전력계통에서의 전압붕괴 메카니즘에 관한 연구

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A Study on Voltage Collapse Mechanism in Electric Power Systems

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Abstract - In this paper, an EMM(Equivalent Mechanical Model) is developed to explain the voltage collapse mechanism by reflecting the effects of reactive powers. The proposed EMM exactly represents the voltage instability mechanism described by the system equations. By the use of the EMM model, the voltage collapse mechanism has been illustrated by showing the exactness of the results. It is also discussed a system transform technique to eliminate the resistance component of the Thevenin equivalent impedance for practical applications.

Keywords : Voltage Collapse Mechanism, Equivalent Mechanical Model, Energy Function, Maximum power transfer.

1. Introduction

The voltage problems are related to the increased loading of transmission lines, and insufficient local reactive power supply. The voltage instability also attributed to the lack of reactive compensation or control. Voltage collapse phenomena have many complicate aspects with various time frames from several seconds to several decades of minutes. This brought about many arguments on whether the characteristics of voltage collapse is static or dynamic, system intrinsic or system-load interacting. This is because the voltage collapse mechanism is not clarified yet.

A majority of the work on the problem to date has been focused on the static problem such as load flow feasibility, optimal power flow, steady-state stability. Although there is extensive literature on voltage collapse, very few deal with the physical mechanism of the voltage collapse phenomenon

This study attempts to develop an EMM model for the voltage collapse mechanism. Since the voltage collapse phenomenon is highly dependent on reactive powers, the EMM model is developed to reflect the effects of reactive powers by modifying the conventional model of mechanical analogy for angular stability analysis. This study shows that the proposed EMM exactly represents the voltage instability mechanism described by the system equations. The proposed EMM model illustrates the voltage collapse mechanism to provide some intuitive physical meanings.

Finally, practical applications are discussed with the use of Thevenins equivalent circuit for the whole power system seen from a load terminal. In this case, the Thevenin equivalent impedance has non-negligible resistance. This paper introduces a system transform technique presented in Ref.[2,3] to eliminate the resistance. Test results are listed.

2. Development of an EMM for Power Systems

The EMM can be easily generalized for multibus systems. For example, we will consider the following three-bus system, which is the smallest system including all types of buses. The line impedance are determined to reflect the generator internal impedance by the bus elimination technique.

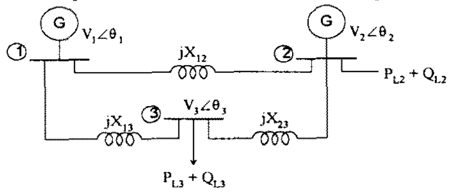


Fig. 1 Three-Bus System

By assuming $\theta_1 > \theta_2 > \theta_3$ we can obtain the following EMM for the above system with the impedance model. By observing the force diagram in Fig.2, it can be shown that the following force balance equation holds for arbitrary point i:

$$\frac{M_i\ddot{\theta}_i}{V_i}\hat{\theta} + \frac{D_i\dot{\theta}_i}{V_i}\hat{\theta} = \frac{P_{mi}\hat{\theta} - P_{Li}\hat{\theta}}{V_i} + \sum_{j\neq i} F_{ij} + \frac{Q_{Gi}+Q_{Ci}-Q_{Li}}{V_i}\hat{r} \quad (1)$$

where $i, j \in \{1,2,3\}$

Substitution of the force vector equation represented with the directional unit vectors θ and γ into the above equation yields the following equations for each component.

$$(M_i\ddot{\delta}_i + D_i\dot{\delta}_i)/V_i - (P_{mi}-P_{Li})/V_i - \sum_{j\neq i}(-B_{ij}V_j\sin\theta_{ij}) = 0 \quad (2)$$

$$\sum_{j\neq i}[B_{ij}(V_i - V_j\cos\theta_{ij})] - (Q_{Gi}-Q_{Ci}-Q_{Li})/V_i = 0 \quad (3)$$

where $\delta_i = \theta_i$ for generaor bus i

$M_i = D_i = P_{mi} = Q_{Gi} = 0$ for load bus

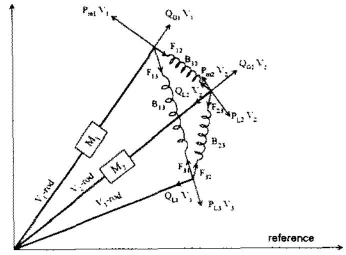


Fig. 2 EMM for Multibus System

The proposed EMM fully represents the system behavior of the multimachine system with the classical generator model. This implies that the voltage collapse mechanism may be visualized by the proposed EMM.

