Enhancement of Transient Stability Limit Using Fuzzy Controlled TCSC

V A Prabhakar Reddy#1, Ch Rambabu#2

Abstract: **Whenever a Power system is subjected to sudden changes in load levels then stability is an important concept which determines the stable operation of power system. For the accurate analysis of transient stability requires a detailed modelling of generating units and other equipment. In general rotor angle stability is taken as index, but the concept of transient stability, which is the function of operating condition and disturbances deals with the ability of the system to remain intact after being subjected to abnormal deviations. In this paper studies have been carried out in order to improve the Transient stability of WSCC 9 bus system with fixed compensation on lines and optimal location have been investigated using "Trajectory Sensitivity Analysis" for better result. In order to improve the Transient Stability a series compensated FACT Device TCSC have been implemented.**

The case study depict the optimal location of fixed compensation in WSCC-9 Bus system based on the stability index (ETA). Further a fuzzy controlled TCSC has been implemented on WSCC-9 bus system to improve stability of the system. The fuzzy controlled TCSC is observed to perform better, compared to conventional PI controller.

Index Terms: Trajectory sensitivity analysis, Stability Index, Transient Stability, Fuzzy Controller, and TCSC.

I.INTRODUCTION

In recent years, power demand has increased substantially while the expansion of power generation and transmission has been severely limited due to limited resources and environmental restrictions. As a consequence, some transmission lines are heavily loaded and the system stability becomes a power transfer-limiting factor. An increasingly competitive market where economic and environmental pressures limit their scope to expand transmission facilities. The optimization of transmission corridors for power transfer has become a great importance. The demand of electrical power is ever increasing. However, the process of development of new infrastructure for power generation and dispatch is restricted due to mainly economic and partially environmental constraint. Power system stability has been recognized as an important problem for secure system operation since the 1920s [1].

The use of FACT controllers can be helpful in improving the efficiency of the power system operation. Improved tools for assessing available stability margin of a system are required due to the open access nature of the deregulated system. This paper demonstrates that the Trajectory Sensitivity Analysis (TSA) can be a variable option. The technique can also be used for determining the suitable location of FACT devices in a large interconnected network.

Transient stability of a power system is its ability to maintain synchronous operation of the machines when subjected to a large disturbance. The occurrence of such a disturbance may result in large excursions of the system machine rotor angles and, whenever corrective actions fail, loss of synchronism results among machines. The nonlinear character of transient stability, its fast evolution and its disastrous practical implications make it one of the most important and at the same time most problematic issues to assess and even more to control, especially today, with the emerging deregulation practices of the electric sector in many countries. Indeed, the deregulated electric energy sector in the United States, in Europe, and in many other parts of the world will call for independent system operators to be responsible for the transmission network[3].The classification of power system stability [2] and many different techniques have been reported in the literature pertaining to investigating the effect of TCSC on the power system stability [9]. In [10] a fuzzy logic controller is designed to use the DCSC for enhancing transient stability in a two-machine two area power system. In [11] an improved fuzzy logic based supplementary controller for static var compensator is developed for damping the rotor angle oscillations and to improve the stability of the power system.

II.TRANSIENT STABILITY ANALYSIS

Transient stability studies provide information related to the capability of a power system to remain in synchronism during major disturbances resulting from either the loss of generating or transmission facilities, sudden or sustained load changes, or momentary faults. Specifically, these studies provide the changes in the voltages, currents, powers, speeds, and torques of the machines of the power system, as well as the changes in system voltages and power flows, during and immediately following a disturbance. The degree of stability of a power system is an important factor in the planning of new facilities. In order to provide the reliability required by the dependence on continuous electric service, it is necessary that power systems be designed to be stable under any conceivable disturbance [4].

Transient stability is the ability of power system to keep its synchronism when a large disturbance, like three phase short circuit, occurs in the system. Nowadays, deregulation in electricity markets, increasing electricity demands and high penetration of renewable energy sources in one The The economic and environmental constraints on installing new transmission lines and building new power plants on the other hand, have pushed the existing transmission systems to be operated close to their critical conditions [6]. So, there is a higher risk of transient instability in today's heavy-loaded and interconnected power systems.

