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# Evaluation of insulated gate bipolar transistor valve converter based unified power flow controller reliability and efficiency

**Eniganti Sreeshobha, Raddymalla Linga Swamy**
Department of Electrical Engineering, University College of Engineering (A), Osmania University Hyderabad, Telangana, India

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**ABSTRACT**

The effectiveness and reliability of the unified power flow controller (UPFC) are determined by the insulated gate bipolar transistor (IGBT) valve. Thermal losses, conduction losses, and switching losses in the IGBT valve all affect the efficiency of UPFC. The failure rate of the converter valves is influenced by junction temperature, which has an impact on the converter's reliability. Piecewise linear electrical circuit simulation (PLECS) was used to simulate two IGBT valve-based converter legs working at 12000 Hz, part number GT30F123. By reference to the switching characteristics produced by PLECS, switching losses, conduction losses, and thermal losses are analyzed. Simulation results are corroborated with analytical measurements. The chance of achieving 100%, 50%, and 0% functioning modes are among the reliability indices that are analyzed. The chance of achieving a hundred percent, fifty percent, or zero percent functioning mode is assessed. The frequency of achieving the state probability and mean time to failures (MTTF) are obtained from probabilities using the Markov model. The thermal losses, failure rate, and lifetime of the UPFC are all quantified to give a complete picture of the UPFC's performance.



***Corresponding Author:***

Eniganti Sreeshobha
Department of Electrical Engineering, University College of Engineering (A)
Osmania University Hyderabad, Telangana, India
Email: shobhasree555@gmail.com, or sreeshobha.e@uceou.edu

## NOMENCLATURE

$P_{UP}$ : Probability of attaining 100% operating mode
$P_{DERT}$ : Probability of attaining 50% operating mode
$P_{DOWN}$ : Probability of attaining 0% operating mode
$f_{UP}$ : Frequency of attaining 100% operating mode (Occ/yr)
$f_{DERT}$ : Frequency of attaining 50% operating mode (Occ/yr)
$f_{DOWN}$ : Frequency of attaining 0% operating mode (Occ/yr)
$P_{COND}$ : Conduction losses [W]
$I_O$ : Output current [A]
$R_{ONH}$ : High device on-state resistance [Ω]
$V_O$ : Output voltage [V]
$V_{IN}$ : Input voltage [V]
$R_{ONL}$ : Low device on-state resistance [Ω]
PSW : Switching losses [W]
$Q_{gl}$ : Gate electric charge – low [C]
Vgs : Gate drive voltage [V]
$T_{HS}$ : Heat sink temperature [°C]
$\Delta T$ : Average temperature rise above ambient [°C]
$T_A$ : Ambient operating temperature [°C]
$\lambda_v$ : Valve failure rate (failures/year)
$\lambda_b$ : Base failure rate (failures/year)
$\pi_T$ : Junction temperature factor
$\pi_A$ : Application factor
$\pi_R$ : Power rating factor
$\pi_S$ : Voltage stress factor
$\pi_Q$ : Quality factor
$\pi E$ : Environment factor

PG : Gate drive losses [W]
FSW : Switching frequency [Hz]
tr : Risetime [sec]
tf : Fulltime [sec]
Qgh : Gate electric charge–high [C]
SS1 : Subsystem1
SS2 : Subsystem2
SS3 : Subsystem3
STPM : Stochastic transmission probability matrix