3. Visual Modeling Of Voltage Collapse Mechanism

For the visual modeling of voltage collapse mechanism, we will consider a simple generator-load system. The generator is represented by the classical model with the round rotor type, and the load is assumed to be a constant power load.

In order to calculate the steady state equilibriums, we may assume the following input-output balance condition ; $P_m = P_L$ (4)

By using (4), the following energy function can be derived from the EMM in Fig.2 in terms of

$$E = \frac{1}{2}M\omega^2 + \frac{1}{2}BV^2 - BE_sV\cos\theta_{12} - P_L\theta_{12} + Q_L\log(V/V_0)$$

where $\theta_{12} = \theta_1 - \theta_2$: load angle (5)

$B = 1/X$,

The above energy function has equilibrium points which can be given by the solution of the following partial equations.

$$\frac{\partial E}{\partial \omega} = 0 \Rightarrow M\omega = 0 \quad (6)$$

$$\frac{\partial E}{\partial \theta_{12}} = 0 \Rightarrow BE_sV\sin\theta_{12} - P_L = 0 \quad (7.a)$$

$$\frac{\partial E}{\partial V} = 0 \Rightarrow BV - BE_s\cos\theta_{12} + \frac{Q_L}{V} = 0 \quad (7.b)$$

The above equations are just the same as the load flow equations, which have two solutions; one high-voltage solution and the other low-voltage solution. Since the energy function(5) well reflects the system behaviors of the EMM, the equilibrium points can be visualized on the proposed EMM. This gives a hint that the proposed EMM may visualize the voltage collapse mechanism. By examining the EMM carefully, we can easily find that the proposed EMM has two equilibrium points. For the convenience of the discussion, we will consider the case where the load varies with a constant power factor.

To begin with, we examine the trajectory of the equilibrium points when the load varies with a constant power factor. Fig. 3 shows the trajectories of equilibrium points for the typical power factors. Fig.3(a) shows the case where the power factor is unity. The equilibrium points must lie on the half circle in order to make the angle between the force P_L/V and V-rod rectangular.

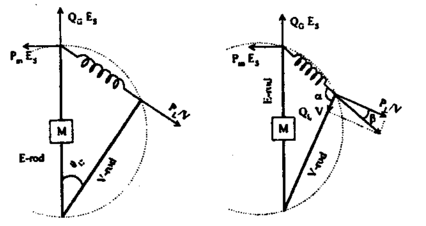


Fig 3. Trajectory of Equilibrium Points with Constant Power Factor

Fig.3(b) shows the trajectory of equilibrium point when the power factor is kept to be pf=cos β. In this case, the angle α between the spring and the V-rod should be kept constant with $\alpha = 90^\circ + \beta$ This means that the equilibrium points must lie on an arc of a circle.

3.1 Behaviors of Equilibrium Point

With the above preliminaries, we can examine the behaviors of the equilibrium points by considering the load fluctuation with a constant power factor. As mentioned earlier, the proposed EMM has two equilibrium points as shown in Fig.4. (The equilibrium points can be obtained by solving the load flow equations.) It is noted that the dotted line must be parallel to the E-rod since both equilibrium points must satisfy

$$P_L = BE_s V_A \sin\theta_{12}^A = BE_s V_B \sin\theta_{12}^B$$

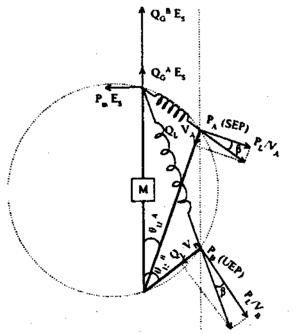


Fig4. Equilibrium Points of the EMM with Constant Power Factor

Say here that the load is increased by positive small perturbation $\triangle P_L$ and $\triangle Q_L$ with constant power factor for a short moment, and returns to the original load P_L and Q_L. Then the incremental load $\triangle P_L$ and $\triangle Q_L$ will increase the length of the spring by moving the system equilibrium along the arc.