A. Modelling of the system

Representation of generator:

The synchronous machine is represented by a voltage source, in back of a transient reactance, that is constant in magnitude but changes in angular position. If the machine rotor speed is assumed constant at synchronous speed, a normal and accepted assumption for stability studies, then M is constant. If the rotational power losses of the machine due to such effects as wind friction are ignored, then the accelerating power equals the difference between the mechanical power and the electrical power. The classical model can be described by the following set of differential and algebraicequation.

Differential Equations:

$$\frac{d\delta}{dt} = \omega - 2\pi f \qquad (1)$$

$$\frac{d^2\delta}{dt^2} = \frac{d\omega}{dt} = \frac{\pi f}{H}(P) \qquad (2)$$

Algebraic Equation

$$E' = E_t + r_a I_t + jx'dI_t \qquad (3)$$

Where E' is the voltage back of transient reactance, E_t is the machine terminal voltage, I_t it is machine terminal current, r_a is armature resistance and x'_d is transient reactance.

Representation of loads:

Power system loads, other than motors represented by equivalent circuits, can be treated in several ways during the transient period. The commonly used representations are either static impedance or admittance to ground, constant real and reactive power, or a combination of these representations. The parameters associated with static impedance and constant current representations are obtained from the scheduled busloads and the bus voltages calculated from a load flow solution for the power system prior to a disturbance. The initial value of the current for a constant current representation is obtained from

$$I_{po} = \frac{P_{tp} - jQ_{tp}}{E'_p} \qquad (4)$$

The static admittance Y_{po} used to represent the load at bus P, can be obtained from

$Y_{p0} = \frac{I_{po}}{E_p}$ Where E_p is the calculated bus voltage, P_{tp} and Q_{tp} are the scheduled busloads. Diagonal elements of Admittance matrix (Y – Bus) corresponding to the load bus are modified using the Y_{PO}.

B. Simulation of faults:

A fault at or near a bus is simulated by appropriately changing the self-admittance of the bus. For a three-phase fault, the fault impedance is zero and the faulted bus has the same potential as the ground. This involves placing infinite shunt admittance, so that the bus voltage is in effect zero. The fault is removed by restoring the shunt admittance to the appropriate value depending on the post fault system configuration.

Simulation of fault in a power system studies:

A symmetrical fault is simulated in one of the lines at a time. The simulation is done in three phases: 1.The pre-fault system is run for a small time (say 1 second) till the system is initialized. 2. The fault is then applied at one end of the line. Simulation of this faulted condition continues till the line is disconnected from the buses at both the ends of the faulted line after a time tcl. The time gap between the tripping of breakers at the two ends is negligible compared to the clearing time. Hence the disconnection of the line at the two ends can be considered simultaneous.3. Next is the post-fault system simulation where the faulted line is totally disconnected from the system. Simulation is carried out for a longer time (say 10-20seconds) to observe the nature of the transients. [5]

Multi machine system:

The following steps need to follow for determining multimachine stability.

1. From the prefault load flow data determine E'_kvoltage behind transient reactance for all generators. This establishes generator emf magnitudes $|E_k|$ which remains constant during the study and initial rotor angle $\delta k^0 = \angle E_k$. Also record prime mover inputs to generators, $P_{mk} = P_{gk}^0$.
2. Augment the load flow network by the generator transient reactance. Shift network buses behind the transient reactance.
3. Find Ybus for various network conditions during fault, post fault (faulted line cleared), after line reclosure.

4. For faulted mode, find generator outputs from power angle equations and solve swing equations step by step (point by point method) or any integration algorithms such as modified Euler's method, R.K fourth order method etc.
5. Keep repeating the above step for post fault mode and after line reclosure mode.
6. Examine δ (t) plots for all the generators and establish the answer to the stability question.

III.TRAJECTORY SENSITIVITY ANALYSIS

Computation of Trajectory Sensitivity:

Multi machine power system is represented by a set of differential equations

$\dot{X}$=⍰ (t, x,λ), $\quad X(t_0) = X_0$ (5)

Where x is a state vector and λ is a vector of system parameters. The sensitivities of state trajectories with respect to system parameters can be found by perturbing λ from its nominal valueλ_0.The equations of trajectory sensitivity can be found as

$\dot{x}_\lambda = [\frac{\partial f}{\partial x}]x_\lambda + [\frac{\partial f}{\partial x}], \quad x_\lambda(t_0) = 0$ (6)

Where $x_\lambda = \frac{\partial x}{\partial \lambda}$ Solution of (5) and (6) gives the state trajectory and trajectory sensitivity, respectively. However sensitivities can also be found in a simpler way by using numerical method

IV.THYRISTOR CONTROLLED SERIES CAPACITOR (TCSC)

The basic Thyristor-Controlled Series Capacitor scheme, proposed in 1986 by Vithayathil with others as a method of "rapid adjustment of network impedance," is shown in the fig.[2].It consists of the series compensating capacitor shunted by a Thyristor-Controlled Reactor. In a practical TCSC implementation, several such basic compensators may be connected in series to obtain the desired voltage rating and operating characteristics [8].

