# EXCITATION CONTROL OF SYNCHRONOUS GENERATOR USING A FUZZY LOGIC BASED BACKSTEPPING APPROACH

**Abhilash Asekar[1]**

[1]*School of Engineering, Deakin University, Waurn Ponds, Victoria 3216, Australia*

---------------------------------------------------------------------***---------------------------------------------------------------------

**Abstract-** *Excitation control of synchronous generators using a Fuzzy Logic-based Backstepping Approach is proposed to enhance the performance of excitation system. The dynamical model of synchronous generator excitation system is considered for designing this proposed controller. The traditional nonlinear control control scheme uses 'Trial and Error method' for selecting tuning function values which does not guarantee the optimum system performance against diverse fault conditions. The proposed controller is designed to evaluate efficient control gains appeared in 'backstepping control law of excitation system' by using Fuzzy Logic Algorithm. First, backstepping controller law is designed using Control Lyapunov functions (CLFs). The control Lyapunov functions (CLFs) are expressed as the negative definiteness or semi-definiteness of the derivatives while designing the backstepping control law. Further, fuzzy logic system is implemented for controlling three tuning gains appeared in backstepping control law for improving the stability of the system. Simulation studies are carried out on single-machine infinite bus power system to evaluate the performance of the proposed scheme. Specific boundary conditions are used for establishing the membership function of fuzzy logic control system. Simulation of the proposed controller is carried out in MATLAB Simulation software. The simulation results of proposed control scheme further validated that the performance of the system against severe faults is improved as compared to traditional controller (Power System Stabilizer) with constant tuning function values.*

***Key Words***: Synchronous Generator Excitation System, Backstepping Control System, Fuzzy Logic Control System, MATLAB/Simulink Software, Power System Stability

## 1. INTRODUCTION

Existing power system consists of discrete complexities due to its nonlinear and interconnection nature. These complexities lead to disturbances and faults in power system. The stability of the power system usually gets deteriorate due to the existence of diverse disturbances. Hence, maintaining load demands without disturbing operation stability has always been challenging for any power system. Some examples of power system disturbances are transient instability, external disturbances, faults, overloads, lightning strokes, etc. Theses disturbances creates oscillating appearances in operating parameters, which shifts the power system towards instability and makes it unpredictable. These nonlinearities demand for robust control designs to overcome or nullify the effects of faults occurred in the system.

In order to overcome these common disturbances or faults in power system, the stabilizers/controllers are commonly practiced even in excitation system of synchronous generator. The principle of these excitation system stabilizers is to damp out the effects of disturbances/errors from the power system by using control input signal as corrective feedback to the system injected by these stabilizers. The commonly used traditional controllers for stabilizing the disturbances in nonlinear excitation power systems, are Linear Quadratic Regulator (LQR), Feedback Linearization (FBL), Automatic Voltage Regulator, Sliding Mode Controller and Backstepping Controller [1]. However, external disturbances present in synchronous generator excitation system has always been an issue while designing the controller [1] [3].

Backstepping Approach is one of the effective approaches to overcome the nonlinearities in power system. Research studies were conducted for designing a robust excitation controller using Backstepping control scheme where Control Lyapunov Function (CLF) was used to ensure the stability of the system. In a study, the robust adaptive backstepping control design was proposed by using two-axis generator model for improving transient stability and voltage regulation and showed promising results [3]. However, after critically analyzing these research studies, it is revealed that the tuning function of the controller is selected by using trial and error method. These selected constant tuning function values does not guarantee the system stability against diverse severe faults. Hence, estimation of optimum gain value appeared in backstepping control law is seems to be questionable. Even though CLFs are designed for ensuring the stability of the system, it does not guarantee the optimum performance against diverse faults. Because the CLFs is proportional to the values of error, and the values of error is always dependent on the severity of fault occurred in the system. Hence, the adjustable tuning function is required to act against diverse range of error. The values of gain should vary with respect to value of error in order to maintain Control Lyapunov Function less than or equal to zero. This demands for collaboration of traditional backstepping control system with Artificial Intelligence system in such a way that the controller gain should vary with respect to the magnitude of fault. Therefore, scope of this research is oriented towards formulation of rule-based algorithm to estimate and approximate the tuning function automatically using AI technique. Research studies also revealed that formulating algorithm is one of the efficient ways for calculating unknown parameters by using fuzzy logic rules [2].

