International Journal of Innovative Technology and Exploring Engineering (IJITEE)
ISSN: 2278-3075 (Online), Volume-2 Issue-3, February 2013

Smoothing the Performance of Hybrid System Output Power Using Fuzzy Wavelet Transform

S.Thangamari, M.S.Jayakumar

Abstract-The battery energy storage system (BESS) is the current typical means of smoothing intermittent wind or solar power generation. In the present study a wind power generation system, PV generation system, and BESS hybrid power generation system were considered. Then, a fuzzy logic and wavelet transform based smoothing control strategy was proposed for instantaneous WP and PV power generations smoothing by on-line regulation of battery output power. The effectiveness of the proposed control strategy was verified using MATLAB/ SIMULINK software.

Key words - wavelet transform, fuzzy control, wind/PV hybrid power system, battery energy storage system, intelligent smoothing Control

I. INTRODUCTION

In recent years, electricity generations by wind power (WP) and Photovoltaic (PV) have received considerable attention worldwide. However, whenever a large number of renewable-power generating stations access a power grid, the necessity of maintaining the power quality of utility- and micro-grid power systems demands that the following issues receive significant consideration and study: i) stabilization of power quality of islanding/interconnected systems, ii) quantifying of economics of new-energy generation, iii) smoothing of output fluctuation in Photovoltaic and WP generation, iv) effective integration with intelligent multiuser power system, v) determination of optimal energy generation/storage capacity, among others. Indeed, WP and PV generations alone might not be sufficient to satisfy the power-quality requirements in the modern power system.

In the present study therefore, a wind power generation system, PV generation system, and BESS hybrid power generation system (Fig. 1) were considered. Then, a fuzzy logic and wavelet transform based smoothing control strategy was proposed for instantaneous WP and PV power generations smoothing by on-line regulation of battery output power[6-15].

This paper is organized as follows, Section 2 presents the modeling of each power source. Section 3 describes the fuzzy wavelet transform based power control strategy. Simulation results are discussed in Section 4 and Section 5 is the conclusions.

Manuscript published on 28 February 2013.
*****Correspondence Author(s)
S.Thangamari, School of Electrical and Electronics, Karunya University, Coimbatore, Tamilnadu, India.
M.S.Jayakumar, Assistant Professor, School of Electrical and Electronics, Karunya University, Coimbatore, Tamilnadu, India.

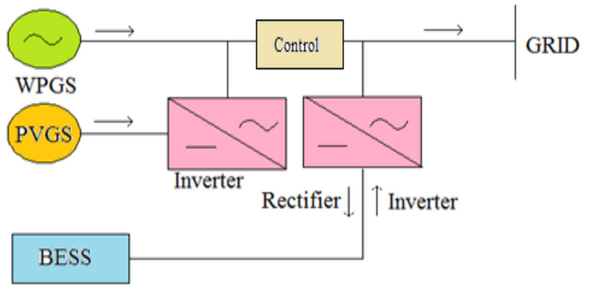

Fig.1. Hybrid power generation system

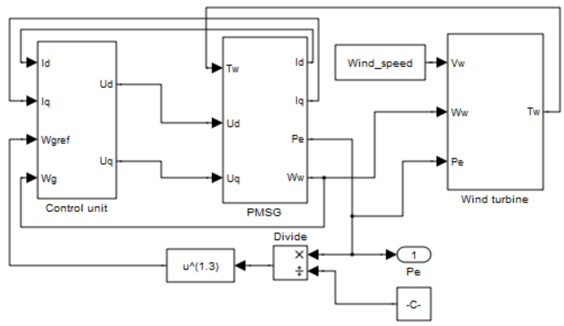

Fig.2. Modeling of WPGS using MATLAB

II. MODELING OF POWER SOURCES

A. Modeling of PV power generation system

The density of power radiated from the sun (referred to as the "solar energy constant") at the outer atmosphere is 1.373 kW/m^2. Part of this energy is absorbed and scattered by the earth's atmosphere. The final solar energy that reaches the earth's surface has the peak density of 1 kW/m^2 at noon in the tropics. The technology of photovoltaic (PV) is essentially concerned with the conversion of the solar energy into suitable electrical energy. The basic element of PV system is a solar cell. By settling solar cells under the sunlight, they can convert solar energy directly to electricity.The light current depends on both irradiance and temperature. It is measured at some reference conditions. Thus,

$$I_{SC}=[I_{SCref}+K_I(T_k-T_{ref})]*S/1000 \qquad (1)$$

Where is the photocurrent in (A) which is the light-generated current at the nominal condition (25oC and 1000W/m2),Ki is the short-circuit current and temperature coefficient at (0.0017A/K), and are the actual and reference temperature in K, is the irradiation on the device surface, and 1000W/m2 is the nominal irradiation. In this propose model, a current source which depends on solar radiation and cell temperature.