This arrangement is similar in structure to the TSSC and, if the impedance of the reactor,X_l, is sufficiently smaller than that of the capacitor, X_c, it can be operated in an on/off manner like the TSSC. However, the basic idea behind the TCSC scheme is to provide a continuously variable capacitor by means of partially cancelling the effective compensating capacitance by the TCR. The TCR at the fundamental system frequency is a continuously variable reactive impedance, controllable by delay angle α, the steady state impedance of the TCSC is that of a parallel LC circuit, consisting of a fixed capacitive impedance,X_c, and a variable inductive impedance, X_l(α), that is, X_{TCSC}(α) = (X_c*X_l)/(X_l(α)-X_c) Where X_l(α)=X_l*π / (π-2α-sinα),

$X_l \le X_l$(α)≤ ∞ $X_l = \omega_l$, and α is the delay angle measured from the crest of the capacitor voltage.

Modelling of the TCSC and the power system:

The TCSC model is given in Fig. 2. The overall reactance XC of the TCSC is given in terms of the firing angle α as

$$x_c = \beta_1(X_{Fc} + \beta_2) - \beta_4\beta_5 - X_{FC} \qquad (7)$$

Where $\beta_1 = \frac{2(\pi-\alpha)+sin2(\pi-\alpha)}{\pi}$,$\beta_2 = \frac{X_{FC}X_P}{X_{FC} - X_P}$,$\beta_3 = \sqrt{\frac{X_{FC}}{X_P}}$,

$\beta_4 = \beta_3 \tan[\beta_3(\pi - \alpha)] - \tan(\pi - \alpha)$,

$\beta_5 = \frac{4\beta_2^2 cos^2(\pi-\alpha)}{\pi x_p}$.

Let us denote the fundamental frequency capacitance of the TCSC, which is equal to 1/($\omega_s X_c$), as Ctcsc. It is to be noted that in this work the TCSC is operated only in the capacitive mode. The capacitive reactance X_{FC} of the TCSC is chosen as half of the reactance of the line in which the TCSC is placed and the TCR reactance X_p is chosen to be 1/3 of XFC.

V.FUZZY LOGIC CONTROLLER

Fuzzy logic is an innovative technology that enhances conventional system design with engineering expertise. Using fuzzy logic, we can circumvent the need for rigorous mathematical modelling. During the past several years, FLC has emerged as one of the most active area of research for the application of fuzzy set theory. A fuzzy set is a generalization of the concept of an ordinary set in which the membership function (MF) values can be only one of the two values, 0 and 1.

A. Fuzzy Controller Model

A.Fuzzy modelling is the method of describing the characteristics of a system using fuzzy inference rules. The method has a distinguishing feature in that it can express linguistically complex non-linear system .It is however very hard to identify the rules and tune the membership functions of the reasoning. Fuzzy Controllers are normally built with fuzzy rules these fuzzy rules are obtained either from domain experts or by observing the people who are currently doing this control. The membership function for the fuzzy sets will be derive from the information available from the domain experts or observed control actions. The building of such rules and membership functions required tuning. That is performance of the controller must be measured and the membership functions and rules adjusted based upon the performance. This process will be time consuming.

The basic configuration of Fuzzy logic consists of four main parts i.e.(i)Fuzzification, (ii)Knowledge base, (iii) Inference Engine and (iv) Defuzzification

(i) Fuzzification

1. Performs a scale mapping that transfers the range of values of input variables into corresponding universe of discourse.
2. Performs the function of Fuzzification that converts input data into suitable linguistic variables, which may be viewed as labels of fuzzy sets.

(ii) Knowledge Base (KB): Knowledge base comprises of the definitions of fuzzy MFs for the input and output variables and the necessary control rules, which specify the control action by using linguistic terms.