The aim of this research study is to design a controller for synchronous generator excitation system using a Fuzzy Logic-based Backstepping Approach. The gains of the backstepping controller are calculated by using specific fuzzy rules. Optimum tuning function value is determined by using set of fuzzy algorithms for formulation of respective tuning function. The proposed control design is based on the detailed dynamic model of synchronous generators excitation system. Firstly, Backstepping Approach is considered for designing the control law for excitation system of synchronous generator where the Control Lyapunov Functions (CLFs) are expressed as the negative definiteness or semi-definiteness of the derivatives in all steps of the control design for ensuring the stability of the system. Simulation studies of Fuzzy Logic-based Backstepping Controller are carried out on Single Machine Infinite Bus to evaluate the performance of the proposed scheme using MATLAB Simulink Software.

## 2. OVERVIEW OF NONLINEAR EXCITATION CONTROL DESIGN USING BACKSTEPPING APPROACH

Backstepping is the control strategy that contains steps from final result of designing stable controllers to beginning of it. It is a Lyapunov-based recursive design procedure for nonlinear systems. The Control Lyapunov Function (CLF) helps in assuring the system stability for the respective control signal [3]. In this section, overview of nonlinear backstepping excitation control scheme is presented for nominal model of nonlinear system.

The generalized equation for nonlinear system can be expressed as;

$$\dot{x} = f(x) + g(x)u$$

Where x is the state of the system which indicates diverse physical properties of the system (Voltage, current, etc.), f and g is the nonlinear function for the respective physical properties of the system (x) and u is the control signal. The objective of the backstepping controller is to make 'x' to follow the desired trajectory $x_d$ with respect to the control input signal (u) [3].

In order to determine the value of control signal, the tracking error can be expressed as;

$$z = x - x_d$$

Where z is the tracking error.

The derivative of the error can be expressed as;

$$\dot{z} = f(x) + g(x)u - \dot{x_d}$$

In the next step, the Control Lyapunov Function W will be used to determine the control input signal that will further converge z to zero.

$$W = \frac{1}{2}z^2$$

The derivative of W can be written as;

$$\dot{W} = z(f(x) + g(x)u - \dot{x_d}$$

If $\dot{W} \leq 0$ then the control signal 'u' will ensure the stability.

Hence the control signal can be selected as;

$$u = -\frac{1}{g(x)}(f(x) - \dot{x_d} + \eta z \qquad (1)$$

Where $\eta$ is a positive constant which helps to tune the output signal [1, 3].

Hence, the simplified derivative of W can be expressed as;

$$\dot{W} = -\eta z^2 \leq 0$$

This negative semi definite verifies the stability of nonlinear system for the selected control signal u (equation 1) [1, 3-6].

**3. FUZZY LOGIC SYSTEM OVERVIEW**

The fuzzy logic system was firstly developed in earlier 1960s by Mamdani. It is an alternative to the classical controlling method which uses decision making logic originated by specific algorithm (Artificial Intelligence). Fuzzy logic provides more intuitive way to tune the controller as compared to other similar decision-making techniques like NN or GA without using complex analytical control theories. Studies have also validated the excellence response of fuzzy logic against nonlinear power system. Fuzzy rules in terms of

'If- Then' statements are used by using boundary conditions of the selected system [7]. The fuzzy logic system operates in four basic steps as shown in figure 1.

Step 1 - Fuzzification: Determination of membership functions by using boundary conditions and converting crisp input values into set of fuzzy variables.

Step 2 - Rule Base: Rule-base can be defined as set of rules by using If-Then statement. Behavioral analysis of the system is essential to implement the appropriate rules. The utmost spread connector is AND but other connectors such as 'OR, NOT, IF AND ONLY IF' is also possible to use with IF THEN rule.

Step 3 - Inference Mechanism: Inference Engine or Mechanism is the heart of the fuzzy logic system. Inference Mechanism applies reasoning to compute the crisp fuzzy output and provides the degree of membership function defined in fuzzification step. Mamdani and Sugeno are the majorly used inference mechanism [2]. The overview of inference mechanism is illustrated in figure 1 below.

Step 4 - Defuzzification: Defuzzification is conversion of fuzzified values into the single crisp output. It is the exact opposite step of fuzzification where the crisp output will be delivered after processing through fuzzy rule-base algorithm. The defuzzified output is demonstrated in figure 1 [7].

