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# Analysis And Improvement of The Transient Power System Stability Using DFACT devices and Cusp of Catastrophe Theory

Maithem Almousawi[1]

1 (Mazaya University collage, cyber security, Iraq).
Maythem.hk@gmail.com

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***Abstract.*** *power systems Transient stability relate to the maintain of system ability to temporal relation when subjected to a intense perturbation of transient like a load changes, fault, sudden loss of generation. The dynamic of the system makes analysis challenging of transient power system stability. Catastrophe theory, focus of attention the sensitive dependence of nonlinear systems on initial conditions small disturbance possible to cause large variable in behavior of system stability. This generalization can be supplement to transient stability improvement by dominant system trajectories away from instability. This manuscript introduces a comprehensive analysis of transient power system stability improvement using Catastrophe Theory and Distributed Flexible AC Transmission System (D-FACTS) devices. The work distinctness on enhancement of the system stability during large perturbation by predicting instability using Catastrophe Theory and kinetic controlling power flows using D-FACTS devices.A demonstration of the suggested analysis of the New England 39-bus power system using power world simulator is provided to confirm that effectiveness*

***Keywords:*** *Catastrophe Theory, Transient Stability, Dfact devices, Cusp Bifurcation, Critical Clearing Time.*

## 1. INTRODUCTION

Stability of Power system denotes the capacity of synchronous machines to transition from one steady-state operating point to some other next a disturbance, all while maintaining synchronism [1]. This way include two key notion power system stability [2]. small perturbation stability refers to sudden or additive alterations. Small perturbation stability survey are required to control phase angles act within acceptable limits, bus voltages meet parameters, and instrumentality isn't unduly emphasized. Systematic to decrease the potential hazards to life and place posed by fire incidents, the photovoltaic power generation system should expert identify and eliminate the emergence of DC arc happening, while also adhering to stringent operational safety guidelines. [3]. Catastrophe theory has been skilled engaged in the transient stability of power system assessment of multi-machine systems. power systems via delineating the region of stability. within the cusp bifurcation surface, articulated in terms of specified control variables [4].Transient of the power system stability include significant disturbances like the, faults, loss of generation in load , abrupt fluctuations, and line switching operations [5]. In the aftermath of a disturbance, the frequencies of synchronous machines experience transient deviations from the synchronous frequency (60Hz), accompanied by alterations (pm)[6]. The primary aim of a transient work is to ascertain where as the device will revert frequency while adopting next situation power angles[7]. In numerous instances, system disturbance is evaluated through initial swing equations subsequent to a perturbation. This initial activity, usually endures for approximately 1s, often presumes

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to remain invariant. Within extensive unified stability of power system, the paramount interest is the safety stability that connected to perturbation.Therefore, the stability appear as progressively critical condition. Comprehensive stability analysis is imperative to ascertain remains stable under conceivable situation prior to making any planning or operational determinations. Each contingency related to every potential disturbance necessitates a substantial number of stability investigations to ascertain the critical clearing angle or the stability thresholds of the system. A typical transient stability analysis involves deriving the time solution of the differential and algebraic equations governing the power system, predicated on particular initial conditions of the system. The important mathematical work that be the transient of power system. must include all to the point parameters that determiner the stability behavior, consider generator controls, protective devices, and stability mechanisms. Transient stability of Power system is a critical aspect of modern electrical grids, ensuring reliable procedure under perturbation. Transient of power system stability relate to the ability of a power system to keep synchronism after large perturbation such as faults or sudden load changes[8]. Traditional methods like Power System Stabilizers (PSS) and FACTS devices (e.g., SVC, STATCOM) have been widely used. However, D-FACTS devices offer a more distributed and cost-effective solution. Catastrophe Theory, a branch of bifurcation theory, provides a mathematical framework to analyze sudden changes in system behavior Utility companies are increasingly using thyristor controlled series capacitors (TCSCs) and other D-FACTS components into lengthy transmission lines[9]. Power flow management,asymmetry reduction, Developed by [10] 1986, the Thyristor Controlled Series Compensator allows for rapid changes to a network's Impedance.[11] proposed using a TCSC controller to enhance the voltage stability of an IEEE 6-bus test system. Reactive power is especially important on the test system's least robust bus. A thyristor-controlled series compensator is used to refine the voltage profile. This paper integrates D-FACTS control with Catastrophe Theory to predict and mitigate instability.