(iii) Inference Mechanism: The Decision Making Logic Which plays an essential role and contains a set of fuzzy if-then rules such as IF x is A and y is B then z is C . Where x, y and z are linguistic variables representing two input variables and one control output: A, B and C are linguistic values. It is kernel of an FLC, it has the capability of simulating human decision making based on fuzzy control actions employing fuzzy implication and the rules of inference in fuzzy logic.

(iv) Defuzzification: Defuzzification coverts the linguistic variables to determine numerical values. Centroid method of defuzzification is used in this study.

(1) A scale mapping, which converts the range of values of input variables into corresponding universe of discourse?

(2) Defuzzification, which yields a non-fuzzy control action from an inferred fuzzy control action.

B. Fuzzy controller:

Fuzzy inputs: Input 1: ERR (t) = (Pref (i)-Pflow (i))

Input 2: CHERR (t) = ERR (t)-ERR (t-dt)

Fuzzy outputs: Output: Xtcsc (t) (compensation to be provided 30-70%)

TABLE I

RULE BASE FOR FUZZY CONYROLLER

		CHERR						
		NB	NM	NS	ZE	PS	PM	PB
ERR	NB	PM	PS	NB	NM	PS	ZE	PB
	NM	PS	NM	NM	NB	ZE	ZE	PS
	NS	PM	NS	NS	ZE	NM	PS	NS
	ZE	PB	ZE	ZE	ZE	NM	PS	NM
	PS	ZE	ZE	PM	NS	NS	PM	NS
	PM	ZE	PM	PM	PS	PB	PM	NS
	PB	PM	PS	PM	PS	PM	PB	NS

VI. ALGORITHM

In the performance of a transient stability study, the following data are needed;

1) All system data are converted to a common base; a system base of 100MVA is frequently used. Form Ybus and run load flow

a. The mechanical power input is taken as (P_m=P_{inj}) of the generators.

b. The loads are converted to equivalent impedances or admittances. The needed data for this step are obtained from the load flow study. Thus if a certain load bus has a voltage V_L, power P_L, reactive power Q_L, and current I_L flowing into a load admittance Y_L=G_L+jB_L, then

$$P_L+jQ_L=V_L V_L X(G_L - jB_L) = V_L^2\ (G_L\ - jB_L\ ) \quad (8)$$

The equivalent shunt admittance at that bus is given by

$$Y_L=P_L\ /\ V_L^2 - j\ (Q_L/V_L^2) \quad (9)$$

c. The internal voltages of the generators Ei ∠ δi0 are calculated from the load flow data. These internal angles may be computed from the pretransient terminal voltages V∠α as follows. Let the terminal voltage be used temporarily as a reference. If we define I= I_1 +j I_2 , then from the relationP+jQ = VI* We have I_1+jI_2 = (P – j Q)/V,since E∠δ' = V+jxd'I, we compute E∠δ'= (V + QX'_d/V) + j (PX'_d/V) d. The initial generator angle δ_0 is then obtained by adding the pretransient voltage angle α to δ', or δ_0= δ'+ α.

2) The Ytrbus matrix for each network condition is calculated. The following steps are usually needed:

a. The equivalent load impedances (or admittances) are connected between the load buses and the reference node; additional nodes are provided for the internal generator voltages (nodes 1, 2… n) and the appropriate values ofX'_d are connected between these nodes and the generator terminal nodes. Also, simulation of the fault impedance is added as required, and the admittance matrix is determined for each switching condition.

b. All impedance elements are converted to admittances.

c. Elements of the Y matrix are identified as follows: Y_{ii} is the sum of all the admittances connected to node I, and Y_{ij} is the negative of the admittance between node j and i.

d. The Y matrix for the reduced network. The reduction can be achieved by matrix operation if we recall that all the nodes have zero injection currents except for the internal generator nodes. This property is used to obtain the network reduction as shown below

For each load bus ytrbus(i,i)=ybus(i,i)+complex(P(i),-Q(i))/(conj(v(i))*v(i))

For each generator bus ytrbus (i, i)=ybus (i, i) +1/complex (ra (i), xdp (i));

3). System data follows:

a. The inertia constant H and direct axis transient reactance $X'_d$for all generators.

b. Transmission network impedances for the initial network conditions and the subsequent switching such as fault clearing and breaker reclosing's.

c. The type and location of disturbance, time of switching and the maximum time for which a solution is to be considered.

4) Find Ytrbus for various network conditions during fault, post fault (faulted line cleared), after line reclosure.