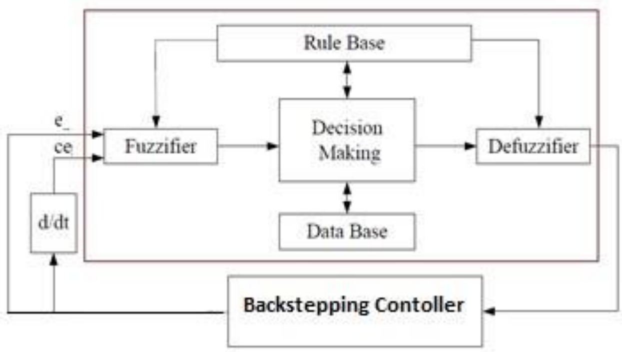


**Fig -1**: Fuzzy Logic Control System Steps

**4. RESEARCH METHODOLOGY**

The aim of this research project is to design Excitation Control of Synchronous Generators using a Fuzzy Logic- Based Backstepping Approach. Single Machine Infinite Bus system (SMIB) and two-axis dynamical model of synchronous generator is considered in this project to compute the required control law for proposed controller after referring the research paper. SMIB system includes synchronous generator, which is connected to infinite bus through transformer and two parallel distribution lines. The objective of this research project is to design an excitation controller to enhance transient stability and voltage regulation of the system from dynamic synchronous generator excitation system model by implementing the fuzzy based algorithm.

### 4.1 Stage 1- Designing a Backstepping Control Law

It is essential to establish a control law for Excitation Control of Synchronous Generators SMIB two-axis dynamical model by using backstepping approach as explained in the research paper. It is important to understand the design of excitation system controller based on backstepping approach in order to formulate fuzzy rule-based algorithm. By referring relevant papers on adaptive backstepping excitation controller design, the backstepping excitation controller design for higher order model of synchronous model is demonstrated in this section below where the symbols carry standard meanings.

Dynamical Model of Synchronous Generator [1, 3]:

$$\dot{\delta} = \omega - \omega_0$$
$$\dot{\omega} = -\frac{D}{2H}(\omega - \omega_0) + \frac{\omega_0}{2H}P_m - \frac{\omega_0}{2H}(E'_q\, I_q + E'_d\, I_d)$$
$$\dot{E'}_q = -\frac{1}{T'_d}E'_q + \frac{(x_d - x'_d)}{T'_{do}}\, I_d + \frac{1}{T'_{do}}E_{fd}$$

The final backstepping control law appeared for the above dynamic model of synchronous generator is;

$$E_{fd} = T'_{do}\left[\frac{1}{T'_{do}}E'_q - \frac{(x_d - x'_d)}{T'_{do}}\, I_d + \dot{\alpha_1} - k_3 e_3\right]$$

Where $\alpha_1$ is virtual control input appeared while designing the control law. Refer [3] for standard meanings of symbols.

### 4.2 Stage 2 - Designing Fuzzy Logic Algorithm

Fuzzy logic formulation is required for calculation of tuning function k1, k2 and k3 as mentioned in backstepping controller design section. In order to formulate algorithm for each tuning function, it is essential to establish boundary conditions. Using these boundary conditions, an algorithm is formulated using fuzzy based rule [2]. Boundary conditions that will be used for calculation of tuning function values as appeared while designing of backstepping are;

- W ≤0, (2)

Where W - Lyapunov Control Function (LCF)

- k1, k2, k3 > 0

Where, k – Tuning function/gain

The inputs of the fuzzy logic system are error and change in error, and the output of the Fuzzy Logic System (FLS) is tuning function value 'k1, k2, k3' for the respective errors e1, e2, e3. Three fuzzy logic algorithms are formulated for three tuning function values k1, k2 and k3. Mamdani Fuzzy Logic Inference System is used with centroid defuzzification method. IF-Then fuzzy rules are established in Rule Editor Section of FLS to find the desired optimum tuning function value as a crisp output. Example: - If Error is Positive and Change in Error is Positive Then Output 'K' is Positive. The fuzzy rules are demonstrated in the table 1, 2, 3 for output k1, k2 and k3 respectively.