## 2. MATERIALS AND METHODS

### *2.1. MATERIALS*

A comparative analysis of Critical Clearing Time (CCT):

- Evaluate the CCT both with and without D-FACTS assistance under standardized fault conditions (e.g., single-line-to-ground, line-to-line).
- Calculate the enhancement.
-

$$\Delta CCT = CCT_{D\text{-}FACTS} - CCT_{base} \quad (1)$$

### *2.2. METHODS*

**A-Mathematical Model of a Synchronous Machine (Swing Equation)**

The dynamic behavior of a synchronous machine is described by the swing equation:

$$M \frac{d^2\delta}{dt^2} = P_i - P_e = P_{ai} \quad (2)$$

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$$P_{ei} = \sum_{j=1}^{n} E_i E_j (g_{ij} \cos \delta_{ij} + b_{ij} \sin \delta_{ij}) \qquad (3)$$

**B- Equal Area Criterion.**

Figure (1) show of a single-machine infinite-bus (SMIB) system, the Equal Area Criterion contents a methodological analysis to measure power system transient stability. It fix that for the system to continue stability leading a fault, the acceleration area (Aa) must be less than or equal to the deceleration area (Ad).

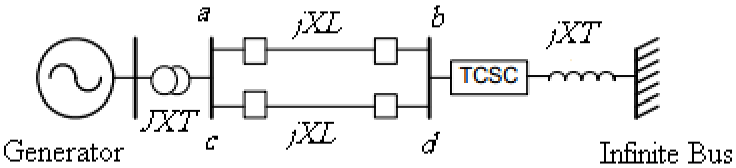


Figure (1) Infinite bus [12]

Inside the domain of power system transient stability, the condition are notably various, defined by two elements action topographic point through the transient quantity one synchronous with the oncoming of the fault and the other happened during the clearance of the fault. Before we get on the petition of catastrophe theory, it is necessary to establish a continuous function that effectively communicates the system's behavior through the transient phase. Additionally, we must articulate the definitions of degenerate and non-degenerate critical points in relation to transient stability.

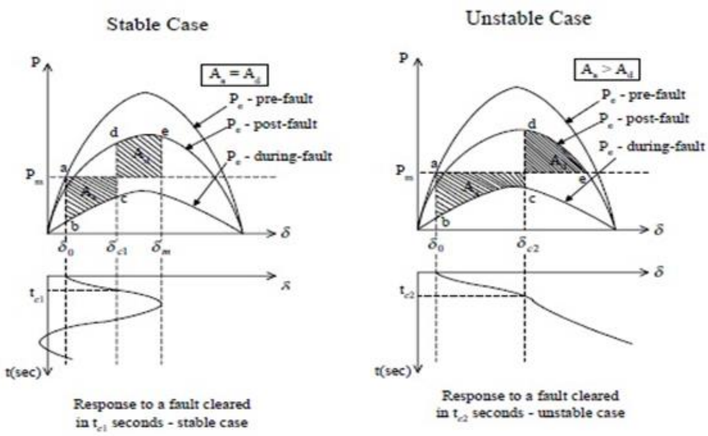


Figure (2) System Criteria [12]

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In Figure (1) Consider in the event of a fault arising on lines adjacent to the bus, rotor of the machine will experience an increase in acceleration and accrue mechanics. If the fault is rectified within the CCT, the kinetic energy given by the fault seamlessly integrated into stability of the system, culminating in a total energy change of exactly zero by the end of the transient period; thus, the system is characterized as critically endangered. A exemplary energy arch exemplifying faults exculpated at varying CT is illustrated in Fig (6). Within the framework of cusp catastrophe theory as shown in fig (7).

### 3. Fundamental Principles of Catastrophe Theory

The principal notion is to articulate the behavior of the system through a potential function V(x,μ), where x represents the state variables (e.g., rotor angles) and μ signifies the control parameters (e.g., mechanical power, line reactance). The equilibrium points of the system correspond to the extrema of the potential function (∇ x V=0). Catastrophes manifest when the characteristics of these extrema undergo transformation (e.g., a minimum vanishes or bifurcates).