## 1. INTRODUCTION

Significant influence of power electronic valves on the performance of flexible AC transmission systems (FACTS), is motivation to analyze the efficiency and reliability of 48 pulse insulated gate bipolar transistor (IGBT) valve-based converter unified power flow controller (UPFC). The lifetime of the power electronic valve has a crucial role in the UPFC reliability and efficiency. Reliable composite power system operation depends on the reliability of UPFC [1]–[3]. A schematic diagram of IGBT valve-based UPFC is shown in Figure 1. Power electronic valve is the key element for the UPFC reliability. Thus, IGBT valve based UPFC is considered for the analysis. Literature was published on, exclusive operational aspects such as losses and efficiency evaluation of the converter [4]–[7], the optimal location of the FACTS devices [8], and power flow control in transmission lines with UPFC [9]–[11] and specifically reliability analysis of the UPFC [12], [13]. The present work proposes a systematic integrated method, which includes both operational aspects and reliability assessment required for the complete understanding of the UPFC performance. The operational performance indices are switching losses, conduction losses, heat losses, and efficiency. The reliability indices are the probability of a hundred percent, fifty percent, and zero percent operation, the frequency of achieving a hundred percent, fifty percent, and zero percent functioning state, and the mean time to failure. The number of IGBT running cycles, or the life duration of the power electronic valve, will be determined by losses. Higher thermal losses result in a higher failure rate of the power electronic valves. The higher failure rate of the valve results in poor reliability of UPFC. Hence to decide a reliable UPFC, quantitative analysis of the reliability and operational indices of the converter, are essential. Based on the thermal resistance offered by the junctions of the IGBT valve, gate charging, switching, conduction and, off-state losses are the total losses, that occur in the converter leg. At any given instant, summation of the total losses of each leg results in the complete losses of the converter. In the present paper, valve losses calculation is given in detail, and efficiency is evaluated by simulating the IGBT-based converter leg in piecewise linear electrical circuit simulation (PLECS). Losses and efficiency of the converter are evaluated based on the switching characteristics obtained by PLECS.

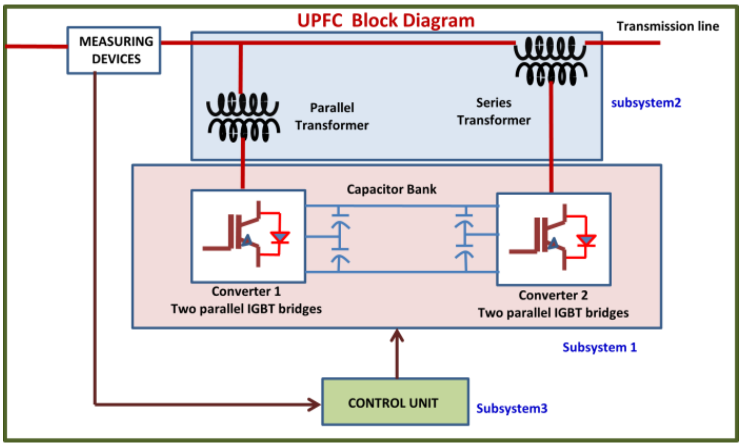


Figure 1. Schematic diagram of UPFC

Basic six-state, UPFC state-space model developed [13]–[15], further, a reduced three-state UPFC model derived by considering the non-repairable converter valve and the different operating modes of UPFC converter are shown in Table 1. Subsequently, with the aid of the Stochastic transition probability matrix Mean time to failure, frequency, and probability are evaluated. Obtained quantitative indices give a comprehensive understanding of IGBT valve-based UPFC operation.

Section 3 of this study describes the notion of thermal and power losses that occur in the valve during UPFC operation and contribute to valve failure. Section 4 deals with the estimation of junction temperature, and rate of rise in junction temperature, which are the main causes of the base failure rate and valve failure rates. Section 5 deals with the method of estimation of IGBT valve failure rate from the base failure rate obtained from section 4. In section 6 Markov model is developed by considering the IGBT valve failure rate obtained in section 5. The UPFC's dependability is estimated by solving the Markov model. Section 7 presents the obtained losses, efficiency, reliability, and mean time to failures (MTTF) data, whereas section 8 presents the conclusions.

## 2. IGBT THERMAL LOSSES EVALUATION

IGBT is a three-layer three-terminal medium power, power electronic switching element from the BJT family, which offers high input impedance and low on-state power losses. Figure 2 and Figure 3 represent the structure, and equivalent circuit–symbols IGBT respectively [16]. Junction $J_1$ is forward biased by applying forward biasing voltage at collector to emitter. By applying sufficient i.e more than threshold voltage across gate and emitter Junction $J_2$ is forward biased and channel current established, due to developed capacitance at the gate. Total losses occurring in IGBT, contribute to the temperature around the device i.e thermal losses [16]–[18]. Compact packing of IGBT and Diodes are leading to higher power density and more thermal losses. Loss of gate control increased leakage current and open circuit failures of UPFC switching valve will lead to high temperature, high electric field, over voltages, ionizing radiation, and high current density conditions. Power losses during turn on and turn-off periods are shown in Figure 4 [16]. $V_{IN}$ is the input voltage for the converter circuit with two switching IGBT valves, Vo and Io are the load voltage and load currents respectively, for IGBT operation with FSW frequency. $R_{ONH}$ and $R_{ONL}$ are the resistance offered by the high and low valves during valve conduction. Conduction losses, switching losses (turning on and turning off losses), and gate charging losses of IGBT are evaluated by using (1)-(3) respectively.