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$I_{pv}=N_P*I_{SC}-N_S*I_O[\exp(q(V_{OC}+I_{pv}*R_s)/N_skTA))-1]$ (2)

Where k is the Boltzmann constant (1.38 x 10-23 J K-1), q is the electronic charge (1.602 x 10-19 C), T is the cell temperature (K); A is the diode ideality factor, the series resistance (Ω) and is the shunt resistance (Ω). is the number of cells connected in series = 36. Np is the numbr of cells connected in parallel = 1, The reverse saturation current is given by[16]

$I_{rs}=I_{SCref}/[\exp(q*V_{OC}/k*T_{ref}*A)-1]$ (3)

The module saturation current varies with the cell temperature which is given by

$I_o=I_{rs}*(T_k/T_{ref})^3*\exp[(q*E_g/k*A)*(1/T_{ref}-1/T_k)]$ (4)

Where is the diode saturation current (A). The basic equation that describes the current output of the photovoltaic (PV) module of the single-diode model is as given in equation.

PV power generation is modeled by using practically obtained PV output power [1]. In this paper, the power level of actual PV generation power is magnified 1000 times. As a result, the power fluctuation of PVGS is modeled as shown in Fig.4.

B. *Modeling of output power fluctuation for WPGS*

A Model of directly driven wind power generation system using MATLAB /SIMULINK is shown in Fig. 2. Directly driven wind turbine with permanent magnet synchronous generator is considered in this paper. The parameters of PMSG used in this paper are shown in Table 1. The extracted power from the wind can be expressed as follows [2-3].

$$P_m=0.5\rho\pi R^2V^3_wC_P(\lambda,\beta) \quad (5)$$

Mechanical torque of wind turbine from the wind can be calculated as follows

$$T_w=0.5\rho\pi R^2V^3_wC_P(\lambda,\beta)/\lambda \quad (6)$$

Where, *Pm* is the power from wind, *ρ* is air density [kg/m3], *R* is blade radius[m], *Vw* is the wind speed[m/s] and *Cp* is the power coefficient which is a function of both tip speed ratio *λ* and blade pitch angle *β*[deg].

$$C_P(\beta\, \lambda,)=0.73(\frac{151}{\lambda_i}-0.58\beta-0.002\beta^{2.14}-13.2)e^{\frac{-18.4}{\lambda_i}} \quad (7)$$

Where λ_i is given by

$$\lambda_i=1/(\frac{1}{\lambda-0.02\beta}-\frac{0.003}{\beta^3+1}) \quad (8)$$

In this paper, wind speed is modeled by multiplying a random speed fluctuation derived from the white noise block in MATLAB/SIMULINK as shown in Fig. 3.

Table 1. Parameter of PMSG

Index	Parameter
Rated power	1980 kW
Inductances(Ld)	0.334(H)
Inductances(Lq)	0.217(H)
Stator phase resistance	0.00117(ohm)
Stator winding resistance(Rs)	0.08(ohm)
Stator winding leakage inductance	0.0334(H)
Pole pairs	11