### 3.1. Catastrophe Theory for Power System

Seven elements of catastrophe are applied drawn-out to the problem of transient stability [13].

### 3.2 Phenomenon of Catastrophe Theory

Catastrophe theory constitutes a physical process wherein unforeseen effects may arise as a consequence of smooth or gradual alterations. Illustrative examples include the degradation of an insulator as voltage incrementally accumulates, the failure of a bridge under progressively escalating loads, desynchronization among generator within stability of the system when subjected to gradual shifts. It signifies such abrupt transformations that emerge from smooth modifications. Catastrophe theory was at first jointed by Thom. He exploited activeness of mathematical to explain sudden change in growth. This conception later charmed the interest of numerous across a various array of scientific subject.It is represents a sophisticated framework that examine the realm of abrupt transformations within dynamic systems, directly addressing the characteristics of discontinuities. It has been defined as the qualitative investigation of the infinite methods in which results to differential mathematical framework may undergo important alterations. Regard a system whose behavior is typically smooth yet at times evidents discontinuities. Expect the system is defined by state variables and is citizenry by m independent variables, with a smooth potential function available to elucidate the system's dynamics. CT elucidates is qualitatively clear may arise does not depend on the state variables quantity, which can be significant, which is generally limited. Notably, if the number of control variables.

Equ (4) show a meticulous computation of the parameters in relation to the system variables during different operating conditions. Furthermore, catastrope theory feature the capability to imagine the operating points for real-time observation. It has been exploited in the assessment of transient power system stability by catastophe theory [14].

$$y^4 + ay^2 + by + c = 0 \quad (4)$$

### 3.3 Catastrophe Theory for Transient Stability Analysis.

CT, a blase branch of mathematics pioneered by René Thom, show mathematical framework for the analysis systems that display abrupt qualitative transformations in their behaviour as smoothly variable control parameters traverse critical thresholds. Within the field of transient stability of power systems, the physical process of transient stability loss can be conceptualized as a catastrophic leap from a stable equilibrium to an unstable point. For atransient stability power system, the potential function can be elaborately associated with the energy function working in direct methodologies for transient stability analysis. The state of the system is hold stable as long as it broadside within a stable equilibrium well. A disrurbance may move the system toward the threshold of this well, and should it breach this boundary, a loss of synchronism ensues.

For multi-machine systems, the function of energy expect a more complex form, across-the-board multiple rotor angles. CT assist the identification of critical regions within the parameter space where abrupt transitions manifest, shown Fig1.

$$\frac{1}{2}M\ \dot{\delta}_c^2 = p_m\cos\delta_c + p_i\delta_c - p_m\cos\delta_m - p_i\delta_m \tag{5}$$

$$K_E = P_E,\quad K_E - P_E = 0 \tag{6}$$

*Moreover,*

$$K_E < P_E \tag{7}$$

$$R = \nabla_{\delta c}V(\delta c) = \frac{1}{2}M\dot{\delta}^2 - P_m\cos\delta_c - P_i\delta_c + P_m\cos\delta_m + P_i\delta_m = 0 \tag{8}$$

Employing the Taylor series expansion to delineate the variables as a function of time has been recognized as a remarkably effective approximation for the preliminary swing transient stability analysis[16].we get

$$\delta_c = \delta_0 + \frac{1}{2}Yt_c^2 \tag{9}$$

Where: The acceleration at the precise moment of fault manifestation, delineated as:

$$Y = \frac{1}{M}[P_i - P_e(t_{o+})] \tag{10}$$

$$K = P_m\delta_m + P_m\cos\delta_m \tag{11}$$

Substituting on behalf of $\dot{\delta}_c$ & $\delta_c$ markdown by means of equations (9) & (11), substituting the cos $\delta_c$ component ,Consequently, equ (8) is reformulated as follows.

$$N = \nabla\delta_c V(\delta_c) = MYX - P_{ma}[1 - \frac{(\delta_0 + X)^2}{2!} + \frac{\delta_0 + X)^4}{4!}.....]$$
$$-P_i(\delta_0 + X) + K = 0 \tag{12}$$

The equilibrium surface N can be aptly represented by the fourth-order truncation, as delineated in equation (12), which is contingent upon the clearing time—an interval that is generally modest.