$$P_{COND} = \left[I_O^2 R_{ONH}\left(\frac{V_O}{V_{IN}}\right)\right] + \left[I_O^2 R_{ONL}\left(1 - \frac{V_O}{V_{IN}}\right)\right] \text{W} \tag{1}$$

$$P_{SW} = \frac{1}{2}(V_{IN})(f_{SW})(I_O)(t_r + t_f)\ \text{W} \tag{2}$$

$$P_G = (Q_{gh} + Q_{gl})(V_{gs})(f_{sw})\text{W} \tag{3}$$

For the constant frequency of 12000 Hz operation, thermal losses, conduction losses, switching losses [19], and efficiency of the converter [20] are evaluated and presented in Table 2.

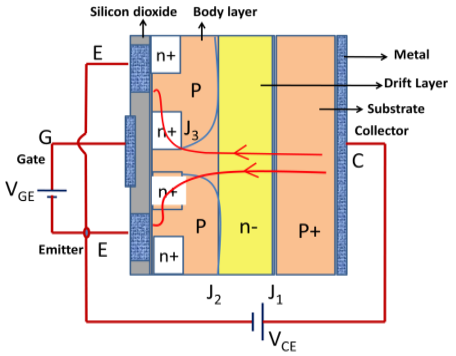


Figure 2. Structure of IGBT

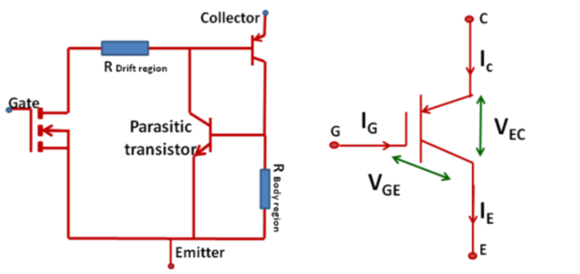


Figure 3. Equivalent circuit of IGBT and Symbol of IGBT

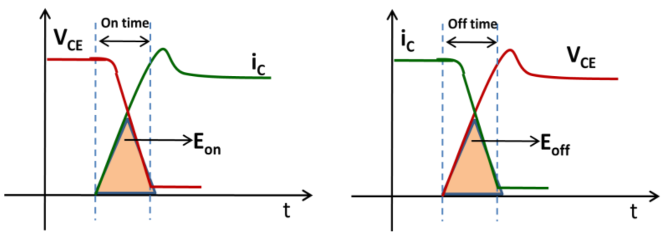


Figure 4. Turn ON and turn OFF switching losses

## 3. PLECS SIMULATION

GT30F123 part number 300 V/200 A at Tj=25 °C IGBT valve, simulated in PLECS. PLECS "heat sink" tool observes and displays the thermal losses dissipated by the component to which it is connected. Before and after each switching operation, PLECS measures the forward current, blocking voltage, and junction temperature of the semiconductor. Utilizing these parameters resulting dissipated energy i.e thermal energy, then thermal losses are calculated, for conduction period, on state and off states. Piecewise linearization of switching instants feature of PLECS resulting in speeded up simulation [21]. The temperature of the power electronic valve depends on the power dissipation during static and switching modes. Thermal losses are calculated by considering twice the average power loss for a one-half cycle of the output phase current. To realize the method of losses evaluation and failure rate derivation, 300 V, 200 A, IGBT converter with 100 V input voltage model, simulated and shown in Figure 5. The operating frequency of UPFC in a composite power system is 1200 Hz. The efficiency and reliability of UPFC are determined by the UPFC valve's losses and junction temperature. As a result, an IGBT valve-based UPFC operating at a frequency of 12000 Hz is simulated. Turning on, turning off and conduction characteristics obtained by simulation are shown in Figure 6, Figure 7, Figure 8 and Figure 9 respectively. Resulting conduction losses and junction temperature are depicted in Figure 9 and Figure 10. Average junction temperature rise ΔT also simulated for IGBT valve which is a key element for the failure rate of the valve, shown in Figure 10.