5) For faulted mode, find generator outputs from power angle equations and solve swing equations by R.K fourth order method etc. Voltages at each bus is obtained by

v=inv (ytrbus) * Inor

6) Keep repeating the above step for post fault mode and after line reclosure mode.

7) Examine δ (t) plots for all the generators and establish the answer to the stability question.

Case (i): Fixed compensation:

Fixed compensation of 50% is provided in the line where TCSC is placed by reducing the line reactance and change the ybus in step1

Case (ii): Variable compensation (PI):

(a.) Initial compensation of (30-50%) is provided in the line where TCSC is to be placed by reducing the line reactance and change ybus in step 1

.(b.) For fault mode (step 5).ytrbus (fb, fb) =ytrbus (fb, fb) +complex (0,0,-999999999),

Where fb is fault bus. For each time step solve swing equations using R.K. fourth order and calculate deltas of generators PID Controller.

error(1)=(Pf(ltc)-Pref(ltc)), where ltc=line having TCSC calculate Xtcsc, the line impedance becomes zl(ltc)=complex(r(ltc),-Xtcsc),change elements in ytransbus
(c.) For post fault mode (step 6) ytransbus is as in prefault mode.

Case (iii): Fuzzy controller:
(a.) Initial compensation of (30-50%) is provided in the line where TCSC is to be placed by reducing the line reactance and change ybus in step 1.
(b.) For fault mode (step 5) ytrbus (fb, fb) =ytrbus (fb, fb) +complex (0.0,-999999999),
Where fb is fault bus. For each time step Solve swing equations using R.K. fourth order and calculate deltas of generators for fuzzy controller taken
Error (1) = (Pf (ltc)-Pref (ltc)), where ltc=line having tcscdelerr=error (1)-error (0) as inputs and output of Xtcsc gives the compensation to be provided. The line impedance becomes.
Zl (ltc) =complex(r (ltc), x (ltc)-Xtcsc), change elements in ytransbus.
(c.) For fault mode (step 5) ytrbus (fb, fb) =ytrbus (fb, fb) +complex (0.0,-999999999), where fb is fault bus.

VII.RESULTS AND DISCUSSION

Static transient stability results for WSCC 9 bus system:

Case (1): Without Compensation

Case(1a):No Damping in the system (Self clearing type), Fault at Bus 5 Here Fault is at Bus 5 and Fault is self-cleared and fault clearance time is 0.2 sec and here no damping in the system, such that oscillations continues. Fig 1 Shows the relative rotor angle variation and active power generation variation when the fault is at bus 5 without damping in the system.

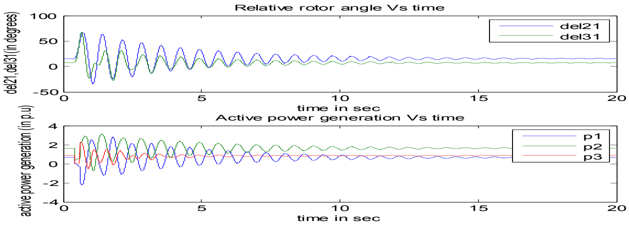

Fig .1. No damping in the system (self-clearing type), Fault at Bus 5

case (1b) : With damping in the system (self-clearing type) Fault at bus 5: By observing the above two cases, we can say that by providing damping to the system the oscillations will die out and they will settle to a final steady state value with in a very short time duration. Fig 2 Shows the relative rotor angle variation and active power generation variation when the fault is at bus 5 with damping in the system.

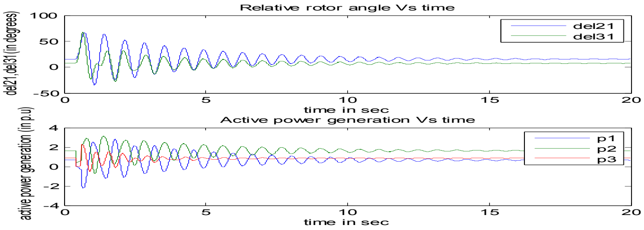

Fig.2. With damping in the system self-clearing type fault at bus 5

Case (2) With Compensation:

Case (2a): Fault is at bus 5: (a) fault is of self-clearing type and it is at bus 5 and fault clearing time is 0.2 sec and with fixed compensation 50% compensation and peak value of first swing is 61.3 as shown in fig 3.