**Table -1:** Fuzzy Rules for k1

| de1 \ e1 | N | Z | P |
|---|---|---|---|
| N | SP | MP | MP |
| Z | MP | MP | BP |
| P | BP | BP | BP |

**Table -2:** Fuzzy Rules for k2

| de2 \ e2 | N | Z | P |
|---|---|---|---|
| N | SP | SP | MP |
| Z | MP | MP | BP |
| P | BP | BP | BP |

**Table -3:** Fuzzy Rules for k3

| de3 \ e3 | N | Z | P |
|---|---|---|---|
| N | SP | SP | SP |
| Z | MP | MP | MP |
| P | BP | BP | BP |

Where,

ei - error (i=1,2,3), dei - change in error (i=1,2,3);

N- Negative, Z- Zero, P- Positive, SP- Small Positive, MP- Medium Positive, BP- Big Positive;

The surface for the rules is demonstrated by using Fuzzy Logic

Surface Viewer in the figure 2, 3 4.

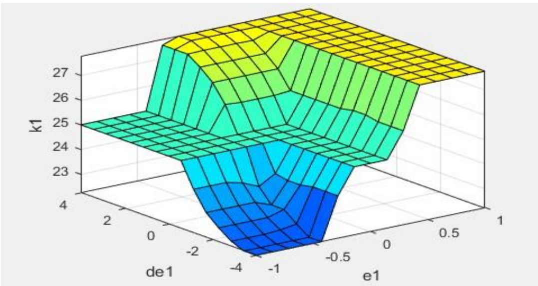


**Fig -:2**: Rules Surface for Fuzzy Logic Output k1

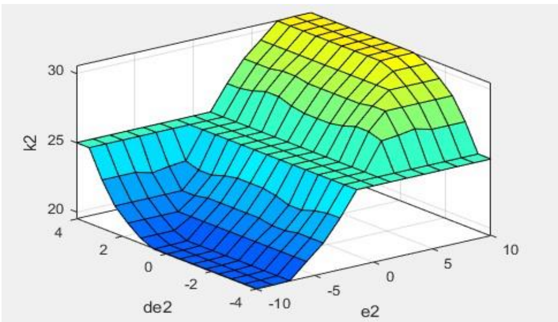


**Fig -:3**: Rules Surface for Fuzzy Logic Output k2

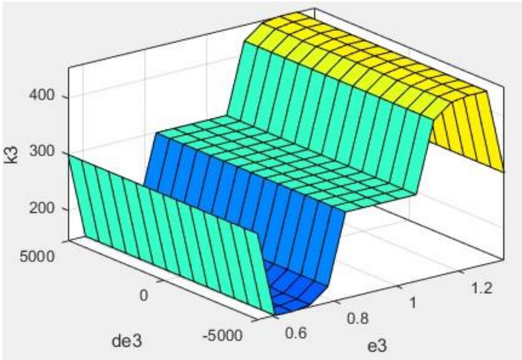


**Fig -4**: Rules Surface for Fuzzy Logic Output k3

The membership function of the fuzzy logic algorithm is basically designed by using the equations of Control Lyapunov Functions (W1, W2, W3) appeared while designing backstepping control lw. Initially, the values of CLF (W1, W2, W3) are calculated and analyzed with constant tuning function as shown in the table 4.

Table 4 shows that the CLF values are positive for error readings collected during simulation of Synchronous generator using Backstepping Controller. However, CLF values should be less than or equal to zero during all the phases of simulation for efficient operation as per equation

2. Therefore, values of tuning function K1, K2 and K3 should change along with the values of error e1, e2 and e3 respectively to improve the system stability. Table 5 shows that the values of CLF W1 and W2 became negative by increasing the tuning function k1 and k2.

## 5. SIMULATION RESULTS

The important parameter of the SMIB system which are used to carry out these studies are as follows; Nominal Power Pn =

200MVA, Vn=13.8 kv, xd=1.305 pu, x'd= 0.296 pu, D=2.5 pu, Tdo=4.25 s, T'd=1.01 s, H=3.2 s, Vref=1 pu, Pref = 0.75pu,

wref = 1 pu, w0= 314.59 rad/s. The performance of the proposed controller is analysed for two faults. Case-1 for fault at the middle of transmission lines and case-2 for fault at the terminal of generator. These faults are the most severe faults that could appear during the operation of synchronous machine. The behaviour of the controller is observed for 20sec during which these faults are implemented to understand the behaviour of proposed controller during fault conditions. The fault is applied at t= 10 sec and cleared at t=10.2 sec for both the cases as mentioned above.