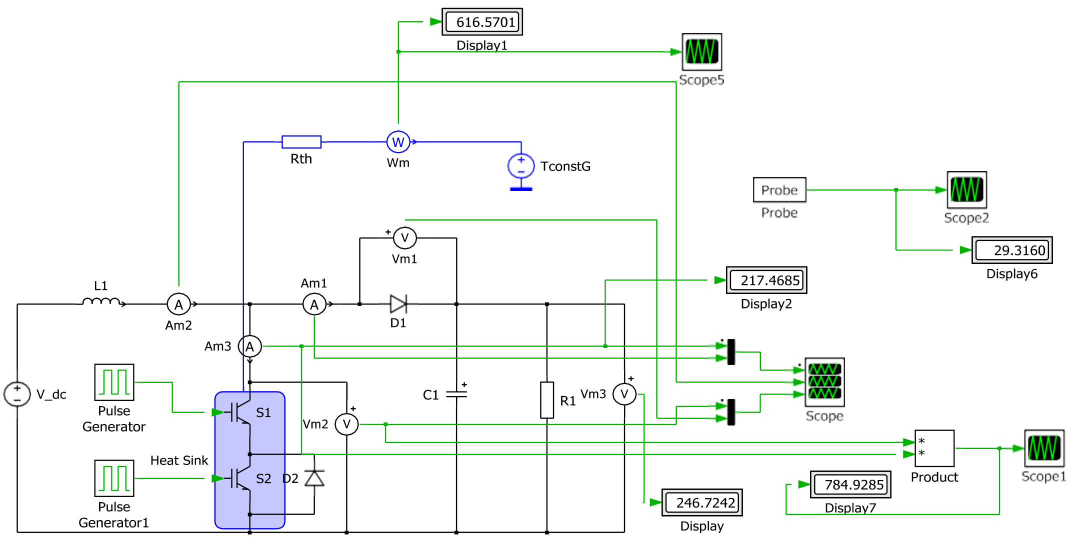


Figure 5. Simulation block diagram of IGBT-based converter

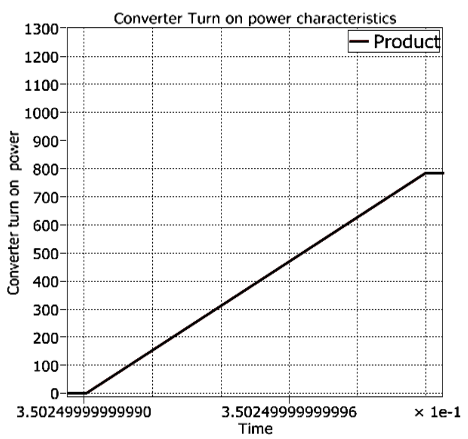


Figure 6. IGBT converter turn-on power characteristics

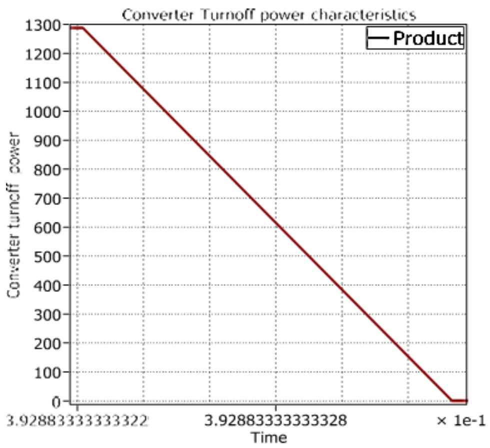


Figure 7. IGBT converter turn-off power characteristics

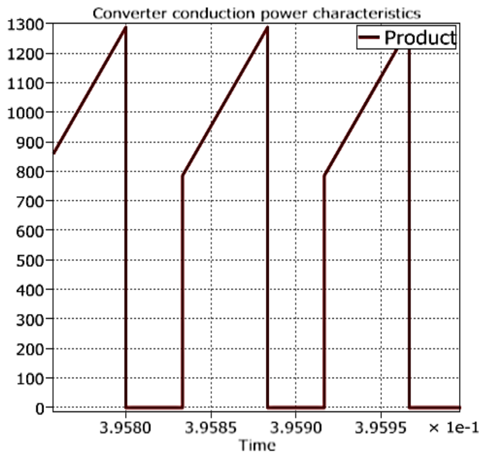


Figure 8. IGBT converter conduction power characteristics

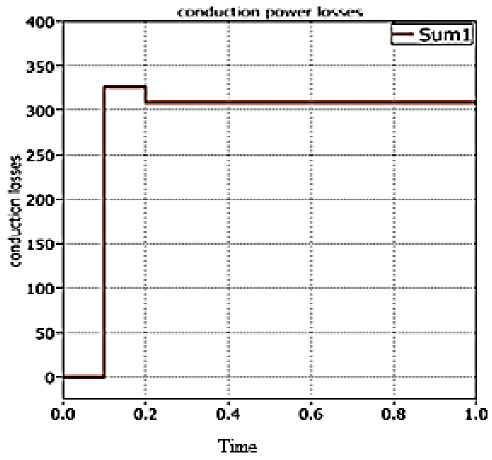


Figure 9. IGBT converter conduction power losses

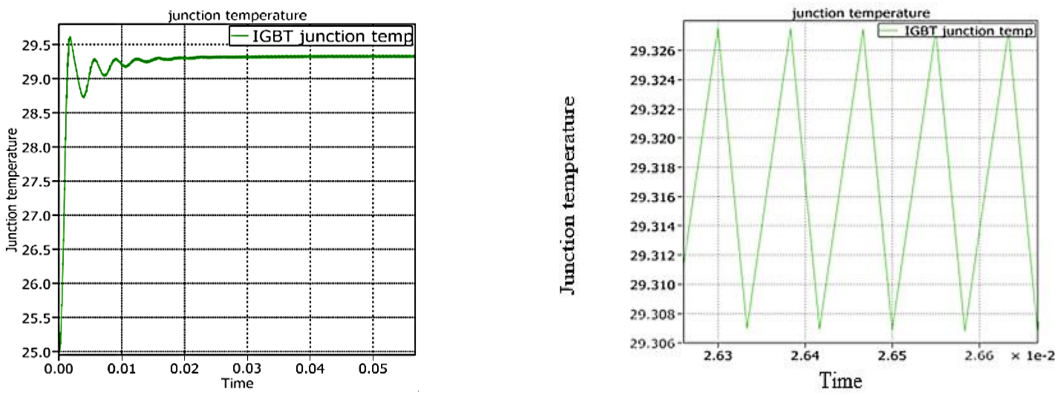


Figure 10. IGBT junction temperature rise

## 4. IGBT FAILURE RATE CALCULATION FROM THERMAL LOSSES

The valve failure rate is a function of the base failure rate, given by (4). Valve failure is proportional to base failure rate, temperature, power rating, voltage stress, quality and, environment factors [22]–[25]. Base failure rate of the valve given by (5) [26]–[28] is the function of operating temperature "T", rise in junction temperature, scaling factor, and stress ration. Average junction temperature rise ΔT, 0.02070C obtained from junction temperature characteristics corresponding to UPFC operating frequency, shown in Figure 10 leading to 0.040302 failures/year for the IGBT valve.

$$\lambda_v = \lambda_b \, \pi_T \, \pi_A \, \pi_R \, \pi_S \, \pi_Q \, \pi_E \quad (4)$$

The life span of the power electronic valve is a function of junction temperature to which it is subjected during conduction and switching. Valve power losses are proportional to the junction temperature. Higher power losses, lead to the higher failure rate of the valve i.e lesser is the life span of the valve.

$$\lambda_b = A \exp\left(\frac{N_T}{273+T+(\Delta T)S}\right) \exp\left(\frac{273+T+(\Delta T)S}{T_M}\right)^{P} W \quad (5)$$

A = Scaling factor
T = Temperature (°C)
ΔT = Rise in temperature from no junction temperature to rated junction temperature
S = Stress ratio
$T_M$, P and $N_T$ are Shape parameters

The failure rate of the IGBT valve is derived from the base failure rate, evaluated by considering the scaling factor, stress ratio, and shape parameters related to the operating frequency, and obtained rise in junction temperature.