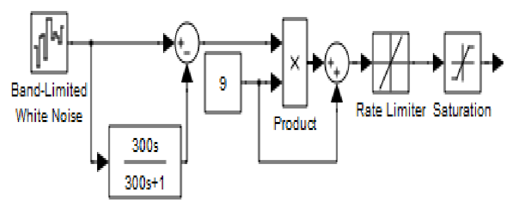

Fig. 3 Model of wind speed using MATLAB/SIMULINK

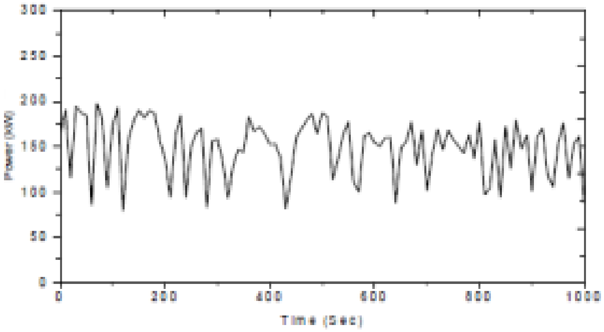

Fig 4. PVGS output power

C. *Modeling of BESS*

A 100kWh lithium iron phosphate, lithium-ion BESS has been modeled presented in [4-5]. In general we know that *Vbat* can be expressed as Eqn.5 Moreover, as shown in Eqn.6 and 7, *Vocv* and *intbat R* are determined by using look-up tables based on experimental data presented in Figs. 5 and 6. That Fig. 5 presents characteristic of open circuit voltage via battery SOC. Fig.6 presents interior resistance via battery SOC, From Eqn.10 and 11 we can calculate the battery SOC, and then *η* is calculated depend on battery charge/discharge status. In this paper, 300kWh BESS is considered by integrating three 100kWh LiFePO4 lithium-ion BESSs in parallel. Specification of 300kWh BESS is shown in Table 2.

$$V_{bat}=V_{ocv}-R^{int}_{bat}\,I_{bat} \quad (9)$$

Where,

$$V_{ocv}=f_1(SOC) \quad (10)$$

$$R^{int}_{bat}=\begin{cases}R_{ch}=f_2(SOC) & charging\\ R_{dis}=f_3(SOC) & discharging\end{cases} \quad (11)$$

$$SOC=SOC_{ini}-\int\frac{\eta I_{bat}}{Q}dt \quad (12)$$

$$\eta=\begin{cases}\eta_{ch}=\frac{V_{ocv}}{V_{ocv}-I_{bat}R_{ch}} & charging\\ \eta_{dis}=\frac{V_{ocv}-I_{bat}R_{dis}}{V_{ocv}} & discharging\end{cases} \quad (13)$$

Where, *Vbat* is terminal voltage of BESS; *Ibat* is current of BESS; *Vocv* is open circuit voltage of BESS;R^{int}_{bat} is interior resistance of BESS; *η is* charge/discharge rate.

Table 2. Specification of battery energy storage system

Index	Description
Whole system	Three 100kWh BESS in parallel
Every 100kWh BESS	10 battery module in series
1 Module	Twenty four 120Ah single batteries in series
Single battery capacity	120Ah(two 60Ah batteries in parallel)
Rated power	300kW
Maximum working voltage	840V
Minimum working voltage	696V

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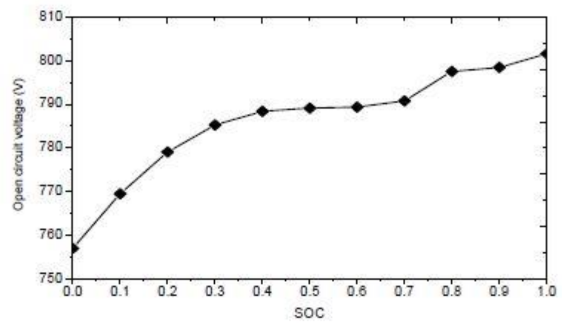

Fig 5 Characteristic of open circuit voltage via battery SOC

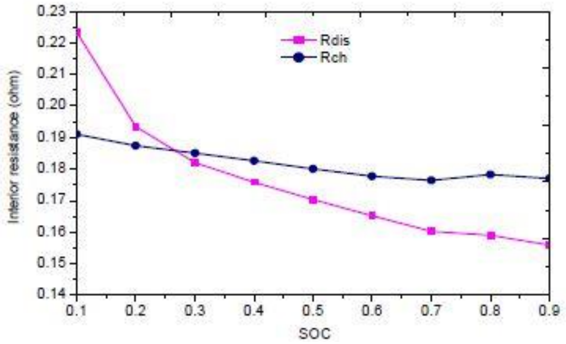

Fig. 6. Characteristic of interior resistance via battery SOC

III. FUZZY WAVELET TRANSFORM BASED SMOOTHING CONTROL STRATEGY

To smooth the output power fluctuations of the WPGS and PVGS hybrid system, a fuzzy wavelet filtering method, by which the power fluctuations can be smoothened, is proposed in this paper. As a result, the output power fluctuations of WP and PV hybrid system could effectively smoothed and consequently BESS charge/discharge could rapidly react to supply the supplementary power.