**Case-1: Controller performance in three phase short circuit fault at the middle of transmission lines.**

The operation of machine with Fuzzy Logic based Backstepping Controller and traditional PSS Controller is compared as shown in the charts 1, 2, 3.

**Table -4:** Backstepping Controller Reading with constant tuning function values

| | e1 | e2 | e3 | k1 | k2 | k3 | Iq | w1 | w2 | w3 |
|---|---|---|---|---|---|---|---|---|---|---|
| Initial | 0 | 0 | 0 | 2 | 3 | 3 | 0.265 | 0 | 0 | 0 |
| Reading 1 | 0.1 | 1 | -170 | 2 | 3 | 3 | 0.7 | 0.08 | 23.5 | -ve |
| Reading 2 | 0.19 | 2 | -80 | 2 | 3 | 3 | 0.6 | 0.3078 | 12.8878 | -ve |
| Reading 3 | 0.38 | 4 | -40 | 2 | 3 | 3 | 1.2 | 1.2312 | -7.3288 | -ve |

**Table -5**: Backstepping Controller Reading with varying tuning function values

| | e1 | e2 | e3 | k1 | k2 | k3 | Iq | w1 | w2 | w3 |
|---|---|---|---|---|---|---|---|---|---|---|
| Initial | 0 | 0 | 0 | 2 | 2 | 2 | 0.265 | 0 | 0 | 0 |
| Reading 1 | 0.1 | 1 | -170 | 20 | 18 | 2 | 0.7 | 0 | -2.58 | -ve |
| Reading 2 | 0.19 | 2 | -80 | 25 | 8 | 2 | 0.6 | -0.0532 | -7.4732 | -ve |
| Reading 3 | 0.38 | 4 | -40 | 25 | 4 | 2 | 1.2 | -0.646 | -41.206 | -ve |

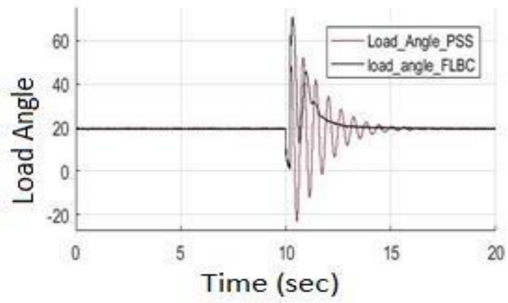


**Chart -1**: Load Angle in case of fault at the middle of transmission lines

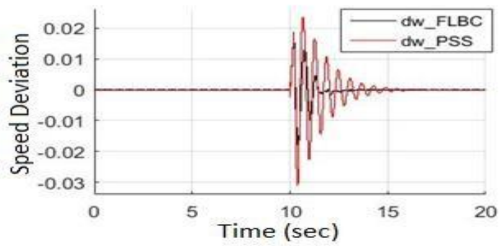


**Chart -2**: Speed Deviation Angle in case of fault at the middle of transmission lines

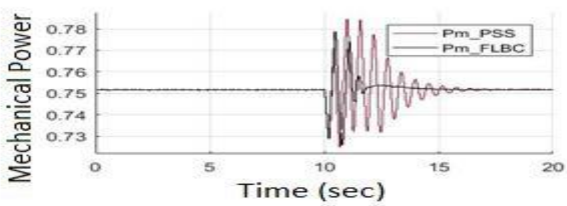


**Chart -3**: Mechanical Power in case of fault at the middle of transmission lines

Load angle, speed deviation and mechanical power of synchronous machine with fuzzy logic based backstepping controller (black line) stabilizes the system far before as compared to traditional Power System Stabilizer (PSS) (red line) as shown in chart 1, 2 and 3 respectively. It is also observed that the fluctuation appeared while stabilizing the faults are also less as compared to PSS.

**Case-2: Controller performance in three phase short circuit fault at the terminal of synchronous generator**

The operation of machine with Fuzzy Logic based Backstepping Controller and traditional PSS Controller is compared as shown in the chart 4, 5 and 6.