Assume that the system state be on the equilibrium point P_A. Then the small perturbation $\triangle P_L$ decreases the load bus voltage, where the sensitivity of the load voltage is much smaller than that of the spring length. Since the load bus voltage is high enough at the equilibrium point P_A, it is guaranteed that the forces P_L/V_A and Q_L/V_A do not change significantly. Consequently, the small load increase moves the system state to a new state with a little increased θ_{12}^A. If the load returns to the original load P_L in the next step, then the system naturally returns to the original state. We can say the same story with the negative $\triangle P_L$. Therefore, the point is a stable equilibrium point.

Assume in the next that the system state be on the equilibrium point P_B in Fig. 4. By a similar way as given above, we can conclude that the low voltage equilibrium is an unstable equilibrium.

In the above discussion, we show that the proposed EMM can be utilized as a fine model to visualize the low-voltage and high-voltage solutions in static voltage analysis for the two-bus system. Here, it is noted that the above interpretation of the voltage collapse by the proposed EMM can be easily generalized for multibus systems by using the EMM as shown in Fig.2. In order to confirm that the proposed EMM can be used as an exact visual model for the voltage collapse mechanism, it is necessary to show that the EMM provides the exact voltage collapse condition with the critical voltage.

3.2 Voltage Collapse Condition on the Proposed EMM

Regarding static voltage stability analysis, the voltage collapse condition can also be derived by the use of the energy function. The energy function method [4, 5] is to determine the system stability by comparing the energy difference between unstable equilibrium points(UEPs) and a stable equilibrium point(SEP). Approaching the SEP to an UEP makes the energy difference zero and brings about voltage collapse. When the SEP coalesces into an UEP, the saddle node bifurcation phenomenon occurs. Consequently, the energy function method provides the following voltage collapse condition :

$$\frac{\partial E(\mathbf{x}_e)}{\partial \mathbf{x}} = 0 \quad (8)$$

$$\left| \frac{\partial^2 E(\mathbf{x}_e)}{\partial \mathbf{x}^2} \right| = 0 \quad (9)$$

where $X = [\omega, \theta, V]$

Equation(8) describes the equilibrium condition of the system which yields a SEP and UEPs as the solutions. Equation(9) represents the condition that the SEP coalesces into an UEP, which can be considered as the actual voltage collapse condition. The voltage collapse condition can be visualized on the proposed EMM as shown in Fig.5.

As the load increases with the constant power factor pf=cos β, the pair of equilibrium points move to the right. The voltage collapse occurs when the SEP and UEP eventually coalesce. At this moment, the triangle in the figure becomes isosceles. By the use of the geometric relations in Fig.5, the maximum load P_{Lmax} and the critical voltage V_C can be easily calculated as follows.

Maximum Load :

$$P_{L\max} = BE_S(V_c \sin\theta^c) = BE_S(\frac{E_S}{2}\tan\theta^c) = \frac{1}{2}BE_s^2 \tan(45^\circ - \frac{\beta}{2}) \quad (10)$$

Critical Voltage :

$$V_c^2 + V_c^2 - 2V_cV_c\cos(90^\circ + \beta) = E_S^2$$

$$\therefore V_c = \frac{E_S}{\sqrt{2}}\frac{1}{\sqrt{1+\sin\beta}} \quad (11)$$

The above results can be easily checked by comparing with those by the conventional methods.

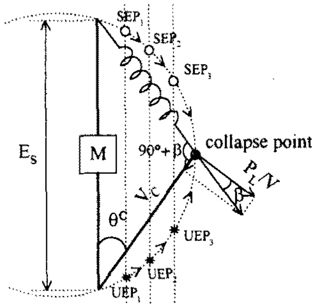


Fig.5 Visualization of the Collapse Condition

4. Applications

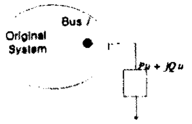
The voltage in stability problem can be interpreted as a complicate parametric in stability with a number of load parameters. The load parameters may vary individually. However, it is impossible to consider the individual variations of load parameters in voltage stability analysis. Instead, two approaches are commonly adopted : one is to assume that all loads vary with one load parameter for the whole system, and the other is to assume that only one load vary with all other loads remaining unchanged. For the second approach, the proposed. EMM can be a useful tool to analyze the voltage stability.

For simplicity, we assume here that all system loads be constant impedance loads and remain unchanged except the load at Bus i. Then, the system can be simplified by using Thevenins theorem as shown in Fig.6. Thevenin equivalent voltage can be determined by using the voltage regulation ratio at the load terminal.