The Daubechies wavelet "db5" in Matlab[10] is used in this paper to calculate the target smoothing power output of WIND/PV hybrid power system, Usually DB wavelet function is no analytical expression. The wavelet is presented by using wavelet filter array.

Calculation steps for wavelet transform can be summarized as follows. Step1, the original data have been decomposed through low and high pass filter, and as a result, the low and high frequency coefficients could be obtained based on wavelet decomposition scale. Step2, high and low frequency components could be determined by reconstructing the low and high frequency decomposition coefficients.

In this paper, the target smoothing power of Wind/PV hybrid power output is determined by using the low frequency component and that of BESS by using the high frequency component, respectively. The fuzzy logic and wavelet transform based adaptive smoothing control method is proposed as shown in Fig. 7. As shown in Fig.7, for the Mamdani-type fuzzy controller, input is *SOC* and output is ΔP_{BESS}^{FUZZY} . For the Takagi-Sugeno-type fuzzy controller, input is P_{BESS} and output is K_d^{FUZZY} . Moreover, for the MFC, the membership functions of *SOC* and ΔP_{BESS}^{FUZZY} are shown in Figs. 8 and 9 respectively. In addition, the membership function of P_{BESS} is shown in Fig.10. Fuzzy rule tables for the MFC and TFC are shown in Table 3 and 4. The proposed power smoothing control strategy based on fuzzy wavelet transform can be formulated by following Equations. (14)-(21).

$$P_{WPPV} = P_{WPPV} + P_{BESS} \quad (14)$$

$$P_{BESS}^{CMD} = P_{BESS}^{TAR} + \Delta P_{BESS}^{FUZZY} \quad (15)$$

$$P_{BESS}^{TAR} = P_{WPPV}^{WT} - P_{WPPV} \quad (16)$$

$$P_{WPPV}^{WT} = f_{WT}(P_{WPPT}, K_d^{FUZZY}) \quad (17)$$

s.t

$$P_{BESS}^{min} \le P_{BESS} \le P_{BESS}^{Max} \quad (18)$$

$$SOC^{min} \le SOC \le SOC^{max} \quad (19)$$

$$\Delta P_{BESS}^{FUZZY} = f_{MFC}(SOC) \quad (20)$$

$$K_d^{FUZZY} = f_{TFC}(P_{BESS}) \quad (21)$$

Table 3. Fuzzy rule table for MFC

SOC	VS	S	M	B	VB
ΔP_{BESS}^{FUZZY}	NB	NM	ZO	PM	PB

Table 4. Fuzzy rule table for TFC

P_{BESS}	NB	Normal	PB
K_d^{FUZZY}	K_1	K_2	K_3

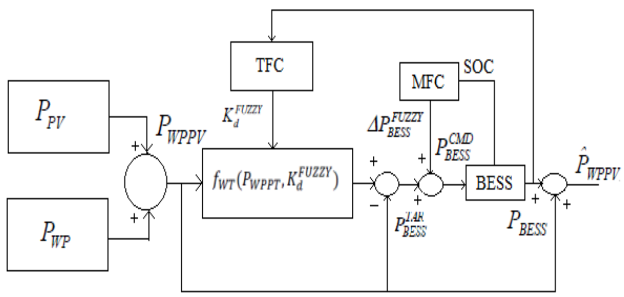

Fig. 7. Proposed power smoothing control strategy based on fuzzy wavelet transform