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$$R = -\frac{Pm}{24}X^4 - \frac{Pm}{6}\delta_0 x^3 + \left(\frac{2-\delta^2}{4}\right)Pmx^2 + \left(MY + \delta P_{ma} - \frac{Pm}{6}\delta^3 - P_i\right)X + (\frac{Pm}{2}\delta^2 - \frac{Pm}{24}\delta^4 - Pm - P_i\delta + K = 0 \quad (13)$$

*LET,*

$$L = \frac{Pm}{24}$$

$$E = \frac{Pm}{6}\delta$$

$$T = \frac{2-\delta^2}{4}\ Pm,$$

$$M = \left(MY + \delta Pm - \frac{Pm}{6}\delta^3 - P_i\right),$$

$$I = \left(\frac{Pm}{2}\delta^2 - \frac{Pm}{24}\delta^4 - Pm - P_i\delta + K\right)$$

*Subsequently, we arrive at*

$$R = -Lx^4 - Ex^3 + Tx^2 + Mx + I = 0 \quad (14)$$

Above Equ (14) represents the manifold associated with the manifold of catastrophe. It is noteworthy that the criterion variable u,v) in this instance is both invariant.
Then *N* becomes

$$u = -(\frac{C}{A} + \frac{3}{8}\frac{B^2}{A^2}) \quad (15)$$

$$v = -(\frac{D}{A} - \frac{1}{2}C\frac{B}{A^2} - \frac{1}{8}\frac{B^3}{A^3}) \quad (16)$$

$$w = -\frac{E}{A} + \frac{D}{4}\frac{B}{A^2} - \frac{C}{16}\frac{B^2}{A^3} - \frac{3}{256}\frac{B^4}{A^4} \quad (17)$$

We obtain

$$R = x^4 + ux^2 + vx + w = 0 \quad (18)$$

So, outcome decrease the bifurcation mathematical dimensions in.Hence possible to scheme the bifurcation set of the transient stability of power system using equ (4)

## 4. D-Facts Devices for Enhancement of Stability.

DFACTS strategies are classy power electronic engineering controllers exactly engineered to augment the controllability systems of power and increase power allocation capabilities. D-FACTS, a focused subset of FACTS equipment, are precisely personalized for concentrated requests along transmission lines, thereby offering improved confined and rough control[16].

### 4.1Types of D-FACTS Devices

D-FACTS devices applicable to power system transient stability contain Spread Static Series Compensator (DSSC) A series-associated expedient that inserts a voltage in series with the line,

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efficiently changing the line impedance. This can growth power handover capacity and progress transient stability. Distributed Static Shunt Compensator (DSSC - Shunt type, often referred to as D-STATCOM for distribution systems): A shunt-connected device that inserts or absorbs reactive power, in that way regulating bus voltages and enhancing stability [17]. Distributed Series Reactor (DSR) / Distributed Series Capacitor (DSC): These are modular devices that can be switched in or out to modify the series impedance of the line.

**4.2 D-FACTS Devices Modeling.**
The outcome of D-FACTS work on the transient power system stability container be defined by regulating the system's entry matrix or by segregation their current and voltage injection capabilities into the dynamic equalities and power flow.

**4.3 Enhancement Integration of D-FACTS Devices and Catastrophe Theory.**
The effectiveness of D-FACTS broadside in their capacity to swiftly change control parameters—such as line electrical phenomenon or reactive power injection thereby transforming the shape of the potential energy landscape and exerting an influence on the stability margin of the system. Catastrophe theory can be engaged to[18]

1. Optimize D-FACTS Control By comprehensively study the affect of D-FACTS devices on the potential function and the critical thresholds, one can formulate optimal control strategies. For instance, a D-FACTS device possesses the capacity to swiftly modulate its impedance, thereby effectively propelling the system from a catastrophic expanding the stable operating point.
2. Real-time Stability Assessment CT shown a swift assessment of stability regions predicated on real-time system parameters, thereby facilitating both emergency control measures and preventive.

