philippines and Vietnam; RISØ - November 2006;

6. *L. S. Burros*, *W. S. Mota*, *D. F. P. Moura*; Matrix Method to Linearization and State Space Representation of Power Systems Containing Doubly Fed Induction Machines Operating as Wind Generators; 2006 IEEE PES Transmission and Distribution Conference and Exposition Latin America, Venezuela.

7. *Poul Sørensen, Anca Hansen, Lorand Janosi, John Bech, Birgitte Bak-Jensen*; Simulation of Interaction between WP and Power System; Risø National Laboratory, Roskilde December 2001

8. *M. Chinchilla*, *S. Arnalte, J.C. Burgos, J.L. Rodrı´guez*; Power limits of grid-connected modern wind energy systems; Journal of RE, Vol 31, 2005.

9. Wind Energy Resource Atlas of ASEAN; WB 2001.

10. *Trinh Trong Chuong*; An investigation into voltage and power relation at the load bus to estimate voltage stability limit in distribution network with wind generations; The First International Conference Sustainable Energy Development (SED), Vietnam 2008.

---

*Contact*: Trinh Trong Chuong - Tel: (+84)904.993.611, Email: chuong.eps@gmail.com
Hanoi University of Industry, Minh Khai commune of Tu Liem district, Hanoi