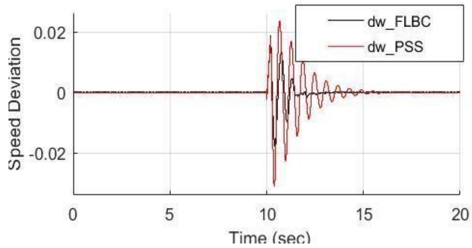


**Chart -4**: Speed Deviation in case of fault at the terminal of generator

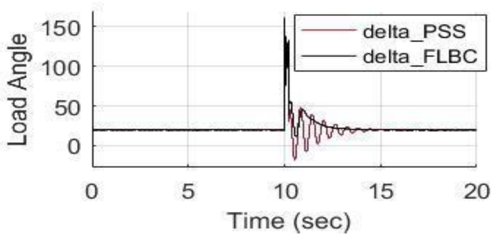


**Chart -5**: Load Angle in case of fault at the terminal of generator

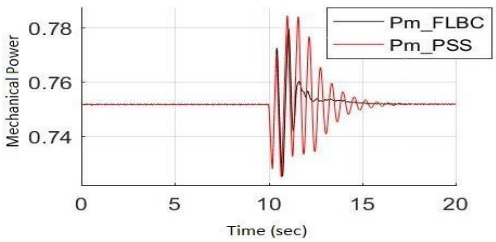


**Chart -6**: Mechanical Power in case of fault at terminal of generator

It is observed that that Load angle, speed deviation and mechanical power of synchronous machine with fuzzy logic based backstepping controller stabilizes the most severe fault at terminal of generator effectively as compared to traditional Power System Stabilizer even with less fluctuations as shown in chart 4, 5 and 6 respectively. The synchronous generator remains stable while operating at synchronous speed. In chart 4, 5 and 6, it can also be observed that the operation of generator is stable till t=10 seconds as machine is operating at synchronous speed which shows overall robustness of the proposed controller.

## 6. CONCLUSION

The Fuzzy Logic-based Backstepping Controller (FLBC) based on dynamic model of synchronous generator is designed for improving the stability of the system. The formulation of backstepping control law is carried out by using Control Lyapunov Functions (CLF) theory. Fuzzy logic algorithm is implemented for calculating the optimum tuning function values appeared in backstepping controller. The effectiveness of the designed controller is evaluated by applying symmetrical three phase short circuit fault at different locations of the SMIB system. The simulation results clearly show that the fuzzy logic based backstepping controller is more effective for stabilizing faults as compared to traditional Power System Stabilizer. Future work will be devoted for designing a higher order backstepping controller with Fuzzy Logic System.

## REFERENCES

1) T. K. Roy, M. A. Mahmud, W. Shen, A. M. T. Oo, and M. E. Haque, "Robust nonlinear adaptive backstepping excitation controller design for rejecting external disturbances in multimachine power systems," International Journal of Electrical Power & Energy Systems, vol. 84, pp. 76-86, 2017/01/01/ 2017.

2) S. Jagannathan and F. L. Lewis, "Robust backstepping control of a class of nonlinear systems using fuzzy logic," Information Sciences, vol. 123, no. 3, pp. 223-240, 2000/04/01/ 2000.

3) T. K. Roy, M. A. Mahmud, A. M.T. Oo, and H. R. Pota, "Nonlinear Adaptive Backstepping Excitation Controller Design for Higher-Order Models of Synchronous Generators," IFAC- PapersOnLine, vol. 50, no. 1, pp. 4368-4373, 2017/07/01/ 2017.

4) M. Mahmud, M. Hossain, H. Pota, and A. M. Oo, "Robust partial feedback linearizing excitation controller design for multimachine power systems," IEEE Transactions on Power Systems, vol. 32, no. 1, pp. 3-16, 2017.

5) T. Roy, M. Mahmud, W. Shen, and A. Oo, "A nonlinear adaptive backstepping approach for coordinated excitation and steam-valving control of synchronous generators," in Control Conference (ASCC), 2015 10th Asian, 2015, pp. 1-6: IEEE.

6) T. Roy, M. Mahmud, W. Shen, and A. Oo, "Nonlinear excitation control of synchronous generators based on adaptive backstepping method," in Industrial Electronics and Applications (ICIEA), 2015 IEEE 10th Conference on, 2015, pp. 11-16: IEEE.

7) H. Tong, T. Maxwell, Y. Zhang, and V. Dey, "A supervised and fuzzy-based approach to determine optimal multi-resolution image segmentation parameters," Photogrammetric Engineering & Remote Sensing, vol. 78, no. 10, pp. 1029-1044, 2012.