## 5. UPFC MARKOV MODELING AND RELIABILITY INDICES

SS1, SS2, and SS3 must operate continuously for a reliable operation of the composite power system. Reliability indices obtained by implementing Markov modeling. Considering each component of SS1 various possible states that SS1 can reside, transition rates between various states are determined as shown in Figure 11. Various possible states of converter 1, bridges of UPFC are tabulated in Table 1. Considering the transition rates, stochastic transmission probability matrix (STPM) developed, and probability of occurrence of each state, and the frequency of occurrence of the states are obtained. The STPM of the converter 1 of UPFC is obtained by (6).

$$\begin{matrix} state1 \\ state2 \\ state3 \\ state4 \\ state5 \\ state6 \end{matrix} \begin{bmatrix} state1 & state2 & state3 & state4 & state5 & state6 \\ -2\lambda_b & 2\lambda_b & 0 & 0 & 0 & 0 \\ 0 & -(\lambda_b+\mu_v) & \mu_v & \lambda_b & 0 & 0 \\ \gamma_v & 0 & -(\gamma_v+\lambda_b) & 0 & \lambda_b & 0 \\ 0 & 0 & 0 & -2\mu_v & 2\lambda_v & 0 \\ 0 & \gamma_v & 0 & 0 & \gamma_v+\mu_v & \mu_v \\ 0 & 0 & 2\gamma_v & 0 & 0 & -2\gamma_v \end{bmatrix} \quad (6)$$

Table 1. Operating states of converter 1 of UPFC

| Converter States | Bridge 1 Operating state | Bridge 2 Operating state |
|---|---|---|
| 1 | 100% operating mode | 100% operating mode |
| 2 | 100% operating mode | Failure mode |
| | Failure mode | 100% operating mode |
| 3 | 100% operating mode | Repair mode |
| | Repair mode | 100% operating mode |
| 4 | Failure mode | Failure mode |
| 5 | Failure mode | Repair mode |
| | Repair mode | Failure mode |
| 6 | Repair mode | Repair mode |

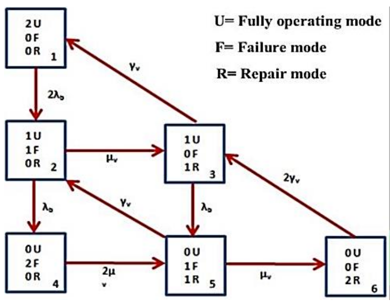


Figure 11. State-space diagram of converter 1 of UPFC

By considering primitive maintenance and primitive and permanent outages of transformers failure and repair rates of subsystem 2 are estimated. The failure and repair rates of subsystem 3, the control system establishing the coordination of UPFC converters are 0.01 f/y and 4380 f/y respectively.

By combining SS1, SS2, and SS3 complete State-space model of UPFC of seven states developed and shown in Figure 12. Primary reliability indices Probability and frequency, based on which further reliability indices can be obtained are evaluated. By implementing the state merging technique (up mode)100%, 50% (derated mode), and 0% (non-operating mode) operating modes, probabilities are obtained. Step 1 to Step 7 indicate the detailed algorithm implemented for Markov modeling of SS1, SS2, and SS3.

- Step 1. Develop valve failure rate based on the junction thermal losses.
- Step 2. Develop state-space model and evaluate STPM for bridge 1 of converter1.
- Step 3. Implement Cramer's rule to assess each state probability.
- Step 4. Develop state-space model for SS1 by considering both the converters and capacitor bank
- Step 5. Implement state merging concept and estimate resultant failure rate and repair rates of SS1
- Step 6. Develop combined state space diagram for SS1, SS2 and SS3, evaluate final failure rate and repair rates of the composite power system.
- Step 7. Implement state merging concept and evaluate MTTF calculation