**4.4 D-FACTS Control Strategy Informed by Catastrophe Theory.**
The primary control accusative for D-FACTS parameters in this context is to manipulate the bifurcation point of the system's dynamics, thereby enabling a more expansive stability margin or prevention the system's descent into an unstable region following a perturbation[19].
Consider a efficient system wherein stability is possible upon a control parameter $\mu$ (for instance, associated with the D-FACTS compensation level). The equilibrium regionss of the system may be determined by an equation derived from the potential function[20]:

$$\partial V/\partial x=f(x,\mu)=0 \qquad (19)$$

If $f(x,\mu)$ catastrophe unfolding can be described by:

$$x3+\mu 1x+\mu 2=0 \qquad (20)$$

Here, $\mu_1$ and $\mu_2$ show the control parameters. A D-FACTS device dominate the capability to influence these parameters. For happening, by adjusting the effective line reactance, a DSSC directly treaty the parameters that specify the power-angle curve, thereby effectively change the $\mu$ values within the catastrophe model. The objective of D-FACTS control is to ensure that the system remains within the points of the catastrophe manifold.

## 5. RESULTS

The important activity of D-FACTS parameters on lines experiencing the most intense happening overload can significantly improve the outcomes. The investigation is passage on the following system, which comprises. Upon the application of a three-phase fault on the transmission line between bus 3 and bus 6, perturbation arise within the system, resulting in power angle oscillations. When the clearing time is set at 1.033 seconds (or 2 cycles), the maximum angle deviation recorded is 106.487 degrees. Moreover, an addition in clearing time leads to a related rise in the maximum angle difference. This trend proposes that the system is progressing towards an unstable mode. To improve power system transient stability, usually working method regard the utilization of fast acting exciters, FACTS, and the consolidation of parallel transmission lines. These plan of action play a important role in bolstering transient stability, increase transmission capacity, and attenuating low-frequency oscillations.