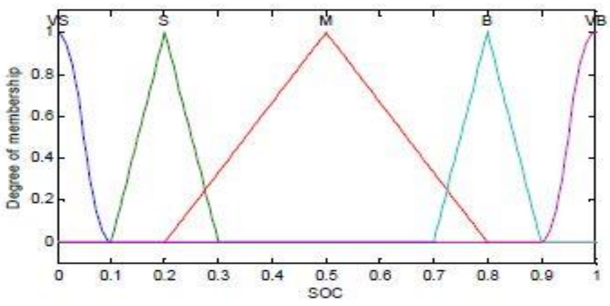

Fig. 8. Membership function for *SOC*

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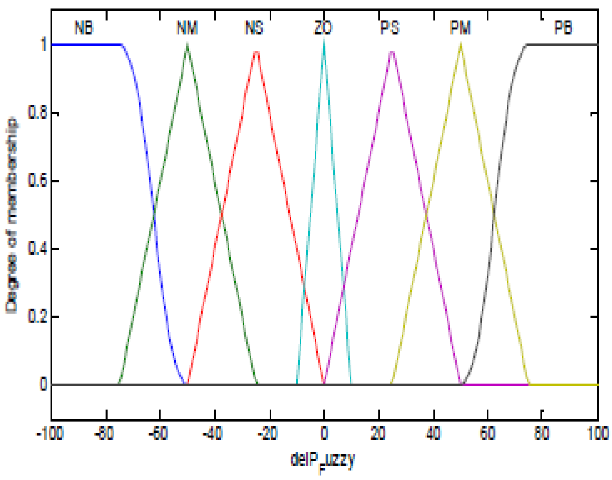

Fig.9.Membership function for ΔP_{BESS}^{FUZZY}

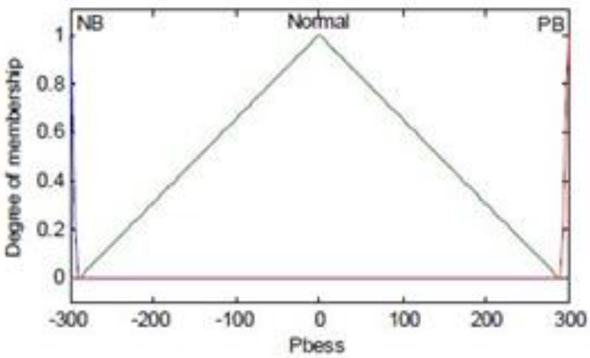

Fig 10. Membership function for P_{BESS}

IV. SIMULATION RESULTS AND DISCUSSION

To verify the simulation analyses were performed with a WPGS/PVGS/BESS hybrid power system model. The BESS was connected with WPGS and PVGS to a utility-grid power system at a common coupling point. A 10%-90% range of SOC was set, which of course was modifiable according to BESS control requirements.

The simulation test was carried out in the MATLAB/SIMULINK software. The time step and the simulation time chosen were 1 and 1000 seconds. Moreover, the wavelet decomposition scales of K_1 and K_2 in Table 4 were set to 1 and 10, respectively.

In order to illustrate the effectiveness of the proposed fuzzy wavelet smoothing control method, the following two initial-SOC cases were considered in this paper.

Case 1: Initial SOC of BESS is 95%

In this case, a high initial SOC of the BESS was assumed. The power profile with fuzzy wavelet smoothing control is presented in Figs. 11. They indicate that, around the high-charging phase, the proposed control strategy could in a timely manner adjust the smoothed power output level by discharging the BESS. Therefore, trough this proposed fuzzy wavelet filtering method, the battery SOC can be restored to its typical conditions. In Fig. 12, the SOC profile of the BESS is presented. Because the upper limit of the battery SOC was assumed, in the present study, as 90%, the proposed method could efficiently adjust the stored kilowatt hours of power during the BESS's high-charging phases, and thereby could augment the performance of the battery hybrid power system without adding energy storage capacity or losing wind power energy.

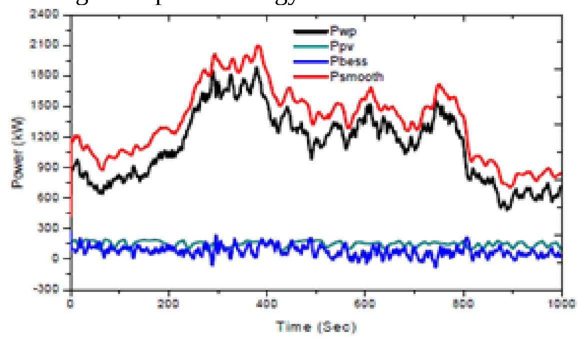

Fig 11. Power profile with fuzzy wavelet smoothing control(SOCin=95%)