Considering the probabilities of SS1 SS2 and SS3 seven possible states are obtained and for the complete operation of UPFC, the transmission rates between the states are represented in Figure 12. By developing and solving the STPM for seven state UPFC model. $P_1$ to $P_7$ state probabilities are estimated. The probability of up mode derated mode and non-operating modes are evaluated by (7) to (9) respectively. $f_{UP}$, $f_{DERT}$, and $f_{DOWN}$ frequency of occurrence of $P_{UP}$, $P_{DERT}$, and $P_{DOWN}$ states respectively, are given by (10) to (12).

$$P_{UP} = P_2 \quad (7)$$

$$P_{DERT}=P_3 \quad (8)$$

$$P_{DOWN}=P_1+P_4+P_5+P_6+P_7 \quad (9)$$

$$f_{UP}=P_{UP}(\lambda_1+\lambda_3) \text{ Occ/yr} \quad (10)$$

$$f_{DERT}=P_{DERT}(\mu_1+\lambda_2) \text{ Occ/yr} \quad (11)$$

$$f_{DERT}=P_{DERT}(\mu_2+\lambda_3) \text{ Occ/yr} \quad (12)$$

The $\lambda ss_2$ and $\lambda ss_3$ are UPFC SS2 and SS3 failure rates respectively. The final complete state- space model of the UPFC, simplified into three states, up mode (100%), derated mode (50%), and non-operating modes (0%) model, shown in Figure 13. The final resultant failure rate, repair rates, and MTTF are given by (13) to (17).

$$\lambda_1=\lambda_{11} \text{failures/year} \quad (13)$$

$$\mu_1=\mu_{11} \text{repairs/year} \quad (14)$$

$$\lambda_2=\lambda_{12}+\lambda ss_2+\lambda ss_3 \text{failures/year} \quad (15)$$

$$\lambda_3=\lambda_{13}+\lambda ss_2+\lambda ss_3 \text{failures/year} \quad (16)$$

$$\lambda= 1 /\text{MTTF failures/year} \quad (17)$$

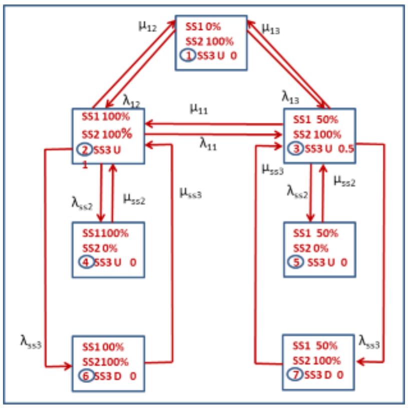


Figure 12. Complete state-space model of the UPFC

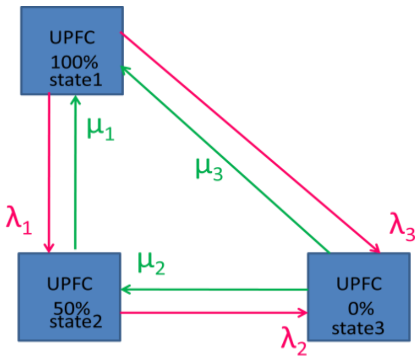


Figure 13. Final three-state model of the UPFC

## 6. RESULTS

The operational parameters of the IGBT valve-based UPFC, corresponding to the initial operating conditions of 1.44 V forward voltage $V_{CEo}$, 0.001677 Ω On-state resistance ($R_{on}$), 0.007 Ω/w Thermal resistance (heat sink-ambient) ($R_{th}$) are tabulated in Table 2. At 12000 Hz operation 19.313 µW gate charge losses, 616.5701 W conduction losses. Analytical thermal losses are 618.450019458 Watts. The resultant efficiency of the UPFC is 96.39%. The reliability indices of the IGBT valve-based UPFC are tabulated in Table 3. The basic valve failure rate of 0.040432 failures/year, leading to $\lambda_1$=9.67 failures/year, $\mu_1$=60.81884 repairs/year, $\lambda_2$=2 failures/year, $\mu_2$=25 repairs/year, $\lambda_3$=0.10 failures/year, $\mu_3$=1.971808 repairs/year, the failure and repair rates of UPFC final three states. The converter is exhibiting 84% probability for the full operating condition, 13% probability for a derated mode of operation, and only 1% probability for non-operating conditions. The frequency of attaining $P_{up}$, $P_{DERT}$, and $P_{DOWN}$ are $f_{UP}$=8.28 Occ/yr, $f_{DERT}$=8.607 Occ/yr, $f_{DOWN}$ = 0.434 Occ/yr respectively. MTTF is 2.34 years. Obtained operational and reliability indices depict the complete picture of the UPFC performance. Obtained 2 years MTTF indicate the accuracy of the proposed reliability evaluation method than the mathematical modeling [29], physics of failure mechanism [30], and accelerated life time test method [31] which are resulting around 8 to 10 years of MTTF.