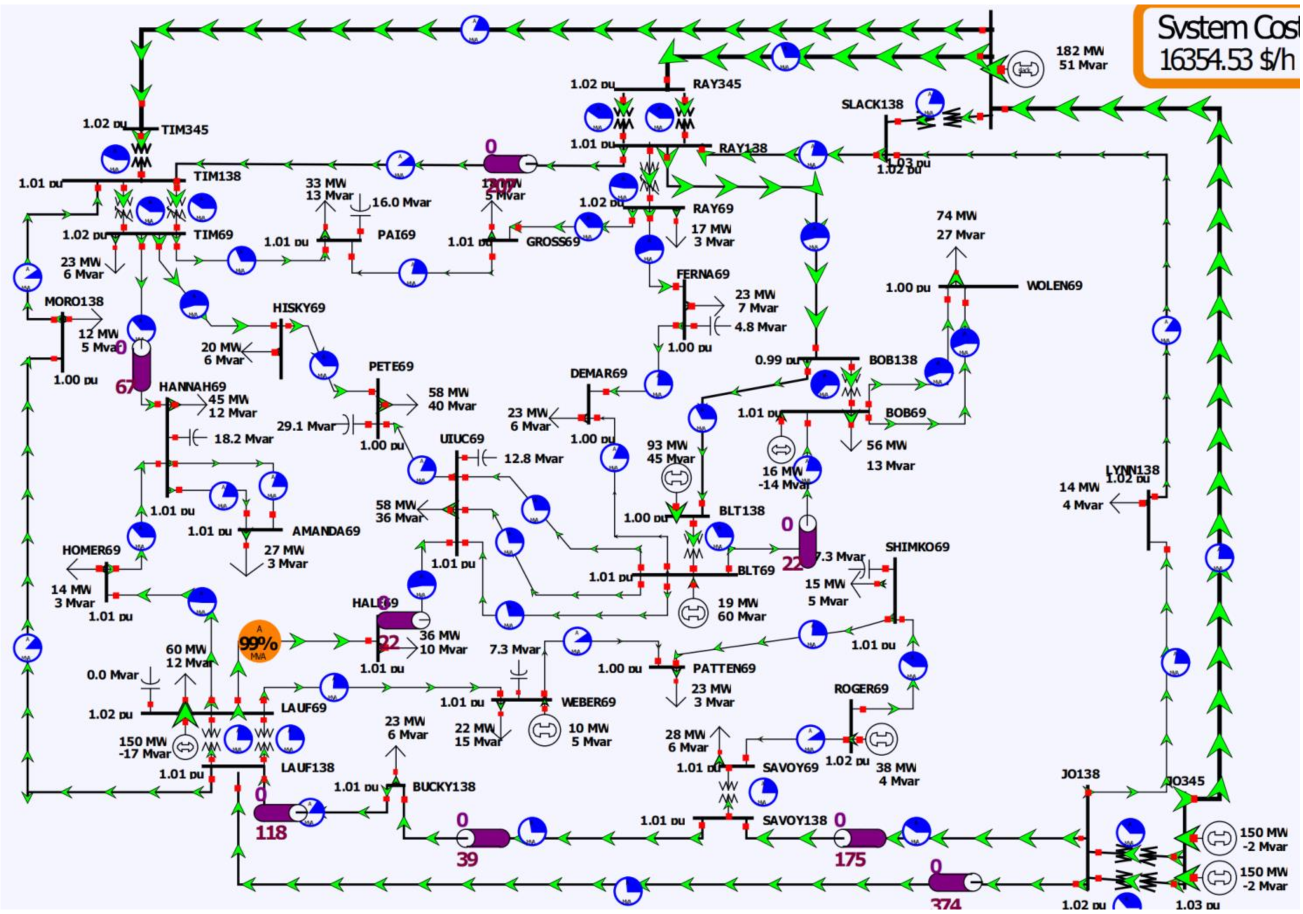


Figure (3) New England 39-Bus Power System

Table (3) Examination with D-FACTS and without D-FACTS

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| Between line | No. of overloads without D-FACTS | No. of overloads with D-FACTS |
|---|---|---|
| 1-2 | 0 | 0 |
| 1-5 | 1 | 0 |
| 2-3 | 1 | 1 |
| 2-4 | 4 | 1 |
| 2-5 | 3 | 3 |
| 3-4 | 4 | 1 |
| 4-5 | 3 | 2 |
| 4-7 | 2 | 2 |
| 4-9 | 3 | 2 |
| 5-6 | 5 | 5 |
| 6-11 | 1 | 1 |
| 6-12 | 0 | 1 |
| 6-13 | 2 | 2 |
| 7-8 | 0 | 0 |
| 7-9 | 2 | 0 |
| 9-10 | 3 | 3 |
| 9-14 | 1 | 1 |
| 10-11 | 2 | 2 |
| 12-13 | 1 | 1 |
| 13-14 | 3 | 4 |
| **Total no of overloads** | **41** | **32** |