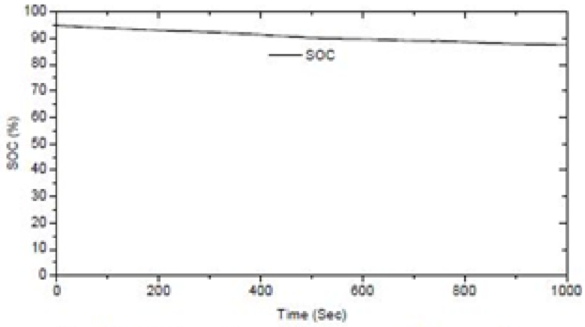

Fig 12. SOC profile with fuzzy wavelet smoothing control(SOCin=95%)

Case 2: Initial SOC of BESS is 5%

In this case, a lower initial SOC of the BESS was assumed. The power profile with fuzzy wavelet smoothing control is plotted in Fig.13. The SOC profile of the BESS is presented in Fig.14. It is evident that using the proposed method, the battery SOC could be adaptively managed according to the charge and WP-PV-output levels during wind and PV power output smoothing control process. Meanwhile, the control target for smoothed WPGS and PVGS power outputs also could be maintained. As a result, the proposed control strategy could efficiently ensure the output power smoothing performance of the wind/PV/BESS hybrid power generation system without adding energy storage capacity or losing wind power energy.

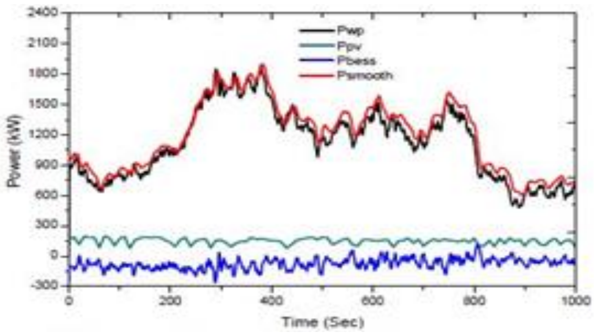

Fig 13. Power profile with fuzzy wavelet smoothing control(SOCin=5%)

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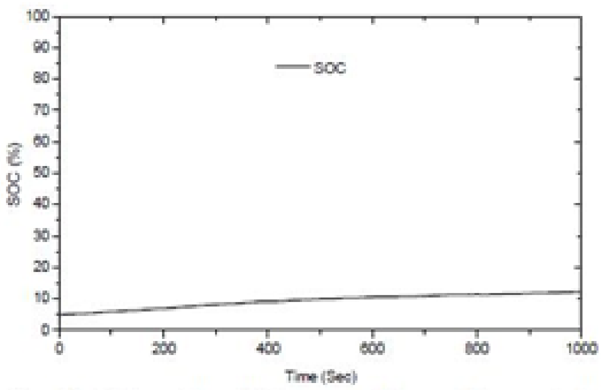

Fig 14. SOC profile with fuzzy wavelet smoothing control (SOCin=5%)

V. CONCLUSION

In this paper, a fuzzy-logic-based wavelet filtering control method is proposed for smoothing the output fluctuation of the WPGS and PVGS hybrid power generation system, because the PV and wind power generation systems have the disadvantage of an unstable power output, which can impact negatively on utility- and micro-grid operations. One means of solving this problem is to integrate WPGS and PVGS with a battery energy storage system. For such hybrid generation systems, control strategies need to be developed to efficiently dispatch power. Simulation results demonstrate that the proposed control strategy can manage battery SOC within a specified target region while smoothing WPGS and PVGS output power.

ACKNOWLEDGMENT

We take immense pleasure in conveying my thanks and deep sense of gratitude to our teachers for their exhilarating supervision, timely suggestions and encouragement during all phases of this work.

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AUTHOR PROFILE

S.Thangamari was born in 07 march 1988 in India. He completed his BE degree from Einstein college of Engineering, tirunelveli, Tamilnadu. Now he is doing his master degree in Karunya University in Renewable Energy Technology. His main interest is in Solar power and wind power.

M.S.Jayakumar,received B.E degree in **(**Electrical and Electronics Engineering) in 2002, Coimbatore. M.E degree from Anna University. Tamilnadu. Currently he is working as Assistant Professor in Karunya University, Coimbatore, India.and doing ph.d in power system in anna university His field of interest are power system and renewable energy.

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