Table 2. Converter losses and efficiency

| S.No. | Parameter | IGBT |
|---|---|---|
| 1 | Current through leg (Icollector) | 217.47 A |
| 2 | Voltage drop across each switch (VCE) | 1.80 V |
| 3 | Voltage drop across leg | 3.60 V |
| 4 | Gate charge losses | 19.31 µW |
| 5 | Turn-on Power losses (Pon) | 369.00 W |
| 6 | Turn-off Power losses (Poff) | 116.20 W |
| 7 | Conduction losses (Analytical value) | 319.99 W |
| 8 | Conduction losses (Simulation value) | 308.93 W |
| 9 | Thermal losses (Analytical value) | 618.45 W |
| 10 | Thermal losses (Simulation value) | 616.57 W |
| 11 | Efficiency of the converter (ηc) | 96.29% |

Table 3. Converter reliability indices

| S.No. | Parameter | IGBT |
|---|---|---|
| 1 | $\lambda_v$ | 0.04 f/yr |
| 2 | $\lambda_1$ | 9.67 f/yr |
| 3 | $\mu_1$ | 60.81 r /yr |
| 4 | $\lambda_2$ | 2.56 f/yr |
| 5 | $\mu_2$ | 25.31 r/yr |
| 6 | λ3 | 0.10 f/yr |
| 7 | µ3 | 1.97 r/yr |
| 8 | $P_{UP}$ | 84.00 % |
| 9 | $P_{DERT}$ | 13.00 % |
| 10 | $P_{DOWN}$ | 1.00 % |
| 11 | $f_{UP}$ | 8.28 Occ/yr |
| 12 | $f_{DERT}$ | 8.60 Occ/yr |
| 13 | $f_{DOWN}$ | 0.43 Occ/yr |
| 14 | MTTF | 2.34 r |

## 7. CONCLUSIONS

Methodology for a comprehensive, systematic evaluation of the UPFC efficiency and reliability, is presented. Complete conduction, switching, and thermal losses occurring in UPFC are simulated and validated with theoretical calculations. Failure rate variation as a function of average junction temperature rise is examined. Valve failure rate estimation from, obtained thermal losses defined. Techniques to develop state space block diagrams and state merging concepts for UPFC are interpreted by employing Markov modeling. Methodology for comprehensive quantitative reliability evaluation, which includes efficiency as well as MTTF evaluation is exhibited. The efficiency and reliability of an IGBT valve-based 48 pulse converter UPFC are evaluated using a clear and systematic technique. The indices obtained will be used as a basis for future research to increase the UPFC's reliability.

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## BIOGRAPHIES OF AUTHORS

**Eniganti Sreeshobha** learned a bachelor's degree in Electrical and Electronics Engineering from Jawaharlal Nehru Technological University, a master's degree in Power Electronics from JNTU College of Engineering in Hyderabad, and is currently pursuing a doctorate at Osmania University in Hyderabad. She currently works as an Assistant Professor in the Department of Electrical Engineering, University College of Engineering, Osmania University, Hyderabad, India, Power Electronics, and Reliability are her research interests. She can be contacted at email: shobhasree555@gmail.com.

**Raddymalla Linga Swamy** received B.Tech degree in Electrical and Electronics from GRIET, Hyderabad, India in 2002 and the M.Tech degree in power electronics and drives from National Institute of Technology, Warangal, Telangana, India in 2004. Currently he is working towards the Ph.D degree in Department of electrical engineering, University College of Engineering, Osmania University, Hyderabad, Telangana, India. He is currently an Assistant Professor and areas of his interest are Multilevel Inverters, Space vector PWM. He can be contacted at email: lingaswamy.r@uceou.edu.