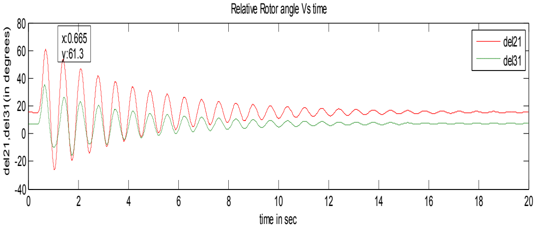

Fig.3. Fault at bus 5 with fixed compensation 50%

2) Case(2b):Fault is of self-clearing type and it is at bus 5 and fault clearing time is 0.2sec with PIcontroller (initial compensation 50% with Kp = 0.5 and K_i = 6.5) and the first swing is 59.65 as shown in fig 4.

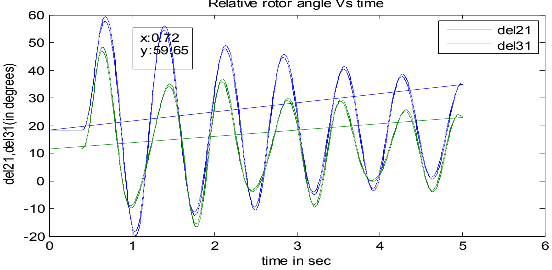

Fig.4.fault is at bus 5 with compensation and PI Controller

TABLE II
NORMALISED (ETA) VALUES OF A NINE BUS SYSTEM FOR
DIFFERENT FAULT LOCATIONS

FAULTED NUS NO,BASED ETA	**TCSC PALCED IN LINE**					
	45	**46**	**57**	**69**	**78**	**89**
5,0.10801	**0.86**	**1.01**	**1.01**	**1.09**	**1**	**1**
6,0.11304	**1**	**0.87**	**1.08**	**0.85**	**1.01**	**1**
8,0.09162	**1.1**	**1.1**	**1.16**	**1.15**	**0.88**	**0.92**

Case(2c): With fuzzy controller, the system with fault clearing time 0.2sec the first swing is 36.88 deg. as shown in fig 5.

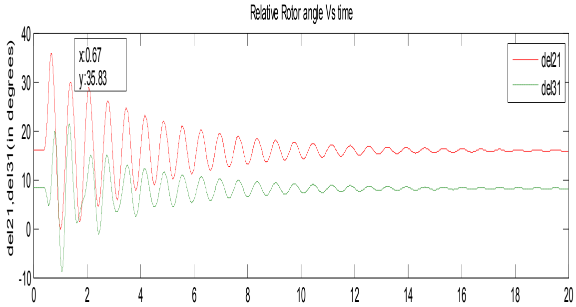

Fig.5. fault at bus 5 with compensation and Fuzzy Controller

By comparing the above results we can conclude that, with TCSC controller incorporated in the line 6-9 for a fault at bus 5. This shows the improvement of transient stability with FUZZY controller over PI controller and there is a significant improvement in the Transient stability with variable series compensation.

VIII. CONCLUSIONS

Transient stability is the ability of the power system to maintain synchronism after subjected to severe disturbance. The synchronism is assessed with relative violations among the different machines. Accurate analysis of the transient stability requires the detailed modelling of generating units and other equipment. At present the most practical available method of transient stability analysis is time-domain simulation in which the nonlinear differential equations are solved by step by step method or network reduction techniques. The transient stability assessment of WSCC-9bus system is done for faults of self-clearing type. The damping of the system is incorporated and the analysis gives the better results. The case study depicts the optimal location of fixed compensation in the WSCC-9 bus system as line 6-9, based on the first swing peak value reduction. The TCSC controller has been modelled and implemented on the WSCC-9 bus system at the optimal location. The results highlight the effectiveness of the application of the TCSC in improving the transient stability of the power system considered.

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V.A.PRABHAKAR REDDY has received Bachelor of Technology degree in Electrical and Electronics Engineering from West godavari institute of science and technology engineering in 2012. Presently he is pursuing M.Tech in Power System Control & Automation from Sri Vasavi Engineering College, Tadepalligudem, Andhra Pradesh, INDIA.

Ch.Rambabu received the Bachelor of Engineering degree in Electrical & Electronics Engineering from Madras University, in 2000 and Master’s degree from JNTU Anantapur in 2005. He is pursuing Ph.D. from JNTU Kakinada. Currently, he is a Professor at Sri Vasavi EngineeringCollege. His areas of interests are power system control,Optimization techniques and FACTS.