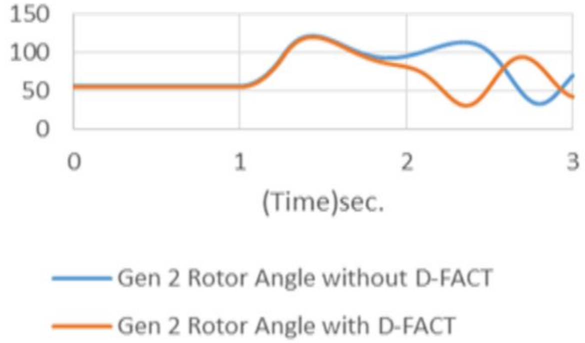

Figure (4) Rotor Angle of Generator 2

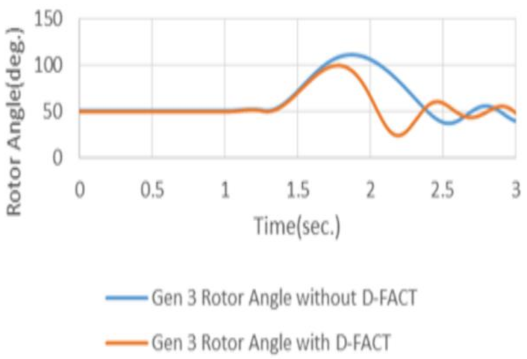

Figure (5) Rotor Angle Of Generator 3

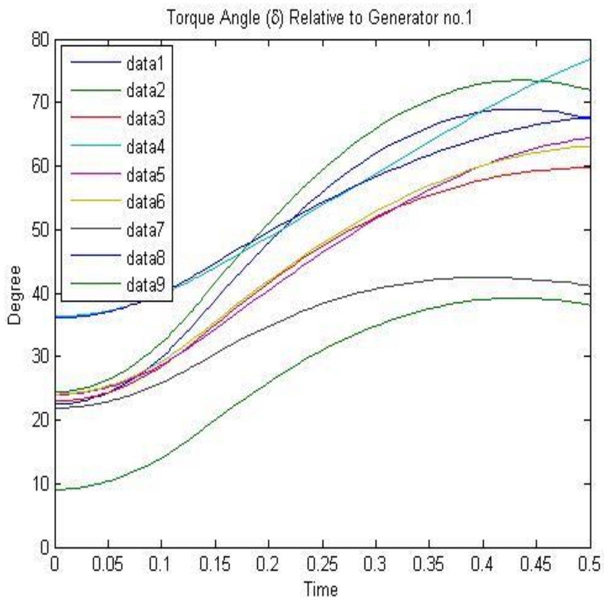


Figure (6) Generators curve during disturbance at (CCT =0.134)

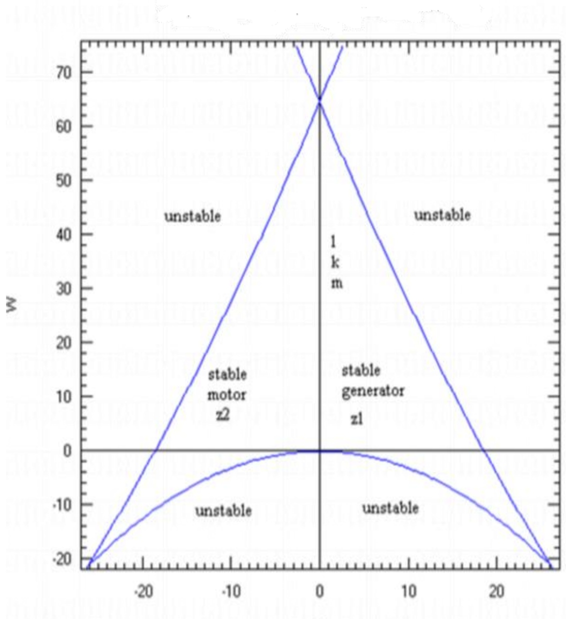


Figure (7) Transient Stability By Catastrophe Theory

Operation location that mention in fig(7) of generators are placed in the control space. It is recovered that these regions internal the furcation, point that generator stability at fault clearing time is to a lesser degree or close to the related CCT [14]. A generator may be explosive if it is seriously impressed by the fault happening and its in operation point place external the bifurcation set conditional the bus perturbation get in that situation.

## 6. CONCLUSIONS

Transient power system stability characterizes a acute concern for present networks of power. D-FACTS strategies present a capable solution due to their quick and exact control competences. By integrating D-FACTS methods with catastrophe theory, unique can reach a deep comprehension of system stability verges and plan more active and urbane control approaches. Catastrophe theory demand a robust direct framework for qualitatively work sudden change in transient stability of power system behaviour, in that way enablingthe foremost position of D-FACTS plan of action to enhance power of transient stability and, therefore, boost the consistency and safety of power systems stability. A technique described in this article purposes to improve transient system stability.Catastrophe theory proposals a robust precise framework for the qualitative analysis of abrupt modifications in system performance, enabling the greatest planning of D-FACTS to enhance transient stability of power system, that technique rise the transient stability of power systems. The power of the proposed method in this article has been showed by determine survey on New England 10 machine 39 bus.

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Maithem AL Hussani was born On November 1981. Received his B.S. degrees in Electrical Engineering from ALmustansiriyah University, Baghdad ,Iraq in 2007. Received his MS.C degree in

electrical engineer (industrial power) 2013. His Ph.D in Electrical Engineering; His research interests include Transient stability of power system using catastrophe theory and DFACT 2024.