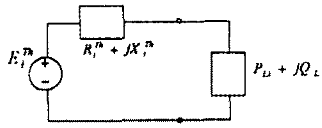
$$E_i^{Th} = (1 + \eta_{vi}) \text{ [pu]} \quad (12)$$

with η_{vi} : voltage regulation ratio at bus i

Here it is noted that R^{th} is not negligible since the system includes resistive loads.



(a) Original system



(b) Equivalent

Fig.6 Thevenin Equivalent system

The equivalent system has only one transmission line to satisfy the uniform R/X ratio. Consequently, the equivalent system can be transformed to eliminate the resistance by using a method presented in Ref.[2,3]. The transformed system can be easily obtained as follows:

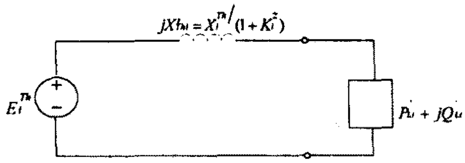


Fig.7 Transformed System

In Fig.7, the transformed parameters are determined by

$$X'_{Thi} = X_i/(1+K_i^2) \tag{13}$$

$$P'_{Li} = P_{Li} - K_i Q_{Li} = P_{Li}(1 - K_i \tan\beta_i) \tag{14}$$

$$Q'_{Li} = Q_{Li} + K_i P_{Li} = Q_{Li}(1 + K_i \cot\beta_i) \tag{15}$$

where $K_i = R_i^{Th}/X_i^{Th}$

By using the transformed system, one can easily find that the critical voltage at bus i is determined by (11)

$$V_{Ci} = \frac{E_i^{Th}}{\sqrt{2}} \cdot \frac{1}{\sqrt{1+\sin\beta_i}} = \frac{1+\eta_{vi}}{\sqrt{2}\cdot\sqrt{1+\sin\beta_i}} \quad \text{[pu]} \tag{16}$$

where β_i: power factor of the transformed load at bus i

Here it should be noted that Eq.(16) shows that the critical collapse voltage is directly related to the voltage regulation ratio. The maximum power transferred to load at bus i can be easily calculated by using (10) as follows :

$$P_{Li}^{imax} = 0.5\, B'_i (E_i^{Th})^2 \tan(45^\circ - \beta_i/2) \tag{17}$$

where $B'_i = 1/X'^{Th}_{Li}$

By using (14), we can calculate the actual maximum power transfer from the result of (17).

$$P_{Li}^{\max} = P'^{\max}_{Li}/(1 - K_i \tan\beta_i) \tag{18}$$

The above algorithm is tested for some of various sample systems with heavy load conditions. The results are listed in the following tables.

The generator internal impedances are appropriately selected within 0.2 ~ 0.3 pu, and the power factors are assumed to be no greater than 0.98 in case of heavy loads to bring about the voltage collapse.

Bus No	$P_L + jQ_L$	η_v	V_C	P_{Lmax}	P_{Lmax}/P_{Li}
1	0	0.00000	0.70711	6.17665	-
2	0.2170 + 0.1270i	0.01137	0.58284	4.36347	20.10814
3	0.9420 + 0.1900i	0.03220	0.65350	4.55709	4.83767
4	0.4780 - 0.0390i	0.00453	0.63598	4.97801	10.41425
5	0.0760 + 0.0160i	0.00260	0.63476	4.86120	63.96313
6	0.1120 + 0.0750i	0.01113	0.57311	2.41668	21.57746
9	0.2950 + 0.1660i	0.03583	0.59988	2.17976	7.38902
10	0.0900 + 0.0580i	0.01625	0.57882	1.81930	20.21449
11	0.0350 + 0.0180i	0.00619	0.58936	1.87342	53.52633
12	0.0610 + 0.0160i	0.01078	0.63821	2.02357	33.17323
13	0.1350 + 0.0580i	0.01985	0.61058	2.21791	16.42894
14	0.1490 + 0.0500i	0.02918	0.63381	1.76807	11.86623

Table.1 Results from IEEE 14-Bus System

5. Conclusions

For the mechanical analogy of the voltage collapse mechanism , an EMM model is developed to reflect the effects of reactive powers. The proposed EMM exactly represents the voltage instability mechanism described by the system equations, which enables us to visualize the vlotage collapse mechanism. Finally, practical applications are discussed with introduction of a system transform technique to eliminate the resistance in the Thevenin equivalent circuit seen from the load terminal concerned.

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